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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Quantum mechanics is a theory that adequately explains the behavior of a wide variety of phenomena ranging from atomic and subatomic scales to the macroscopic level. It is based on a clear formalism, has huge importance for the natural sciences and engineering, realizes phenomenal predictive success, and plays a vital role in technological developments. The perspective implied by quantum mechanics, not only encourages the understanding of modern applications, but also establishes the cognitive foundation for the interpretation of, both, the structure of matter and the evolution of atomic and subatomic phenomena (Kalkanis et al., 2003). Its foundational investigations, both experimental and theoretical quantum mechanics, gave birth to the field of quantum information technology. Quantum mechanics is, thus, an important part of the undergraduate physics curriculum and it is also important for many undergraduate students majoring in other sciences and engineering disciplines. Nevertheless, the conceptual changes that quantum mechanics has brought in our understanding of the nature of the subject matter are far-reaching and often counterintuitive to our everyday experiences. It is abstract, involves counterintuitive conceptual matter and does not fit into the macroscopic world we are used to where position and momentum are deterministic variables and their time evolution are seen to be governed by classical physics (Muller, 2008; Zhu, 2011). Quantum phenomena cannot be explained using the classical conception of subatomic entities and the mechanistic-deterministic perception of the physical world. Contrary to the situation in classical physics, in quantum mechanics, for example, the position, momentum, energy and other observables for a quantum entity are in general not well-defined. There is an inherent uncertainty in quantum phenomena: identical conditions lead to different, and thus unpredictable, results. Quantum mechanics only makes predictions about the probability of measuring different values based upon the wave function when a measurement is performed (Zhu, 2011).

This probabilistic interpretation of quantum mechanics is indeed challenging for most physics students since they do not conform to the experiences in the classical world. It is noteworthy that even most talented physics students who had passed the undergraduate quantum mechanics courses (at the modern physics and introductory quantum mechanics level) demonstrated many failures in understanding the fundamental quantum concepts and principles (Ireson, 2002; Singh, 2006). To most students who encounter quantum mechanics after introductory courses in the undergraduate physics program, it is mathematically formidable. However, far more difficult than the mathematics of quantum mechanics are its conceptual abstraction (Abhang, 2005; Singh et al., 2006). While studies dealing with conceptual understanding can be found in many areas of classical physics (see McDermott and Redish, 1999), physics education research on students' conceptions in the area of quantum mechanics are rarely studied (McDermott & Redish, 1999; Singh, 2001; Domert et al., 2006). Relatively little quantum mechanics education research has been done at the university level, and that which has been carried out has focused on pre-university and first year students primarily in the few topics of duality, atoms and quantum measurements (see Vokos et al., 2000; Ambrose, 1999; Johnston et al., 1998; Singh (2001); Fletcher, 2004; Singh et al., 2006; Olsen, 2002; Zhu & Singh, 2012). There has been, however, a steady increase in interest in research in the conceptual understanding of quantum mechanics over the last few years. For instance, some physics education researchers have focused on identifying, documenting and addressing students' conceptual frameworks of quantum mechanics in the undergraduate classroom settings (e.g., Vokos et al., 2000; Ambrose, 1999; Ireson, 2002; Mannila et al., 2002; Domert et al., 2005; McKagan et al. 2008(a); McKagan et al. 2009; Singh et al., 2006; Carr and McKagan, 2009); others have studied the effect of instructional strategies on students' alternative conceptions and conceptual difficulties (Muller et al., 2002; Budde et al., 2002; Singh, 2008; Wittmann et al., 2006; Zhu and Singh, 2013).

In the aforementioned studies, indeed, it is empirically established that traditional teaching methods are not particularly effective for student learning of quantum mechanics, and that research-based strategies, in which students participate more actively in class, lead to improved student learning. The studies repeatedly documented that student conceptions of quantum phenomena are often perceptually dominated, driven by naïve and classical conceptions and resistant to change in spite of the traditional quantum mechanics teaching. In general, these studies purported that these conceptual difficulties and misconceptions arise because of inability of many students to identify the conceptual frameworks of classical and quantum mechanics, producing epistemological obstacles to the attainment of the required knowledge. Many of the studies were carried out in the United States, Europe and also in Australia, there seems to be broad agreement across these studies about students' misconceptions with quantum mechanics, suggesting that the misconceptions are real, stable over time and cross-cultural (Singh et al., 2006; Ireson, 2002). Nevertheless, students' types of conceptual understanding may depend on context, particularly, on how and what students in a given physics course are taught in terms of their prior knowledge and experiences. For instance, in his research, Baily (2011) reported that university student perspectives on quantum phenomena can vary significantly by program setting or context. Thus, as reported by Baily (2011), it may be unrealistic to adopt a universalistic set of ideas for quantum mechanics teaching and learning in physics department as suitable for all cultures. Another problem recognized, relevant for research on physics students' learning of quantum mechanics, is that there has been, and still is a need for more qualitative research that aims to identify the descriptive categories which form the basis for physics students' understanding of quantum mechanics.

On one hand, most of the studies on students' conceptions of quantum mechanics have been carried out primarily at the first year level, using the common quantitative assessment tools and in western countries. On the other hand, the ineffectiveness of the traditional instructional method has not yet been tested on Ethiopian physics students in undergraduate contexts. Thus, there is a need for further exploration of our university students' conceptual understanding of quantum mechanics in Ethiopia. Furthermore, an important notion of improvement with regard to specific quantum mechanics learning and teaching is to be aware of the difficulties students typically face while learning and using the results to develop strategies to improve students' understanding (Singh et al., 2006).

In general, the present study is focused on physics students' depictions of quantum mechanics, the qualitative ways in which physics students' depictions differ and the dynamics by which physics students' depictions change. In particular, the principal aim of the investigation is to get a rich description of the variation in the undergraduate physics students' different depictions of the basic concepts of quantum mechanics and categorizing their depictions according to a set of categories using phenomenographic perspective (Linder, 1989; Marton & Booth, 1997; Bowden, 1995; Bowden & Walsh, 2000). The findings formed the basis for the development of research-based learning strategies to contribute towards efforts aimed at improving physics students' understanding of quantum mechanics at the university that provided the context for the study. In other words, using the findings of the principal investigation as a background, multiple representations-based instructions and an interactive quantum learning tutorials were developed to teach the conceptual topics of quantum mechanics. The aim of the subsequent study was, thus, to look at the influences of these instructional strategies and interactive tutorials involved in the conceptual topics of the undergraduate quantum mechanics course.

1.2 THE RESEARCH PROBLEM OF THE STUDY

The study of quantum mechanics has always presented huge learning challenges to the students who study these abstract concepts for the first time. For instance, wave-particle duality causes much confusion, as students' experience has been with things that act like particles, or like waves, but never both. It is usually easier (and more intuitive) to use classical physics than the more abstract quantum mechanics. To assist students to overcome the difficulties of understanding abstract and counterintuitive concepts, it is a common trend to resort to classical images of quantum mechanical effects (Fiol et al., 1997). The theoretical framework employed by quantum mechanics, however, differs drastically from that of the classical paradigm. Certainly, the transition from a classical to a quantum milieu marks an indisputable revolution in our understanding of the physical world. In view of this disconnect, it is particularly difficult for students to grasp the new concepts (Fiol et al., 1997). In order to overcome the obstacles in learning quantum mechanics students have to be made aware of the conceptual difference between classical and quantum physics, as well as the radical conceptual change called for quantum mechanics. Students, therefore, have to set aside some preconceived notions that they are brought up with and which stem from their experience of the macroscopic world. However, students who are educated according to the scientific norms found in classical physics and key concepts, such as determinism, causality, etc., can be easily influenced. Having accepted the key concepts of classical physics, they find it difficult to adjust to quantum mechanics concepts such as wave-particle duality, uncertainty, probability, etc. (Bao, 1999; Abhang, 2005). Furthermore, in learning classical physics students have already developed visualizable, qualitative mechanical models to understand abstract theoretical concepts used to explain physical phenomena (Brown, 1992). Such an understanding of classical physics with its use of mechanical models and concepts to explain the physical phenomena contributes to the difficulty of learning quantum mechanics and students' conceptions of quantum entities are essentially simple extensions of classical representations (Fischler & Lichtfeldt, 1992). The reason behind this is that ''classical models are persistent and prevalent mental images and very little advancement happens during further teaching'' (Mannila et al., 2002).

Despite the fact that the learning of quantum mechanics is hindered by students' preconceived classical conceptions, an understanding of many classical concepts is a prerequisite to a meaningful understanding of advanced physics such as quantum mechanics and others. When studying quantum mechanics, researchers exemplify two research results to illustrate the impact of student understanding of classical concepts (Steinberg et al., 1999). Typically, physics students first study mechanical waves and then physical optics before moving on to the courses such as modern physics and quantum mechanics. The reasons behind this argument are that the wave properties of matter, wave-particle duality, and atomic spectroscopy make no sense if students do not understand superposition, wave representations, and diffraction (Steinberg et al., 1999). Furthermore, ''Quantum physics builds on a classical base, using many classical concepts, variables, and representations. If students are weak on these items, learning of quantum physics may be difficult'' (Bao, & Redish, 2002). Nevertheless, many introductory quantum physics students still face significant challenges when they first learn about the probabilistic features and nonlocal theory of quantum mechanics, which disallows any classical interpretation (Ozcan, 2010; Baily & Finkelstein, 2010).

The empirical studies cited above and many others dealing with students' conceptual understanding of quantum mechanics can be found in many developed countries. This is not, however, the case in developing countries. Specific well-documented examples of student difficulties in conceptualizing quantum concepts are often lacking, and the exact nature of the difficulty is often uncertain mainly in a developing country like Ethiopia (Ayene et al., 2011). A finding from a previous study, in general, confirmed that students' problems in learning quantum mechanics are widespread and may originate from many other sources (Muller, 2008). To overcome this problem, there is a general agreement among physics education researchers that it is important to gain a better understanding of how students conceptualize and understand key concepts in physics (Prosser & Trigwell, 1999). This was justified as "The key to improving learning is not to be found by searching for 'the best teaching techniques' or 'the vital learning skills'. The truth is much more challenging. The puzzle can only be unlocked by examining what students already know about subject matter and the educational setting in which they learn it'' (Ramsden, 1988, p. 263). Thus, asking a phenomenographic question, such as, what are the different ways in which students depict the phenomena under investigation (e.g., the concepts of photon), could contribute to an understanding of the challenges. The principal purpose of this study is to characterize the variation in the ways that undergraduate physics students depict the basic concepts of QM and to extrapolate the results to scaffold possible changes to instructional practices at the university that provided the context for the study. In so doing, an adaptation of a developmental phenomenographic perspective is chosen (see Section

2.2.4 and 3.4). The study is focused on physics students' depictions of the fundamental concepts of quantum mechanics, which is about physics student learning of quantum mechanics. Physics students' depictions of quantum mechanics are purposefully chosen before looking at teaching aspects of quantum mechanics in Ethiopia undergraduate course settings. On one hand, physics education research into quantum mechanics still has a long way to go. On other hand, it is widely argued that physics education research into student learning acquaints instructional practice, rather than vice versa (Ramsden, 1988, p. 263; Falk, 2007).

In general, this study is conducted in two phases (i.e., the principal investigation and the subsequent study). Firstly, the principal aim of the investigation was to get a rich description of the variation in the undergraduate physics students' different experiences of the basic concepts of quantum mechanics. In particular the study was directed at identifying the description categories which form the basis for physics students' depictions of the basic concepts of quantum mechanics. Empirically, the study was approached through in-depth interviews with undergraduate physics students from two Ethiopian governmental universities (Wollo and Bahir Dar Universities) after they had been exposed to the traditional QM course for one third of a semester. In order to adequately investigate the research purpose, the theoretical framework for the analysis of the data was carried out using the developmental phenomenographic approach (Bowden& Walsh, 2000; Bowden, 1995; Bowden, 2005). The results from the first investigation were used to first sort the participants in terms of the categories that I had constituted. The results of the "picture" that emerged guided the design of the research-based learning strategies to contribute towards efforts aimed at improving physics students' understanding of quantum mechanics at Wollo University. The aim of the subsequent study was, thus, to look at the influences of the modified instructional strategies involved in the instructional topics of the undergraduate quantum mechanics course.

1.3 RESEARCH QUESTIONS

The principal purpose of this study is directed at identifying the nature of the categories of description (i.e., that form the outcome space at a collective level) which form the basis for a group of undergraduate physics students' depictions of the basic concepts of quantum mechanics. The research questions are, therefore, divided into one overall and several detailed questions. The overall research question is:

- What depictions of the basic concepts of quantum mechanics do a group of undergraduate physics students have, if any?

In particular, this is investigated through the following four detailed questions in the principal part:

1. How do a group of undergraduate physics students depict energy quantization, the quantum model of radiation and the photon concept?
2. Do physics students use a consistent depiction of one key quantum concept when presented with different physical situations?
3. Do physics students with inappropriate depictions of one concept also give inappropriate depictions of other concept in quantum mechanics?
4. How do a group of physics students depict the quantum model of matter waves and the uncertainty principle?

One of the main goals of physics education research is to understand students' experience of physics in ways that can inform improving teaching, curriculum and learning outcomes in physics education. Often, this has involved incorporating the findings of systematic research on students' difficulties into innovative instructional materials. As noted earlier, the findings of the study into physics students' depictions of quantum mechanics were extrapolated to scaffold possible changes to instructional practice at the university (i.e., Wollo University) that provided the context for the principal study. Thus, using the findings of the principal investigation (referred as Part I), multiple representations-based instructional strategies and interactive quantum learning tutorials were developed to teach the conceptual topics of quantum mechanics. While the investigation into student depictions of quantum mechanics and the instructional development and modification portions of the subsequent project took place in different year of physics student populations, it is expected that several identical issues exist at the university that provided the context for this study. Furthermore, Morgan (2006) claimed that the results we have identified in the investigation into student depictions of quantum mechanics provide useful insight for instructors at any level of quantum mechanics instruction.

In the subsequent part of the study (often referred as Part II), the effectiveness of the multiple representations-based instructions and the interactive tutorials were assessed to help undergraduate physics students develop a better conceptual understanding of quantum mechanics. The following research questions have guided the entire assessment of these instructional strategies:

1. How do physics students' depictions of the fundamental concepts of quantum mechanics differ from pre- to post-instruction and from post- to seven weeks after completion of the instructions on the topics of quantum mechanics?
2. What are the patterns of physics students' conceptual pathways of quantum mechanics from pre- to post-instruction to 7 weeks after completion of the new instruction on the topics of quantum mechanics?

1.4 SIGNIFICANCE OF THE STUDY

Quantum physics education research into the concepts held by students is insufficient and specific in only few topics of quantum mechanics. The few studies that have been carried out, have concentrated on secondary school education and first year university students.

The condition with regard to undergraduate physics students is, again, such that little or no research is present within the Ethiopian context. Specific well-documented examples of physics student difficulties in depicting quantum concepts are often lacking, and the exact nature of the difficulty is often uncertain. Indeed, context-specific research is necessary at a time when the physics departments in Ethiopian universities is faced with multiple pressures from the government and employers, from social economic and technological changes, and finally from the specific and changing demands of our undergraduate students. The principal research project described in this dissertation attempted to characterize the possible experiences in terms of categories of description which form the basis for the sorting of physics students' depictions of the fundamental concepts of quantum mechanics. The results of the study provide useful insight about physics students' conceptual learning and comprehensions relating to the fundamental concepts of quantum mechanics. They also provide evidence in identifying physics students' possible difficulties in learning quantum mechanics. The results of the study provide evidence to make suggestions for how the aspects of quantum mechanics should be taught and what should be taken into account by the instructional strategies that focus on improving physics students' perspectives in quantum mechanics courses. Most of the previous studies (Niedderer et al., 1990; Mashhadi, 1993; Ireson, 2000; Olsen, 2002) were conducted with pre-university students concerning their conceptions of quantum mechanics, but only a few studies (Vokos et al., 2000; Zhu, 2011; Baily, 2011) have specifically examined university students' (mainly at first year level) conceptions of the quantum mechanics so that the results of the present study are of significance to the field of physics students' conceptions literature as it extends the knowledge base that currently exists in the field of quantum mechanics. It is also hoped that this study will provide a baseline to allow other local physics researchers to continue investigations into the conceptions about the learning and teaching of advanced physics courses in the Ethiopian higher institution system.

As a final point, the subsequent study (i.e., at Part II; Chapter 6) has evidenced that the multiple perspectives-based instructions incorporated with the interactive quantum learning tutorials are the means to the best possible understanding of the wave- and particle-like properties of quantum entities and quantum phenomena. The findings have, therefore, potential to inform quantum mechanics instructors, physics teacher educators and quantum physics education researchers on the effectiveness of this research-based instruction in improving undergraduate physics students' understanding of quantum mechanical concepts.

1.5 CONTEXT AND SCOPE OF THE STUDY

In Ethiopia, starting from 2009, a new harmonized national curriculum for undergraduate physics was designed and has been implemented in all 22 public universities that are administered by the Federal Ministry of Education. Most of these universities (13 out of 22) opened during the last decade. In this harmonized national curriculum, the undergraduate physics program reflects the importance of quantum mechanics in modern physics courses. In the physics curriculum, quantum mechanics courses are often preceded by a modern physics course (along with special relativity), but these are typically rather introductory; the highly abstract and fundamental concepts of quantum mechanics only start in the second year quantum mechanics courses. Thus, in the second- and third-year physics program, basic quantum mechanics concepts and its most important applications are studied in detail. The quantum mechanics course descriptions, the recommended text and reference books and the modes of course delivery for all the courses are the same through the public universities in Ethiopia.

This study focuses on the undergraduate level of quantum mechanics course in two universities found in the Amhara regional state of Ethiopia. They are Wollo (i.e., selected from the newly constructed public universities) and Bahir Dar (from old universities) Universities. The participants were physics majors and at the time of the study they were taking their second semester of a quantum mechanics I course in the Department of Physics at Wollo and Bahir Dar Universities. As discussed earlier, these students have similar experiences concerning the course contents, the textbooks, and the teaching approaches.

For example, they had completed a modern physics course which comprises 45 lecture hours in their first year in 2010/11. The modern physics course covers a broad range of the modern physics course including topics such as special relativity and some of the concepts of quantum mechanics (see Table 1.1). In 2011/12, the sample students had also been exposed to the traditional approach to quantum mechanics I, a three-credit quantum mechanics course, for one third of a semester. During this time, they had been introduced to the basic quantum concepts (i.e., included in the phenomenographic interview for this study) and some postulates of quantum mechanics necessary to follow the remaining topics and courses. Table 1.1 presented the summary of the modern physics and quantum mechanics I courses completed by physics students who were recruited for interviews.

Table 1.1: Summary of the two quantum mechanics courses completed by the students

Quantum Mechanics Course	**Description of Topics**	**Lecture Hours Devoted**	**Texts and Referencing Books**
Modern Physics	Principle of Special Theory of Relativity; Michelson-Morley experiment; Galilean transformation; Lorentz transformation; length contraction; time dilation; relativistic momentum and energy; Blackbody radiation; photoelectric effect and Compton effect; matter waves; uncertainty principle, and atomic structure.	45	(Beiser, 2002; Serway, 2004)
Quantum Mechanics I	Limitations of classical mechanics, origin and development of quantum mechanics, review of modern physics (particle aspect of radiation, wave aspect of particles, particles versus waves, Heisenberg's uncertainty principle, probabilistic interpretation, wave packets); Mathematical foundation of quantum mechanics; operator algebra, Schrodinger and Heisenberg	16 + 5 hour tutorials	(Brandsen and Joachain, 2000; Townsend, 2000)

Quantum Mechanics Course	Description of Topics	Lecture Hours Devoted	Texts and Referencing Books
	equations, and the harmonic oscillator.		

As presented in Table 1.1, the Quantum Mechanics I course consists of two parts with different emphasis. The emphasis in the first part, chapters covering basic topics, is on purely conceptual understanding and qualitative reasoning. In the second part, chapters covering quantum postulates and necessary mathematics, an introduction to the quantum mechanical formalism are presented. In investigating physics student understanding in any area of the undergraduate physics courses, it is common to focus on a rather specific and well-defined core content area. In this study, the focus was on the first emphasis of the Quantum Mechanics I course, physics students' conceptual understanding and qualitative reasoning of basic topics in quantum mechanics.

1.5.1 Why Concepts of Quantum Mechanics?

Quantum mechanics is widely regarded as a notoriously difficult subject for undergraduate physics students due to its abstract, counter-intuitive conceptual foundations and highly mathematical nature (Fletcher, 2004). For most undergraduate physics students, however, Abhang (2005) claimed that far more difficult than the mathematics of quantum mechanics are its conceptual foundation. This conclusion is also supported by Singh et al (2006) that "most students who do well on quantitative quantum problems have difficulty when essentially the same problems are posed qualitatively". In most instances, conceptual understanding and/or qualitative reasoning is much more difficult than capability with the mathematical aspects (Singh et al, 2006). While we cannot ignore the role of mathematics and abstract formalism in quantum mechanics, obtaining a conceptual understanding of fundamental quantum concepts has been recognized as important especially in the undergraduate courses. Thus, studies which focus on the development of conceptual understanding have a better opportunity to determine the progress of student learning of basic concepts through the undergraduate quantum mechanics course. The research presented in this thesis is, therefore, bounded on investigating physics students' depictions of basic concepts in Quantum Mechanics I course, including quantization, the photon concept, the interaction between light and matter and the photoelectric effect, the wave-particle duality and double-slit experiment, the wave nature of matter and the uncertainty principle. These quantum mechanical concepts were chosen as the content area for this study for the following reasons:

- that they have been regarded as the most distinguishable features in which quantum mechanics differs from classical theories of the physical world;
- that they are features of quantum phenomena that can serve as the foundation in understanding postulates of quantum mechanics;
- that they are seen as parts of threshold concepts in Quantum Mechanics, "A threshold concept opens up a new and previously inaccessible way of thinking about something. It represents a transformed way of understanding, or interpreting, or viewing something without which the learner cannot progress"(Meyer & Land, 2003). This is valid, for example, of the wave-particle duality and the uncertainty principle, as failure to comprehend either concept prevents real and appropriate understanding of other quantum topics. Indeed, failure to understand these concepts may create an obstacle to any further study of quantum mechanics;
- that research into the concepts held by undergraduate physics students mainly in Ethiopia and elsewhere is very rare in these concept areas.

Thus, throughout the principal part of this thesis (i.e., Part I), using the developmental phenomenographic perspective, the different elements of physics students' depictions of these quantum concepts were discerned and the structure of their categories of description was constructed. By interpreting these differing qualitative categories of description that were drawn from students' depictions, specific student difficulties associated with these quantum concepts were also identified and discussed. The results from Part I were applied to develop the research-based learning strategies (i.e., based on incorporating multiple representations-based instruction with interactive quantum learning tutorials) to contribute towards efforts aimed at improving physics students' understanding of quantum mechanics. These research-based learning strategies are discussed in Part II of this dissertation (Part II; see Chapter 6).

1.6 TERMINOLOGY USED IN THE THESIS

Throughout this thesis, various terms and/or phrases were used which have specific meanings. As an organizer for these terms this section will provide a centralized place for the definitions. The following is done logically rather than alphabetically. More complete definitions can also be found in the thesis when the terms are first introduced.

Student Depictions:

It is difficult to give a general definition of the term, depiction. Its definition in the literature, however, consists of an inclusive body of knowledge about an idea or a phenomenon (Falk, 2007). In this study, the term students' depiction is refereeing something wider than the common "students' conceptions". The choice to use the term depictions is that the research in this thesis is a detailed investigation of physics students' depictions of quantum mechanical concepts and phenomena through verbal descriptions, graphical and pictorial descriptions, writing, and the language of mathematics. As argued by Falk (2007), the intention for using depiction is a matter of choosing a wider term or "an inclusive term that would allow many types of student descriptions, and also to create a neutral theoretical-perspective stance for these descriptions".

Conceptual Understanding:

Conceptual understanding involves the ability to picture and describe concepts (e.g., determinism or uncertainty), the ability to distinguish between closely related concepts, as well as the ability to reason about physical process without detail mathematics and decide how changes affect the outcome of the process (Allen, 2001).

Concept:

In the literature, the use of the word concept is broad. On the basis of Ausubel's (2000) and (1968) work, Novak (2002) defines ″concept″ as a perceived regularity or pattern in events or objects, or records of events or objects, designated by a label.

Conceptual Change:

Knowledge structures that become fundamentally changed, expanded and restructured as a result of strategic planned instructional activities and finally become the conceptual framework that students use to solve problems, explain phenomena and function in their world (Posner et al., 1982; Ebenezer, 1991).

Phenomenography:

A research approach which aims at mapping the possible qualitatively different ways in which students depict, conceptualize, and understand a special domain of knowledge or various phenomena (Marton & Booth, 1997). Trigwell (2000) has summarized the key elements of a phenomenographic perspective by stating that Phenomenography: "…takes a relational (non-dualist), qualitative, second-order perspective, that it aims to describe the key aspects of the variation of the experience of a phenomenon rather than the richness of individual experiences and that it yields a limited number of (internally related), hierarchical categories of description of the variation" (p. 1). Outcomes of the phenomenographic research are portrayed analytically as a number of possible qualitatively different ways of depicting, for example, the quantum phenomenon (called 'categories of description'), but also counting the structural relationships linking these different ways of depicting this quantum phenomenon (Åkerlind, 2005). According to Åkerlind (2005), these structural relationships describe the structure of the 'outcome space', in terms of presenting an explanation of relations between different ways of depicting the quantum concept, in this study for example, quantization, the photon concept or light quanta in the double-slit experiment.

Categories of Description:

It is an interpretative descriptive category of description that characterizes a depiction or conception; an interpretation of students' interpretation or understanding of a quantum phenomenon. Each category should represent a possible qualitatively different kind of understanding a quantum phenomenon or concept.

Outcome Space:

In phenomenographic analysis, the description categories are based on the most distinctive features that differentiate one way of depicting of (e.g., the photon concept) from another in the hierarchical system called 'outcome space'. The qualitatively different ways of depicting are represented in the form of categories of description, which are further analyzed with regard to their logical relations in forming a hierarchical system outcome space. The outcome space is, thus, an abstract space made up of categories of description in which the students' depictions of the phenomenon under investigation (e.g., the photon concept) may range (Marton & Booth, 1997). It presents variation in the structure of collective awareness which reflects the line of development from fragmented understanding of, for example, the photon concept as a whole towards more discerned and complex whole-part relationships.

Traditional (conventional) teaching methods:

It is a common instructional method that is "relying primarily on passive-student lectures, recipe labs, and algorithmic problem exams" (Hake, 1998, p. 65).

Multimodality:

Multimodality refers to the orchestrated use in knowledge construction of different types of representations in terms of modality (verbal, graphical, mathematical, pictorial or visual) or number (more than one representation of the same type) to portray scientific analysis and interpretation (Waldrip, Prain & Carolan, 2006; Airey & Linder, 2009).

Multiple representations-based instructions:

Multiple representations can be generally defined as providing the same information in more than one mode of representation (Goldin & Shteingold, 2001; Fredlund et al., 2012; Linder, 2013). Multiple representations-based instructions are, thus, a kind of instructional strategy that involves multiple representations in concepts explanations. Representation and visualization of physics concepts and microscopic phenomena using (e.g., textual, pictorial, graphics and equations), simulation and analogy, using virtual laboratory and connections among key phenomena and concepts (Abdurrahman, 2010) can be counted as what multiple representations-based instruction provide for physics students in the subsequent study (i.e., Part II; Chapter 6) of this thesis.

Interactive Quantum learning tutorials:

It is an interactive quantum mechanics learning environment that exploits computer-based visualization tools in which students have an opportunity to confront their misconceptions, draw qualitative inferences and build links between the formal and conceptual aspects of quantum mechanics (Singh, 2008). Different computer-based visualization tools from a number of sources and a Physics Education Technology Project (PhET) Interactive Simulation developed at the University of Colorado (McKagan et al., 2009) were adopted in this thesis. In this study, the interactive quantum learning tutorials are given as part of laboratory session to reinforce conceptual understanding after the physics students have worked on the main weekly multiple representations-based instructional sessions.

1.7 LAYOUT OF THE THESIS

This thesis has begun with the description of the background to this study. It has introduced the problem statements and the rationale for conducting the study in the area of quantum mechanics, as well as the significance of the research in the higher education system of Ethiopia. The research contexts and scopes specific to this study were explained. Terminologies used in the thesis were also provided. Chapter 2 provides a comprehensive review of physics education research and specific quantum mechanics education research in physics as well as the research framework and the theoretical viewpoint from which the research was conducted. Chapter 3 has set the methodological frameworks used in the principal part of this study. It presents the general philosophical framework of the research and outlines the choice of research paradigms. It explains the research methodology and clarifies how the principal study was performed. It also outlines the qualitative approach of the research, the framework and the methods used for collecting qualitative data.

The analysis, results and findings are done in two chapters coinciding with the areas of the principal research emphasis and questions (Part I; Chapters 4 and 5). For instance, Chapter 4 discusses the analysis, results and the main findings of physics students' depictions of energy quantization, the photon concept and light quanta interference. Similarly, Chapter 5 gives a detailed analysis and findings of physics students' depictions of the wave nature of matter and the indeterministic nature of quantum phenomena. Thus, the two chapters (Part I; Chapters 4 and 5) present: the analysis of qualitative data, results and findings (i.e., discuss the categories of description of physics students' depictions of the basic concepts of quantum mechanics) and the conclusions, discussions and implications arising from this principal study.

In general, in Chapters 4 and 5, identifying the description categories which form the basis of students' depictions of quantum mechanics gave us an idea of the types of possible difficulties that physics students have in expounding quantum entities. These findings served to inform the development of instructional materials designed to positively influence physics students' conceptual understanding of quantum mechanics. A subsequent study (Part II; Chapter 6) was conducted during the implementation of these instructional materials and interactive learning tutorials in the basic concepts of quantum mechanics. The details of the development, implementation and findings of these instructional strategies and learning tools are presented in Chapter 6.

The thesis is concluded with Chapter 7, which contains some concluding remarks, outlines of implications for quantum mechanics teaching and learning as well as an outlook and topics for future considerations.

CHAPTER 2
LITERATURE REVIEW AND FRAMEWORK OF THE STUDY

2.1 LITERATURE REVIEW

2.1.1 Introduction to Physics Education Research

Physics Education Research (PER) is a relatively new area of research that come into view from physics practitioners' interest in teaching and learning of physics (Redish & Steinbereg, 1999). It has been hypothesized in PER that physics is widely recognized as an exceptionally demanding discipline to understand (McDermott, 2001; van Heuvelen, 1991). In PER, detailed investigations of the learning and teaching of physics are conducted that can influence the development of more interactive learning environments. The convincing evidence of several PER studies have proved that students have great difficulties in understanding the basic concepts of physics, and despite good performance in physics courses students emerge after conventional physics instruction with severe misconceptions (Halloun & Hestenes, 1985;Trowbridge & McDermott, 1980). The scope of the problem was first recognized when systematic research into physics education started in the middle of 1970's. From the late 1970's on-wards, considerable amount of work has been done in identifying and describing student conceptions about physics that differ from the accepted scientific ideas. In the last three decades, PER has shown strong evidence that students do not learn much from a conventional lecture course in physics and many physics students seemed to emerge from physics teaching with substantial gaps in their understanding of physics (Hake, 1998). Later, with inspiration from general science education, PER has moved into a central role in exploring students' difficulties in learning physics, and developing and analyzing new teaching methods (McDermott, 1998).

Researchers in the area have presented several purposes for physics education research: Redish and Steinberg (1999) proposed that PER aims at answering questions like what is involved in understanding physics? What do students bring to physics classes? And how do students respond to physics instruction? McDermott (1998) has emphasized the improvement of instructional strategies, and pinpointed that the aim of PER is "to investigate the relationship between teaching and learning and strengthen the link." Generally, research in physics education has been successful in identifying some of the fundamental problems students have with understanding physics concepts and with the development of instructional materials and curricula development for effective ways to overcome some of these problems (McDermott & Shaffer, 1998). However, hundred years after the beginning of quantum mechanics very little PER work has emerged on student understanding of such revolutionary phenomena.

Based upon the distinct emphasis of the study in this dissertation, in the subsequent sections, related literature reviews are organized in the following way:

- Physics education research in relation to quantum mechanics
- Students depictions' of quantum mechanics
- Research on development of instructional innovations on quantum mechanics
    a) Computer simulations and interactive learning tutorials in quantum mechanics
    b) Multiple representations-based instructions in quantum mechanics.

2.1.2 Physics Education Research in Relation to Quantum Mechanics

Quantum mechanics is the set of ideas that scientists use to study the microscopic world. It has become the basic tool of modern physics, and has been applied to an enormously diverse range of fields and applications just as successfully to the challenges of modern day research and technology. Since its development over the last century, quantum mechanics has not only turned into the basic theory of microscopic physics but also play a central role in chemistry, molecular biology and nuclear medicine (Falk, 2004). However, it is widely acknowledged as an exceptionally academically demanding subject to understand particularly for students who study the area of physics for the first time (Fiol et al., 1997; Muller, 2008).

Understanding quantum mechanics requires that students have to set aside some preconceived notions that they are brought up with and which stem from their experience of the macroscopic world. However, students are educated in the norm of classical physics, and key concepts, such as determinism, causality, etc are very persuasive. Having accepted the key concepts of classical physics, they find it problematic to amend to those of quantum mechanics concepts such as uncertainty, probability, etc (Bao, 1999; Abhang, 2005). Furthermore, Brown (1992) indicated that in learning classical physics students have already developed visualizable, qualitative mechanical models to understand theoretical concepts used to explain physical phenomena. Such an understanding of classical physics with its use of mechanical models and concepts to explain the physical phenomena contributes to the difficulty of learning quantum mechanics (Fischler & Lichtfeld, 1991). For example, Fischler and Lichtfeld (1992) found that students' conceptions of quantum entities are essentially simple extensions of classical representations. According to Mannila et al. (2002) the reason behind this is that "classical models are persistent and prevalent mental images and very little advancement happens during further teaching."

Despite the fact that classical pictures of students' hinder learning quantum mechanics, understanding many classical concepts are prerequisite to a meaningful understanding of advanced physics such as quantum mechanics and others. When learning quantum mechanics, researchers exemplify two research results to illustrate the impact of student understanding of classical concepts (Steinberg et al., 1999). Physics students first typically study mechanical waves and then physical optics before attending to the courses such as modern physics and quantum mechanics. The reasons behind this argument are that the wave properties of matter, wave-particle duality, and atomic spectroscopy make no sense if students do not understand superposition, wave representations, and diffraction (Steinberg et al., 1999). Furthermore, Bao and Redish (2002), proposed that "Quantum physics builds on a classical base, using many classical concepts, variables, and representations. If students are weak on these items, learning of quantum physics may be difficult.” Keeping these difficulties in mind, recently, various groups in different parts of the world have been carrying out research on the investigation of students’ difficulties of quantum mechanics and on making quantum mechanics both understandable and interesting. A comprehensive list of physics education research in relation to quantum mechanics had been presented by Fletcher (1997), Falk (2007) and Muller (2008).

With reference to the secondary school instruction, there is solid evidence that the unsystematic introduction of subatomic phenomena by means of classical analogies or semi-classical models causes inappropriate intermixture of the conceptual systems of classical physics and quantum mechanics (Niederer, Bethge & Cassens, 1990; Millar, 1999). Students’ knowledge is also characterized by a rather ‘classical perception of quantum physics’ that shows elements of both mechanistic and quantum ideas (Ireson, 1999; Mashaldi, 1995). Other studies conducted by Johnston, Crawford and Fletcher (1998) investigated that participating students had difficulty describing what characterizes a particle or a wave. Moreover, Ambrose (1999) and Vokos et al. (2000) studied students’ understanding of the wave nature of matter in the context of interference and diffraction of particles and discovered that students had difficulty interpreting interference and diffraction in terms of a wave model. Other examples of studies of conceptual understanding in quantum mechanics are Bao and Redish (2002), which is an investigation of university students understanding of classical probability and the implications of this understanding for teaching quantum mechanics. There is also a study in quantum mechanics that proposes ways of presenting the material that are found to improve the learning of the students some on quantum concepts (Singh, 2008). For example, Singh developed a quantum interactive learning tutorials (QuILTs) which are suitable for undergraduate courses in quantum mechanics. The material is based on students difficulties in learning quantum physics and one can be used both as supplements to lectures or a self-study tools. The development of probing instruments that can provide effective measurement on the various aspects of students understanding of quantum mechanics has also been studied (e.g., Falk, 2004; Wuttiprom et al., 2008). In conclusion, it is evident from the cited studies that PER related with quantum mechanics has been involved on various areas, such as, detail investigations of students difficulties in learning specific topics of quantum mechanics; on the development of learning theories to characterize the learning process particularly the conceptual learning that take place in the context of learning quantum mechanics; on the development of probing instruments that can provide reliable and effective measurement on the various aspects of students understanding of quantum mechanics; and on the development and implementation of the innovative instructional tools that can provide students with a more effective learning environment (Bao, 1999).

2.1.3 Students' Understanding of Quantum Mechanics

Physics education research in quantum mechanics has been growing in the last fifteen years with an increased number of research concentrations ranging from pre-university to university level. For example, there has been considerable research interest on students' depictions of quantum phenomena (Falk et al., 2007). Based on the research reviewed by Falk et al. (2007), findings in quantum mechanics education research revealed that students are struggling with the subject. Falk et al. (2007) reported that: "qualitative studies show that many students have considerable problems to depicting a vast array of quantum mechanical topics in an accepted way" (p. 92). In PER, student understanding of atoms, and trying to improve this understanding, is the obvious concepts documented (Mashhadi, 1993). The most important finding in this research is that most students use classical atomic model in their expressions. Fischler and Lichtfeldt (1992) have also reported that in a German pre and post study, 63% of 270 pre university students used the classical orbits depiction prior to a course dealing with quantum mechanical orbital theory and 22% of the students still used the classical orbits depiction after the pre quantum course.

A study in Norway also indicated that students depicted photons as having a dual-nature existence, having both wave and classical particles, whereas electrons were depicted as classical particles only (Olsen, 2002). Unlike the case of the Norwegians, a study in Finland revealed that a classical depiction of both electrons and photons was common among a group of physics students (Mannila et al., 2002). Mannila et al. (2002) has explored student depictions of quantum phenomena in the specific context of a single-quanta double-slit experiment. In their study, Mannila et al. (2002) found that student responses were highly dominated by quasi-classical and/ or trajectory-based frameworks, and that very few students depicted descriptions that were aligned with quantum models. These researchers also reported that many instances of mixed student perspectives within that specific context of a single-quanta double-slit experiment (Mannila et al., 2002). As with other studies, Morgan et al. (2004) found that all six students that they interviewed depicted that the particle lost energy when it went through a potential barrier. Based on their findings, Morgan et al. (2004) speculated that students' depictions that energy is lost were built on intuitive classical ideas about a particle passing though a barrier. In the same vein, Baily and Finkelstein (2010) explored that the majority of students participated in their study demonstrated a preference for classical-like interpretations of quantum phenomena.

In the case of quantum phenomena and entities, previous studies have tried to illustrate how the depiction used to describe certain quantum mechanical systems may in fact pose extraordinary difficulties, especially if students are not aware of how and why quantum terms are being used (Fletcher, 2004; Kalkanis et al., 2003; Singh et al., 2006; Baily & Finkelstein, 2010). The depictions, grounded in the classical framework, may encourage students to associate extra (classical) properties with the quantum mechanical system as they try to coordinate these new representations with their prior understanding of the macroscopic world (Mannila et al., 2002; Kalkanis et al., 2003; Baily & Finkelstein, 2010). These over-extensions of the interpretations seem to be the source of the majority of students' difficulties in learning the basic ideas of quantum mechanics. However, studies have reported that student depictions may be sensitive to context and it may not be possible to make generalizations about student ideas based on explorations within a limited contexts and problem areas (Baily & Finkelstein, 2010).

As already stated, very limited physics education research has been undertaken regarding students' perspectives of quantum mechanical ideas in higher education and none in the higher institutions of Ethiopia (Ayene et al., 2011). As a result, it is not known that after traditional instruction, whether physics students in Ethiopia are likely to show classical misconceptions and to confuse classical and quantum notions or not. There is clearly a need for more sensitive approaches to the process and practices of teaching and learning of quantum mechanics in Ethiopian universities. A detailed investigation into physics students' depictions of quantum mechanical concepts are therefore necessary, since it is an aspect of understanding quantum mechanics, and have implications for how traditional content and approach in the undergraduate quantum mechanics course might be modified. The research described in this thesis is intended to strengthen the current research base in quantum mechanics education literature and extend it to include topics that have not fully explored in Ethiopia and elsewhere.

2.1.4 Research on the Development of Instructional Innovations on Quantum Mechanics

Physics education research has evidenced that after traditional instruction, many students are likely to show classical ideas and to confuse classical and quantum models (Hadzidaki, et al., 2000; Muller & Wiesner, 2002). As a result, researchers have given a great deal of energy and attention to the question of how to help students learn/construct the concepts of quantum mechanics faster/better and the difficulties that students have in changing their classical and naive ideas. For instance, in the studies about how to teach quantum mechanics, Jones (1991) and Hood (1993) tried to develop an improved way of teaching of quantum mechanics by exploiting concepts and using simple mathematical methods. Fischler and Lichtfeldt (1992) also advocated a teaching approach, which considered possible conceptions of students and provided room for these conceptions to develop in class, which would lead the students to gain with the subject. In a continuing effort to modify the traditional teaching practice, Roussel (1999) identified new ways to improve conceptual understanding in quantum mechanics. He proposed to put more emphasis on the quantum mechanical concepts instead of the application of complex mathematics used by experts in typical introductory quantum mechanics courses. Similar qualitative and conceptual teaching approaches have been suggested to provide students with comprehensive and visual experiences related to the basic ideas of quantum mechanics. Hadzidaki, et al (2000), for example, argued that conceptual understanding of topics in quantum mechanics requires that students develop a new way of understanding about the physical world. As a solution, they acknowledged a quantum mechanics teaching reform that would involve more qualitative teaching approach based on epistemological and pedagogical foundations rather than on mathematical problem-solving approaches (Hadzidaki et al., 2000). According to these researchers, a qualitative approach in teaching quantum mechanics could limit the development of serious misconceptions and support the students to form a more comprehensive understanding that is compatible with experts understanding of the classical and quantum worldviews (Hadzidaki et al., 2000).

Recently, various groups of researchers interested in instructional innovations have focused on computer simulations and other visualizations of quantum phenomena. For example, the Physics Teaching Research Group at the University of Maryland is involved in various projects to study student understanding of quantum mechanics and to build a model course for scientists and engineers (Redish & Steinberg, 2002). The visual quantum mechanics project at Kansas State University is also concerned with presenting quantum phenomena using visual aids other than traditional lectures (Rebello & Zollman, 1999). Research has pointed out, in general, the importance of computer simulations and visualization (e.g., McKagan et al., 2008b; Zollman et al., 2002), virtual environment and interactive tutorials (e.g., Steinberg et al., 1996; Müller & Wiesner, 2002; Singh, 2008; McKagan et al., 2009) and multimodal representations (e.g., Gunel et al., 2006; Abdurrahman, 2010) in learning and teaching and developing scientific understanding of quantum mechanical concepts. The following subsections review studies that have pointed out the importance of computer simulation, interactive tutorials and multiple visualizations in learning and teaching and developing quantum mechanical understanding.

2.1.4.1 Computer Simulations and Interactive Learning Tutorials in Quantum mechanics

In quantum mechanics the need for visualizing quantum entities presents a huge problem in pre-college and university physics teaching environments. Conventional models used to represent the quantum world have proven to be counterintuitive for many students. In fact, instructors used conventional models to describe the behaviors of microscopic entities, but many students have problems relating the macroscopic observations to the underlying atomic behavior. Recently, advances in computer-based technology have lead to various innovative educational materials including PhET simulations, interactive tutorials, static and dynamic visualizations and also virtual laboratory experiments. These innovative instructional materials are found useful to visualize, in particular, microscopic processes facilitating for better conceptual understanding of the subject matter.

On this basis, for example, Styer (2000) has developed computer-based tools for use in visualizing quantum phenomena and argues that using simulation and visualizations provide a useful vehicle for developing quantum intuition. To eliminate the classical point of view in describing quantum topics, Hadzidaki et al (2000) also proposed computer simulations as one key instructional tool to represent quantum phenomena and replace the missing sensory experience of quantum mechanics. In particular, these researchers created visualizations of the hydrogen atoms orbital using computer simulations and argued that this visualization accomplishes: (a) eliminates the classical concepts of fixed orbits and states in quantum worldview; (b) shows that the orbital is a picture formed by the possible positions of the electron; (c) breaks the limits of practical knowledge of microscopic systems ($\Delta p \Delta x \geq \hbar$); and (d) depicts the density of the point-per-unit volume, which visualizes the probability density of finding the electron inside this volume (Hadzidaki et al., 2000). Other researchers have reported even more empirical studies. Zollman et al (2002) have integrated quantum mechanics as part of the introductory level physics with developed visual quantum mechanics (VQM) materials. The preliminary results asserted that VQM material can enhance novice physics students' understanding of quantum phenomena (Zollman et al., 2002). Müller and Wiesner (2002) have also developed computer-based laboratory experiments in their course designed for gymnasium students. They discuss two simulations (i.e., a Mach- Zehnder interferometer simulation and a second simulation that uses a double-slit apparatus which electrons pass through) used in the redesigned quantum mechanics course. By contrast the control group, Müller and Wiesner (2002) found that the correct quantum models were successfully imparted to most of the students of the experimental group. In the same way, Pereira et al (2009) have introduced a computational simulation of the Mach–Zehnder interferometer to help students' understanding of the dual behavior of photons. The computational simulations provide the properties of a photon by avoiding the misinterpretation in which quantum objects are seen as classical particles. By analyzing transcribed dialogues, the researchers observed that the virtual interferometer helps the students to perceive how quantum phenomena deviate from our classical everyday experience (Pereira et al., 2009).

Interactive computer-based tutorials have also been shown to be especially effective in activity-based learning environments to provide concrete learning experiences, improve student motivation toward quantum mechanics, and to improve student conceptual learning (Steinberg et al., 1996; Singh, 2008; Pereira et al., 2009; McKagan et al., 2008b; McKagan et al., 2009). Steinberg et al (1996), for example, investigated a computer-based tutorial on the photoelectric effect. The researchers have used the interactive tutorial both as a support to instruction and as a probe to explore further ideas about the nature and persistence of particular difficulties. They found that students who involved in the interactive tutorial make better explanations than students who have not had this interactive tutorial (Steinberg et al., 1996). Furthermore, similar interactive learning tutorials that assist students' visualization of quantum phenomena by creating an active learning environment have been associated with gains in conceptual understanding among students in quantum topics, such as: the time development of wave function, the uncertainty principle and the formalism of the addition of angular momentum (Singh, 2008; Zhu & Singh, 2012; Zhu & Singh, 2013). Singh (2008) designed interactive environments, the Quantum Interactive Learning Tutorials (QuILTs), for the time development of wave function, the uncertainty principle and the Mach–Zehnder interferometer. The design of each QuILT starts with an analysis of the difficulties students have in learning related quantum mechanical concepts. The design of the QuILT, then, went through cyclic stages from developing the preliminary version based upon theoretical analysis to refinement and modification based upon the feedback from the implementation. Preliminary evaluation evidenced that the QuILTs are efficacious in improving students' understanding of the targeted quantum mechanical concepts (Singh, 2008; Zhu & Singh, 2013).

In summary, researchers have concluded that effective use of PhET and/or other simulations, visualization tools, interactive learning tutorials has been shown to lead to a number of important outcomes, such as effective conceptual learning, improved critical thinking, better qualitative reasoning and problem-solving skills, as well as the developing of other innovative learning tools that can enhance related scientific abilities (Müller & Wiesner, 2002; Singh, 2008; Pereira et al., 2009; McKagan et al., 2008b). However, teaching and learning techniques with these computer-based innovative learning tools remain relatively under-reported.

2.1.4.2 Multiple Representations-based Instructions in Quantum Mechanics

In the process of depicting their ideas and findings, scientists often use multiple of representations such as, figures (both static and animated), graphs, diagrams, mathematical equations, pictures, computer-based simulations or a combination of these forms to articulate their understanding. All of these ways of representing scientific ideas and concepts are different modes (multimodal) of representation. From this perspective, multimodality can be seen as the integration in science discourse of different modes to represent scientific ideas, concepts, reasoning and findings (Waldrip, Prain, & Carolan, 2006). Multimodal representations are, thus, simply the ways scientists communicate ideas or concepts by representing them in the form of these multiple modes. Researchers have argued that just as scientists represent ideas and concepts in these multiple modes to communicate with others so, also, do science students learn about those ideas and concepts using the same forms of representation (Mayer, 2003; Bennett, 2011). Recently, it has become part of a science teacher's task not only to use multiple modes of representation in the classroom to support student learning but also to make such resources accessible to students for sense-making within a constructivist framework (Gunel et al., 2006).

Advances in visualization and computer technologies have also created new possibilities in designing and implementing multiple representation-based instructions. For example, de Jong et al (1998) have studied the pedagogical functions of using more than one form of computer-based representation software or multiple representations. As noted by these researchers, multiple modes of representation in computer-based learning environments are very important to display learning material that contains a variety of information. In the same way, Ainsworth (1999) claimed that multiple modes of representation can support learning by providing complementary information, by constraining interpretations or misinterpretations of phenomena and by supporting deeper learning of concepts through: abstraction, extension or extending knowledge learned in one representation to new situations with other representations and relations (i.e., translating between two or more unfamiliar representations). There is also evidence to suggest that single modes, for example, text only do not always work and that for deep understanding to occur, science students need opportunities to move between multiple modes (Mayer, 2003). As Benedict et al (2002) underlined, when a scientific topic is abstract, counterintuitive and complex, well designed multiple modes of computer-based representations can bring its concepts closer to the student. This is especially true for quantum phenomena which require an adequate use of multimodal representations and a deep conceptual understanding of the underlying abstract concepts. Because of the complex and invisible nature of quantum phenomena and the abstract nature of many of the concepts of which it comprised, the multiple modes used to understand these phenomena have a strong impact on physics students' understanding of quantum concepts (Robblee et al., 1999; Zollman et al., 2002; Gunel et al., 2006; Abdurrhman, 2010; Kohl & Finkelstein, 2006).

Gunel et al (2007) compared student understanding of two quantum concepts (i.e., photoelectric effect and Bohr's atom model) when embedding multimodal representations into two different writing formats: presentation format versus summary report format. A pre –post test method was used to compare performances of these two groups across these two quantum concepts. These researchers found that for both topics students using the presentation format group scored significantly better on tests than the summary report format group. In the results, the effect size difference between the groups increased for the second concept, referring that more practice was leading to better student conceptual understanding of the quantum concepts. Furthermore, the findings in the study would suggest requiring students to explain concepts using multiple modes, and minimizing the amount of text available for interpretation is beneficial to conceptual understanding (Gunel et al., 2007). Abdurrhman (2010) also completed similar research on designing learning and teaching quantum physics with rich environment based on multimodal representation and its influence toward quantum concepts mastery, generic science skills and critical thinking disposition for physics teacher students. In particular, the study compared a multimodal representation-based instruction with a the conventional instruction for pre-service physics students learning concept covering Photoelectric effect, Bohr's atom model and solution of the Schrödinger Equation for a 1 D quantum box system and the Hydrogen atom. A mixed design study was conducted on pre-service physics students of the Mathematics and Science Education Department, at a public University in Lampung Province. The results showed that multiple representations based-instructions had a significant effect toward pre-service physics students' quantum concept mastery of the Photoelectric Effect, Bohr's Atom Model and Schrodinger's Equation. This result clearly revealed that multiple representation-based instructions were better than the traditional instructions. Furthermore, significant differences on students' Generic Science Skills in indirect observation, sense of scale, symbolic language, logical self-consistency and mathematical modeling were reported in the study (Abdurrhman, 2010).

Based on the results of these studies, it is expected that teaching and learning environments that integrate multiple representations based-instructions with interactive learning tutorials can be effective in helping physics students learn the basic concepts of quantum mechanics. However, without sound pedagogy, teaching and learning with multiple modes of computer-based representations may not intuitively yield significant educational gains in all contexts (Wieman & Perkins, 2005). As Singh et al (2006) underlined, the first most important step in designing improved instructional strategies that can support physics students is to be aware of the difficulties our physics students typically face while learning quantum mechanics in our contexts. Based on this governing idea, from the phenomenographic analysis of physics students' depictions about aspects of quantum mechanics, the possible origins of students' difficulties with quantum mechanics were identified. Using this background, multiple representations-based instruction treatments and interactive quantum learning tutorials were developed to teach the basic concepts of quantum mechanics. Chapter 6 describes investigations into the use of multiple representations-based instructions incorporated with interactive quantum learning tutorials in physics student understanding of the basic concepts of quantum mechanics.

2.2 THEORETICAL FRAMEWORK OF THE STUDY

2.2.1 Outline of the Framework

The interplay between teaching and learning is a complicated process. Education researchers have developed many theoretical frameworks to model students' learning of general knowledge of their environment. In order to understand the learning of physics, physics education researchers have established strategies to investigate students understanding when learning physics. In PER, research has been done to look for new ways to study students' problems with physics and further improve our understanding of student learning (Bio, 1999). In contrast to other areas of science, PER, is on the one hand a relatively new science of scholarly inquiry and on the other hand a science dealing with a complex systems ; students trying to learn physics. Therefore, it may not be amazing that physics education researchers are far from reaching an agreement upon the most appropriate theoretical framework for physics learning. In fact, there are a large number of various theories with substantial overlap.

The following subsections have focused on building a theoretical framework for the study depending on the goals and purposes of the research. It starts with review of theoretical models for describing physics learning. It then discusses some of the current learning theories that have substantial influence on our understanding of student learning of science. The main tenets, theoretical framework, Phenomenography, and the methodological perspective that influence the research design and analysis phases and the links between context and the conceptual aspect of physics are then discussed.

2.2.2 Models for Describing Physics Teaching and Learning

Research on the teaching and learning of physics has occurred only in the last three to four decades. Debates have erupted among educational researchers and practitioners over how to approach the teaching and learning of physics. Driver and Erickson (1983) argued that the view of students as blank slates, ready to be stamped with facts and knowledge about physics, is inappropriate for understanding student learning. Much of the earlier PER work into students'learning was mostly a theoretical; with the aim of understanding students' conceptions rather than establishing theory that relates students conceptions with their learning (Smith et al., 1994). Smith et al (1994) further argues that even these theoretical frameworks consider the representation of a misconception as something that needs to be confronted and replaced as being inconsistent with constructivist perspective of learning. Thus, the conceptions of learning become in contradiction with the dominant science education ideology of the past three decades. According to the constructivist perspective of learning the focus is on how more advanced knowledge states are adjoining with prior knowledge states. Smith et al. (1994), therefore, characterized misconceptions as "faulty extensions of productive prior knowledge". For instance, typically undergraduate physics students first study mechanical waves and then physical optics. The reason behind this is that the wave properties of matter, wave particle duality, and atomic spectroscopy make no sense if one does not understand superposition, wave representations, and diffraction. In a traditional teaching setting, clearly, most students do not develop a reasonable wave model for the behavior of light. When studying more advanced topics in physics that follow waves and physical optics, students appear to accumulate these difficulties and this can lead to misinterpretations of, among other things, the quantum nature of light. This is what they characterized as "faulty extensions of productive prior knowledge". In a similar argument, diSessa (1993) viewed that novice physics learners' ideas about the physics world do not constitute an organized structure. Rather, diSessa argues that novice physics students possess a set of loosely connected ideas that are induced in particular situations. Thus in the learning of physics these sets of loosely connected ideas become refined, not replaced. Inspired by the theory of diSessa, another model for understanding physics learning has been proposed by Hammer et al. (2004). The principal model of Hammer et al. (2004) involves the idea of the more fine grain resources. In this model, resources cannot be thought about as correct or incorrect, rather they are key to an expert understanding of physics by applying the correct set of resources for a given context. The fundamental feature of this model view teaching as facilitating students to gain knowledge of the cognitive resources they already have and to be able to apply these correctly across variety of contexts. Briefly speaking, there has been a step forward from believing students prior ideas as misconceptions that need to be replaced to a belief of it as resources for learning that can be activated through teaching. This view is aligns better with constructivist principles, in which new knowledge must be built on the basis of prior knowledge.

2.2.3 Learning Theory in Physics Education

In PER, the constructivist view has become a familiar belief since the late 1970's. Their belief is that learning is the result of the interaction between what the students is taught and their current ideas or concepts. This is by no means a new view of learning. The roots of constructivism are attributed to Jean Piaget who proposed that learning is an internal process and that essential learning occurs when one's previous thinking is challenged (Driscoll, 2004). Driscoll contrasts constructivist conceptions with those of the objectivist (dualist) epistemology where knowledge is perceived to exist independently of learners, and learning is the transfer of this outside knowledge to within the learner (Driscoll, 2004). "The human mind as a computer" metaphor suggests an objectivist perspective where knowledge is interpreted as input to be processed and/or stored by the learner. This objectivist perspective stands in stark contrast to that of the constructivist whose view is that knowledge is constructed by the learner as he attempts to make sense of an experience. Driscoll states that, "Learners, therefore, are not empty vessels waiting to be filled, but rather active organisms seeking meaning" (2004). Driscoll further states that new and conflicting experiences are discrepant causing the learner to construct a new idea in order to make sense of the new information. For example our everyday experience of the term “uncertainty” could imply doubtfulness, not confident or unpredictability. Even within the discipline of physics, it carries different meanings depending on the context it is used. The term uncertainty in classical measurement refers to a range of values for which the measured result lies, arising from unavoidable discrepancies from measurement to measurement. Nothing about our general day–to-day existence or classical physics would tell us otherwise.

Uncertainty as measurement error or doubtfulness conception works sufficiently in our experience and in classical physics as long we are not expected to think critically about the idea of “uncertainty” in response to the wave particle duality of microscopic object in quantum mechanics. Trying to understand these changes using a model of the “uncertainty” that is measurement error or doubtfulness result in a discrepancy. Faced with this discrepancy, the quantum mechanics student may have to re-evaluate and possibly discard the unsatisfactory mental construct in favor of the construction of a new and satisfactory construct. In the context of constructivism, conceptions are understood to be constructed by the learner in order for the learner to make sense of the context and the curriculum. Thus, constructivist perspective of learning suggests that learners actively construct their own knowledge, strongly influenced by what they already know. Puolimatka (2002), in contrast, has criticized constructivist views of learning for not having emphasized the realistic view of knowledge, that is, knowledge has to be in accordance with reality. According to Puolimatka, the most important aspect in learning is that it happens when the learner is in touch with reality. The conceptions the learners construct have to be correct in the sense that they are in accordance with reality. Moreover, Puolimatka (2002) has condemned constructivist views for giving too much responsibility for the learner. He has argued that the learner needs an external guide in order to learn about the world around him, and act meaningfully in it. The central foundation of constructivism, that learning is an active, conscious activity of a learner is not generally open to discussion.

According to the theory of constructivism, learners should be exposed to different phenomena and then requested to make meaning of their experiences. At the explanation time the instructor may help direct students towards the acknowledged scientific view. Social constructivism, on the other hand, emphasizes the social interactions involved in learning some of which involve extensive guidance. For example, it is often difficult for students to replace the basic convictions of a deterministic worldview with the probabilistic view of quantum mechanics. As pointed out by Redish and Boa (2002),"A student's first course in quantum physics can be quite difficult. They have to think about phenomena for which they have no direct personal experience, they have to follow long chains of inference from experiment to what appear to be bizarre conclusions, and they have to deal with phenomena that fundamentally involve probabilities." This introduces a number of difficulties instead of constructing their own meaning that matches with the accepted scientific view. Despite the fact that, scientific knowledge is seen as constructed, it is viewed as the cumulative product of many scientists' efforts, working together with a shared set of understandings and practices. Learning involves, therefore, a 'cognitive apprenticeship' with some significant guidance from experienced members of the group (Collins, Brown & Newman, 1987). In conclusion, while the study situate in the psychology of constructivism, with its focus on the learner's active role in acquiring knowledge, it underlines not only how learners receive materials to be learned and how they construct such material inside their mind, but it is also very important how they and their teachers construct it between them through interaction.

2.2.4 Phenomenography: A Theoretical Framework and Analysis to Research in Physics Education

Phenomenography is a research specialization that focuses on the variation of ways in which individuals can experience a specific phenomenon, such as the concept of Newtonian motion, Big bang, the concept wave particle duality or the concept of political power. Its roots can be traced into a set of studies of learning among university students carried out at the University of Gothenburg, in the early 1970s. The idea of phenomenography began with the observation that some people learn better than others. This observation led the research group led by Marton to consider research questions such as: What does it mean that some people are better at learning than others? Why are some people better at learning than others? The attempts to answer these questions paved the way for what would eventually become phenomenography. It has arisen from these investigations into learning variations, and the term was first used by Marton (Marton, 1981). According to Marton and Booth (1997), the phenomenographic approach deals with describing the "qualitatively different ways in which people experience, conceptualize, perceive, and understand various aspects of, and phenomena in, the world around them".

The main idea of phenomenography is therefore concerned with the ways of experiencing different phenomena, ways of seeing them, knowing about them and having skills related to them. This suggests that, phenomenography is not focused merely on the phenomena, nor the people, the teacher and the student who are experiencing, the phenomena being investigated. It is, rather, focused on the internal relationship between the two, i.e., the variation in ways people experience the phenomena (Marton, 1986; Bowden, & Walsh, 2000). The unit of the phenomenographic approach is, thus, a way of experiencing something which is an internal relationship between the experience and the experienced. In phenomenography it is this underlying ways of experiencing the concept, phenomena, situations while revealing and describing the variation therein, especially in an educational context that are made the object of research (Marton & Booth, 1997). Figure 2.1 gives a graphical depiction of the object of study in phenomenography approach. As exemplified in Figure 2.1, the phenomenon under investigation cannot be perceived separately, since the objective in the study is the way the phenomenon under investigation is conceptualized, depicted, understood and experienced by the learners. Figure 2.1 further demonstrated that there is an inevitable relationship between the researcher and the phenomenon (example, the basic concepts of quantum mechanics) that is investigated in the research; that is why, in phenomenographic approach, the researcher is expected to have an in-depth knowledge and understanding of all facets of the phenomenon that they are trying to analyze (Stamouli & Huggard, 2007). However, researchers in phenomenographic approach must be cautious not to impose their own understanding and interpretation of the phenomenon on the student cohort.

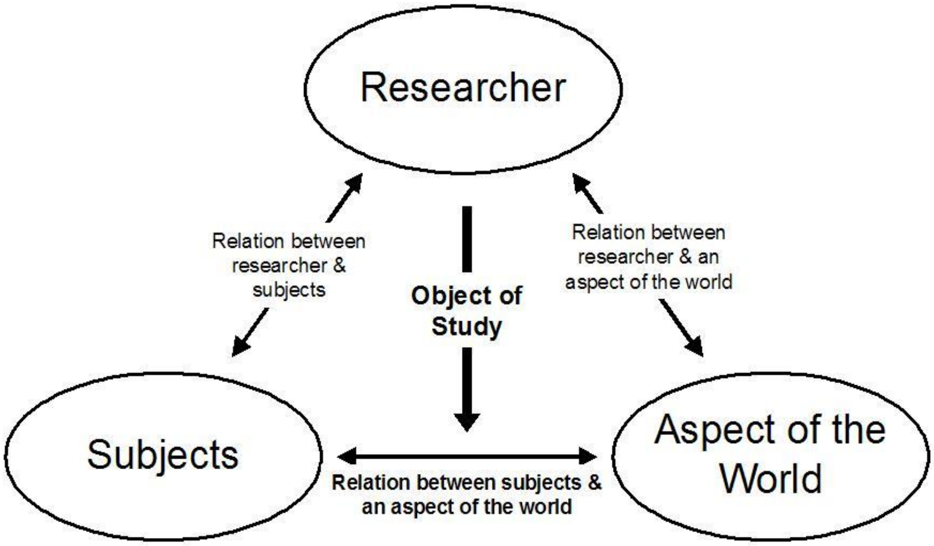


Figure 2.1: Focus of Phenomenographic Research (Based on Bowden, 2005)

In the phenomenographic approach, the principal aim is not to find one particular essence, but the variation and the type of this variation in terms of the different features which define the phenomena (Marton & Booth, 1997). Therefore, the variation in ways people experience phenomena in their world is the main interest for phenomenographic studies, and phenomenographers aim to describe that variation (Adawi & Linder, 2005). Different people will not experience a given phenomenon in the same way. However, the phenomenographic approach assumes that there are a finite number of qualitatively different ways in which different people can experience the same phenomenon. Marton and Booth (1997) argued that if the number of ways of experiencing a phenomenon were infinite, then we would live in different worlds, being incapable to communicate with each other. Because this is not the issue, the number of ways of experiencing a phenomenon should be finite (Marton & Booth, 1997). These finite categories of description are discerned from one another in terms of the presence or absence of certain basic feature of the phenomenon, and it is for this reason that the categories of description are said to be qualitatively different. These qualitatively different categories of description and the relation between them provide the resulting set of logically related and empirically grounded categories of description called the outcome space that represents the possible ways a concept or phenomena can be understood or experienced. The outcomes of phenomenographic analysis are represented as a set of categories of description that are structurally linked to one another. The assumption of a structure among the categories is an element of the epistemology that underlies phenomenography. Akerlind refers to this as the phenomenographic proposition, "ways of experiencing represent a relationship between the experiencer and the phenomenon being experienced, leads to the expectation that different ways of experiencing will be logically related through the common phenomenon being experienced" (2005, 322).

Phenomenography is based on the important assumption that the categories of description may not be descended as qualities of individual students. The categories of description are systematically drawn from all the collected data (e.g., interviews and/or written comments), the collection of meaning, while individuals are only perceived as providing fragments of data to a given category of description. Marton and Booth (1997) suggest that the description researchers reach is a description of variation on the collective level, and hence individual voices are not primarily considered. Therefore, the categories of description characterize the different ways of conceptualizing or depicting the phenomenon at the group level. The phenomenographic analysis ends in a consistent framework for understanding what is presented, giving both a method to analyzing data and a theory for scrutinizing the structure of the variation in experiences of the phenomenon being researched (Marton & Booth, 1997). Figure 2.2 gives a graphical depiction of the categories of description, or the outcome space of a study in the phenomenographic framework.

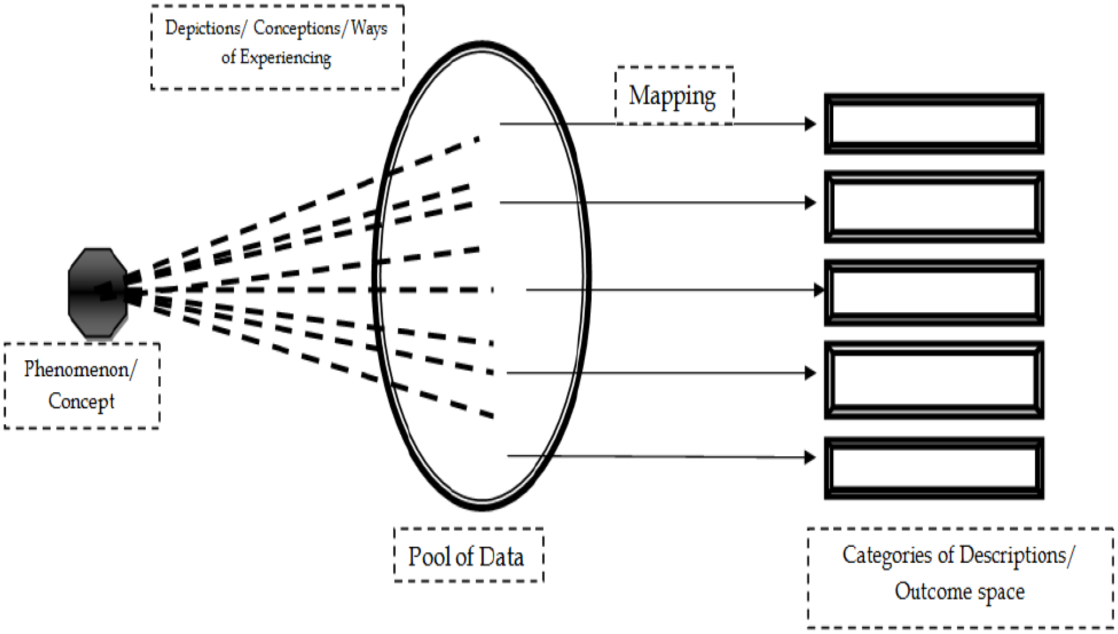


Figure 2.2: A graphical representations of the phenomenographic approach

As an educational instrument, phenomenography takes a non-dualistic ontological perspective; meaning that object and subject are not separate and independent of each other. In other words, phenomenography aims to study ways of experiencing from the second-order perspective, that is research is oriented towards people's ideas about the world, or their experience of it, not the world itself (the first-order perspective) (Adawi & Linder, 2005). The main difference between the first- and second-order perspective is "the difference between considering a statement to be a statement about the physical world, or about some specified situation, and judging it in light of other statements about the physical world, or about the same situation"(Marton & Booth, 1997). For example, one might explore the qualitatively different ways of conceiving the theory of the atom or the Heisenberg Uncertainty principle. There is another well known knowledge claims that are used to analyze qualitative data namely Phenomenology (Creswell, 2003). Phenomenology is often employed when there is need to study the participants' understanding of some phenomena. Sometimes, phenomenography is confused with phenomenology. While the relationship between phenomenology and phenomenography has been regarded as ambiguous, and phenomenography is sometimes seen as a subset of phenomenology, it did not emerge or derive from phenomenology. Equivalent to phenomenography, phenomenology is also a field of knowledge that is acquired by having experience as the subject of the study (Walker, 1998). Even though both aim to discover human experience and awareness, phenomenology is a different approach and should not be confused with phenomenography. A phenomenological approach is an ordinary assumptions regarding things and to describe the phenomena of experience as they appear, rather than attempt to explain why they appear that way, whereas phenomenography aims to find out the qualitatively different ways of experiencing or thinking about some phenomena. Marton (1981) describes that the aim of phenomenology is “to describe either what the world looks like without having learned how to see it or how the taken for granted world of our everyday existence is ‘lived’.” In phenomenographic research, the researcher chooses to study how people experience a given phenomenon, not to study a given phenomenon as described in Figure 2.1.

The research in Part I of this thesis, in general, is revolved around variation and change in physics students’ ways of depicting the basic concepts of quantum mechanics. Therefore, it entails a description of the physics students' ways of depicting about the basic concepts of quantum mechanics and, also, the qualitative changes in their depicting. For this purpose, phenomenography has been used as an analytical tool. However, it is not a “pure” phenomenographic approach. In this case, the research outcomes are not the only objectives of the projects in it. The results from the research outcomes are, rather, used afterwards to enhance the particular educational development issues that were the origin of the study. Developmental phenomenography (Bowden, 1995; Bowden, 2000) has, therefore, been used for this kind of applied research which contrasts with a pure phenomenographic interest that Marton (1986, p.38) refers to as: “describing how people conceive of various aspects of their reality. In most cases, the concepts under study are phenomena confronted by subjects in everyday life rather than in course material studied in school.” Developmental phenomenography is different from the 'pure' phenomenographic interest in a number of ways (Bowden, 1995). Bowden proposed that, in developmental phenomenography, the research methods that are used are determined both by the general principles of Marton’s dominant phenomenography and also by the particular needs of the application that generated the research concern. Therefore, “it is this second influence that distinguishes developmental from pure phenomenography” (Bowden & Green, 2005). Bowden et al

(1992) have carried out a number of investigations into student learning in physics using a developmental phenomenographic approach. For example, he has been involved in the study since 1988, which investigated students' understanding of fundamental physics concepts using developmental phenomenography. Various aspects have been published, each dealing with a different perspective such as the relation between students' understanding and textbooks' treatment of acceleration, or implication for physics teaching and evaluation of students understanding of frame of reference (Bowden et al., 1992; Walsh et al., 1993). Sharma et al (2004) adapted a phenomenographic methodology to explain the differences in the way in which students understood the concept of gravity. It has also, for example, been used to examine students' understanding of sound (Linder & Erickson, 1989; Linder, 1993) and to undertake an empirical investigation of how physics students made sense of their study situation (Booth & Ingerman, 2002). With similar interest, Adawi and Linder (2005) investigated how adults, taking an introductory survey course in physics conceptualize the notions of heat and temperature. Therefore, these outcomes of the phenomenographic research, the different conceptions that students grasp for a certain phenomenon may be informative to teachers who are developing ways of helping their students experience or understand a phenomenon from a particular perspective.

The methodology that Bowden's et al project team took was intended to enable subsequent use of the outcomes of the phenomenographic research, in a teaching and learning context. It is undertaken with the purpose of using the outcomes to help the subjects of the research, usually students, or others like them to learn. Therefore, this theoretical framework, developmental phenomenography, and the methods used and developed by these researchers, was adapted as a theoretical framework and research approach to undertake the research presented in this thesis. Like any methodological framework, the phenomenographic approach influenced how the sample interviewees were selected and how methods of data were collected and analyzed in the principal investigation of this thesis. These details are described later in the following chapter.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

In chapter 2 the conceptual framework of the present study was presented but apart from the choice of appropriate theories there are also additional methodological considerations to take into account when doing research, for example, how to collect the empirical material and how to establish trustworthiness. Such methodological considerations are the focus of this chapter. This chapter presents justification of the research paradigm, the selected research methodology and provides a detailed description of the phenomenographic research approach and the rationale for its use in this study. The research design is presented, along with details of how the study is implemented, how the empirical data is collected and the reflections involved in the collection and treatment of the data. Furthermore, questions regarding the trustworthiness of the research and ethical considerations are also discussed.

3.2 RESEARCH PARADIGM

The word paradigm connotes the ideas of a mental picture or pattern of thought (Kuhn, 1970). According to Henning et al (1974), a paradigm is a framework within which assumptions are built, that fundamentally influences how we visualize the world, determines our perspective, and shapes our picture of how things are related. It is the identification of the underlying basis that is used to construct a scientific investigation; or, "a loose collection of logically held together assumptions, concepts, and propositions that orientates thinking and research" (Bogdan & Biklan, 1982, p. 30). A paradigm, according to Guba and Lincoln (1994), is defined as a system of philosophical beliefs that leads and governs an investigation. So, the research paradigm shapes the whole research process and gives valuable directions and principles about the approach, methods and techniques for conducting a research within its philosophical setting (Guba & Lincoln 1994). In the literature, two leading research paradigms are acknowledged by methodologists in many disciplines; i.e., the positivist and the interpretive paradigms (Patton 1990).

The positivism paradigm believes that human life is governed by generic laws (Denzin & Lincoln, 2000); thus, the people can be studied in a natural scientific manner (Smith, 1983). Positivists believe that reality is stable and can be observed and interpreted from an objective viewpoint, that is without interfering with the phenomena being investigated. Consequently, this epistemological standpoint relies heavily on measurements that epistemological framing needed for investigating some phenomenon (Krauss, 2005; Smith 1983). On the other hand, the interpretive paradigm's emphasis is on holistic and qualitative information to provide rich insights into components of a phenomenon (Husen, 1988). The interpretive theorist views that the best way to understand the world is from the collective view points of the investigated participants (Husen, 1988). The study of phenomena in their natural environment is key to the interpretivist paradigm, together with the acknowledgement that scientists cannot avoid affecting those phenomena they study. This implies different modes of research to allow us to understand different phenomena and for different reasons (Deetz, 1996). The type paradigm selected depends on what one is trying to do rather than a commitment to a particular paradigm (Cavaye, 1996). Thus, the methodology employed must match the particular phenomenon of interest. Different phenomena may require the use of different methodologies.

The main objective of the principal study in this thesis is to investigate ***"What depictions of the basic concepts of quantum mechanics do a group of undergraduate physics students have, if any?"*** Accordingly, the research problem is descriptive rather than prescriptive, which require a theory-building approach (inductive) rather than a theory testing one (deductive). Therefore, the qualitative/interpretive paradigm is more suited than the positivist paradigm (deductive) because the research is concerned with picturing the actual world of investigated phenomena rather than providing statistical details about the cause-effect relationships between variables within the examined phenomena. Constructivist qualitative/interpretivist research avoids the quantification of learning and focuses instead on the categorization of true nature and diversity of individual understanding. It is from this qualitative/interpretivist perspective and the assumptions described above that the study of the depictions of quantum concepts among physics students has its philosophical basis.

3.3 QUALITATIVE RESEARCH METHODOLOGY: THE PHENOMENOGRAPHIC PERSPECTIVE

The selection of research methodology is consistent with the selected research paradigm and dependent on the nature of the investigated phenomena, the type of the research questions, the research population and the expected outcomes of the research (Cavaye, 1996; Patton, 1990). The qualitative research methodology is, therefore, selected as having epistemological associations with the philosophical assumptions of the interpretive paradigm explained above. In most cases, qualitative research includes any research that produces findings that are not derived by statistical procedures or other means of quantification. The aim of qualitative research is primarily to gain insight into the individual's subjective interpretative patterns, experiences and positions (Ueltzhoffer & Ascheberg, 1999). Denzin and Lincoln (2003) also suggest that qualitative research is most interested in processes and meanings that are not experimentally examined. A qualitative approach allows the research participants to speak for themselves as well as their ways of experiencing phenomena. This can be achieved through interviewing individuals and directly asking them questions about how they arrange their world, the researcher enters those persons' worlds and perspectives, thus, discovering what is on their mind (Patton, 1990).

In this study, the investigation is directed at eliciting undergraduate physics students' depictions of the basic concepts of quantum mechanics and constructing the description categories which form the basis of their ideas. Explicitly, the study was aimed at exploring the range of qualitatively different ways of depicting the basic concepts of quantum mechanics within a sample group of physics students as a group. As a result, this primary focus on the collective variation made it likely to choose phenomenography as a qualitative research approach. As it has been discussed in section 2.2.4, phenomenography was seen as the most appropriate qualitative approach for this study because it is a research specialization aimed at revealing different ways in which students see, experience, understand and depict various phenomena in the world around them (Marton & Booth, 1997). It is also found that phenomenography can be understood as an analytical framework to gain an empathetic understanding of physics students' depictions of quantum mechanics. Therefore, the phenomenographic approach was employed in this study. However, it is not a pure phenomenographic approach. Principally, in this study, the interest in phenomenography has much in common with the developmental interest described by Bowden (1995; 2000). Bowden (1995, p.146) elaborates his idea of developmental phenomenography as: "The phenomenographic research that I engage in is situated within a particular kind of context. I focus on research which, through finding out how people experience some aspect of their world, will enable them or others to change the way their world operates, normally in a formal educational setting. My perspective is developmental. My reasons for undertaking the research are concerned with how I can use the research outcomes to affect the world I live and work in." Therefore, the outcomes of the developmental phenomenographic research, the different conceptions that students grasp (e.g., students depictions of the photon concept, the wave-particle duality, the uncertainty principle) may be informative to teacher-researcher who is developing ways of helping their students understand a phenomenon under investigation from a particular perspective. In this type of research approach, the preferred method of data collection is the semi-structured interview (Bowden, 1995; Marton & Booth, 1997), although other methods have been used (e.g. collecting written comments or filming group work). The semi-structured interview depends on a limited number of predetermined questions, but has an open structure, where the interviewee is encouraged to talk over all thoughts and ideas that come to mind. This type of an interview therefore provides a rich way of exploring the ways in which a set of students conceptualize, depict or conceived the phenomena under investigation. Bowden and his associates have carried out a number of studies into student learning in various topics of physics using a developmental phenomenographic approach (Bowden et al., 1992; Walsh et al., 1993). Bowden et al, for example, used this research methodology to investigate students' understanding of displacement, velocity, and frames of reference. The researchers interviewed a number of undergraduate students about their conceptual understanding of these particular physics concepts, encouraging the participants to give full descriptions of their conceptual understanding. Participant students' interviews were then transcribed and subjected to phenomenographic analysis. The description categories that represented the qualitative variations in conceptions were drawn from the data, with the focus on the students' meaning rather than on particular sentences.

The main emphasis in this study is set in the aim of developmental phenomenography (i.e., to understand the qualitative variation in the ways that undergraduate physics students depict the basic concepts of quantum mechanics so that teaching practice can be meaningfully informed in ways that potentially enhance learning outcomes). This developmental phenomenographic approach, and the methods and procedures used and developed by these researchers (e.g., Bowden et al., 1992; Bowden, 1995; Marton & Booth, 1997), was adapted to undertake the research presented here.

3.4 QUALITATVE RESEARCH DESIGN AND PROCEDURE

Kinnear and Taylor (1996) proposed that a research design is a basic plan that guides the data collection and analysis phases of the research project. Research design provides the framework that identifies the type of data to be collected, its sources, and the collection procedure. This study has been introduced as a phenomenographically based study. Bowden (2000) summarizes the phenomenographic study process as having four stages:

plan, data collection, analysis and interpretation. In all of these stages, the researcher must maintain focused on the principal aim of the study. This is vital to consider for obtaining trustworthy results (see Section 3.5). Obviously, what drives the phenomenographic research is an underlying question that the research process tries to address. Thus, describing the research design and procedures are much more tangible. Many pragmatic questions had to be answered during this stage: How will data collection instruments be constructed? From whom will data be collected? How will subjects be selected? How will data be collected? How will data be analyzed? It was well decided that the methods employed in this study are qualitatively-based, and data are collected through in-depth semi-structured interviews with undergraduate physics students taking quantum mechanics. For this reason, it was necessary to plan and organize appropriate research procedures and data collecting instruments (the semi-structured interview questions). To this end a preliminary research project was conducted based on the study setting. The preliminary phase study was implemented for two reasons: First in order to uncover which concepts are considered most important in the undergraduate quantum mechanics so that physics students need to understand to learn quantum mechanics; and secondly, using this earlier work as the basis of a fact finding study, it was expected that the results would provide valuable information, allowing the researchers to make informed judgments concerning the form and content of the instruments (the interview questions) used later in the main study.

3.4.1 Preliminary Study for Designing Interview Questions

This section describes the procedure and setting of the preliminary research project plan. It has already been noted that, the major goal of the preliminary studies were: to identify the key concepts that undergraduate physics students need to understand in order to learn quantum mechanics and from that to determine content areas for preparing and organizing the semi-structured interview questions. In order to uncover which key concepts are considered most important in the undergraduate quantum mechanics, analyses of the current undergraduate physics program course syllabuses (first year Modern Physics and the second year Quantum Mechanics I courses) from two universities in Ethiopia (Wollo University and Bahir Dar University) were undertaken. The analyses were conducted as follows:

- The key topics which have been taught across the two universities in Modern Physics and Quantum Mechanics I courses were identified.
- The frequency of these key concepts appearing in the syllabuses were ascertained
- These topics were categorized into basic concepts of quantum mechanics

Nevertheless, only analysis of course syllabuses cannot perfectly indicate which key concepts are important for the introductory quantum mechanics. Thus, the Delphi technique was also applied to ask experts from the Department of Physics at Wollo and Bahir Dar Universities considering the significance of these concepts to the teaching and learning of quantum mechanics at tertiary level. From these iterative processes (i.e., the analysis of course syllabuses and consensus among physics experts), the basic concepts that students need to learn quantum mechanics successfully were categorized under two major themes: Light and Matter. The two major themes and these basic quantum mechanics concepts under each theme are presented in Table 3.1.

Table 3.1: The basic concepts of quantum mechanics under each theme

Themes	Basic concepts of Quantum Mechanics
Theme A: Light	1. Quantization of energy in the Blackbody radiation
	2. The photon concept in the photoelectric experiment
	3. Light quanta in the double-slit experiment
Theme B: Matter	4. Matter waves (the de Broglie wavelength, wave–particle duality, analysis of the double-slit experiment with quantum entities)
	5. Uncertainty principle

Consequently, predetermined interview questions used to explore physics students' depictions of quantum mechanics were organized under the five basic quantum concepts: Quantization of energy, the photon concept, light quanta, matter waves and uncertainty principle. We have conducted pilot interviews on initial versions of the predetermined interview questions with undergraduate students. In this stage, five physics major students with similar backgrounds to the students involved in the main study, volunteered to become involved in the pilot study interviews. These interviews helped us to modify the wording of the predetermined interview questions, understand student thinking, and eliminate some questions that were not serving their intended purpose. Finally, all of the recent versions of the interview questions were reviewed and commented by two experts who have experiences with teaching undergraduate quantum mechanics courses. The final version of the predetermined interview questions are presented in Appendix I. The interview questions were also presented in the analysis in Chapters 4 and 5 to accommodate the results and findings. Section 3.4.3.1 elaborates more on the interview procedures.

3.4.2 Undergraduate Physics Student Sample

The sample sizes reflected in phenomenographic studies are consistent with other qualitative studies. Researchers suggest that qualitative research usually involves much smaller sample sizes than in quantitative research (Strauss & Corbin, 1998). In phenomenographic research, a sample of between 15 and 25 is considered to be sufficient, without becoming unwieldy, to reveal most of the possible viewpoints and allow a defensible interpretation (Trigwell, 2000b). Developmental phenomenographic studies cite larger sample sizes of between 25 to 30 participants that could be interviewed in a block of time (Bowden & Green, 2005). In general, in phenomenographic research, the predominant method for collecting the data is through semi-structured interviews with students, and the researcher must select the students carefully and consider why they are a good choice.

This study involved interviewing 35 second year physics major students from an undergraduate physics program in two government universities (Wollo and Bahir Dar Universities) in Ethiopia, about their depictions of the basic concepts of quantum mechanics. The program is a three-year degree physics program identical across all higher education institutions in Ethiopia. The classroom setting is a predominantly traditional manner ("relying primarily on passive-student lectures, recipe labs, and algorithmic-problem exams" (Hake, 1998), although the lecturers are different (see Section 1.5). In general, 'Maximum variation sampling' a strategy for purposeful sampling was considered in selecting these interviewees (Patton, 2002). This approach was taken because phenomenographic methods work best with a variation in understanding. For example, interviewees were carefully selected from two universities (i.e., 18 students from Wollo and 17 from Bahir Dar Universities) to obtain variation and quality in the interviews. All the sample physics students had gone through a course on Modern Physics in their first year based on Beiser's (2002) well-known textbook on the subject in both universities (see section 1.5). The competency levels of the students in Modern Physics and concurrent physics courses were not tested, but this can be gauged from the following: (a) out of the 35 physics students, thirteen had got "A" grade and twenty two had got "B" grade in the preceding full-semester course on Modern Physics mentioned above and (b) all of them had successfully completed other concurrent undergraduate physics courses in their first year. On average, the interviewees scored marginally higher than the class mean grade on Modern Physics course in both universities, indicating that they were generally better than average students, as might be expected for a group of volunteers. In 2011/12, these students were all enrolled in their second year of a second semester courses in the undergraduate physics program. During this time, they had been exposed to the traditional approach to Quantum Mechanics I, a three-credit quantum mechanics course, for one third of a semester. Thus, before the phenomenographic interviews were conducted, they had been introduced to the basic quantum concepts (i.e., included on the phenomenographic interview questions) and some postulates of quantum mechanics necessary to follow the remaining quantum topics and concurrent physics courses.

3.4.3 Data Collection

The methods selected, in this study, support the developmental phenomenographic orientation. In the developmental phenomenography, the semi-structured interview is regarded as the preferred data collection method, with an emphasis on providing open-ended questions that encourage the participants to express their own perspectives (Bowden, 2000; Bowden & Walsh, 2000). The phenomenographic interviews were designed to obtain a qualitative description of the conceptual understanding of the interviewee. As discussed, in this study, data was collected using the phenomenographic interviews (i.e., semi-structured interviews) since the aim is to find categories of qualitatively different ways of depicting the basic concepts of quantum mechanics. The phenomenographic interview questions were designed based upon the analysis of the preliminary study which preceded this study (see Section 3.4.1). Thus, the major sources of data used for analysis in this study were from the phenomenographic interviews, which included qualitative problem solving, reasoning tasks, explaining the observed phenomena and interpretations for their observations and questions probing student way of using quantum mechanical ontology in explaining microscopic phenomena. In the next section (Interview Protocol), the two themes (i.e., Light and Matter) involving the five basic concepts of quantum mechanics and some of the interview questions are presented.

In both universities, the interviews were held in a physics laboratory and a small meeting room with closed doors to assure privacy. The research interviews were conducted in person, with the interviewee's consent, and were digitally audio-recorded. The length of the phenomenographic interviews in the various studies has varied. In this study, the interviews took between 45 and 90 minutes to complete. All interviews were conducted in English. It was important to spend time in conversation with the interviewees prior to conducting the formal interview and the audio recording thereof to put the students at ease and to offer them a safe and comfortable atmosphere in which to speak. The time before the main interview allowed for a clarification of the purpose of the study and for the interviewee to obtain a pre-knowledge of the subject matter being investigated, including necessary definitions. For example, in this phase of the interview, it was emphasized that the interview was not meant to be an examination of their quantum mechanics knowledge but the interviewer wanted to characterize how the different contexts led them to think about quantum phenomena.

During the interview, the students' were allowed to proceed at their own pace, occasionally interjecting prompts or questions to probe students' thinking. These interjections were usually minimal and clarifying in nature, such as, "what do you mean by that?" or "can you explain that more?" In all times, students were free to explain their understanding of quantum phenomena in written and diagrammatic/graphical forms. But they were urged to think aloud as they answer the interview questions in written explanations and diagrammatic/graphical forms and, in particular, to articulate the reasoning they are using to arrive at their responses. At the end of the interview, the students were also asked to clarify issues they had not made clear in their earlier explanations.

3.4.3.1 Interview Protocol

Undergraduate physics students' depictions of quantum mechanics (e.g., students' ideas of the wave particle duality) were investigated using a semi-structured interview protocol within the following themes and associated quantum concepts:

Theme A: Light (Quantization of energy, the photon concept and light quanta).

Theme A-A1 (Quantization): Exploring into the nature of students' depictions, the set of interview questions includes the concept of the quantum of energy to explain the phenomenon of blackbody radiation. First, the students were asked to explain about the relationship between the total energy radiated (particularly the observed color change) with rising temperatures. Students were, then, shown two figures presenting the blackbody spectrum (i.e., radiation energy versus wavelength at different temperatures) and blackbody spectrum (i.e., radiation energy versus frequency at different temperatures) and they were asked to give answers in words and written (pictorial and graphical) explanations to the questions such as:

1. When a solid object is heated, it glows and emits heat radiation. As the temperature increases, the object becomes red, then yellow, then white. What underlying reason do you think is behind the change in color of a heated object as its temperature increases?

2. In a BBR versus frequency curve, you found that at a given temperature the energy radiated at given frequencies increased as the frequency was raised, reached a peak, and then why began to decrease as the frequency was raised still further? Why should blackbody radiation be distributed in the manner as actually observed over the entire range of frequencies?

Theme A-A2 (The Photon Concept): In this second context, quantum phenomena associated with the concept of photon, selected for in-depth interviews were the qualitative analysis of the photoelectric effect and Compton scattering experiments. Students were, therefore, asked to describe the critical features of these quantum experiments, for example, how would students predict the results of these quantum experiments, and describe how these results lead to the photon model of light (see the full set interview questions in Appendix I).

Theme A-A3 (Light quanta interference): At this stage, in order to construct a picture of students' depictions of the concept of light quanta to explain the light quanta interference in the double-slit experiment, the gradual formation of an interference pattern in the cases of low-intensity light beam was used as a basis for the semi-structured interview questions (the full set questions with necessary figures is given in Appendix I). Students were shown a series of figures presenting the gradual formation of an interference pattern, and they were asked, for example:

1. Explain what is discovered in figure (a), and how the occurrence of white 'dots' in it can be explained. What can you say about the behavior of light on the basis of this situation?

2. Explain briefly what is discovered in figure (d), and how the occurrence of white 'stripes' in it can be explained. What is the process or course of events that causes the observed phenomenon?

A similar type of questions has been used in previous studies and found effective since it covers a variety of ontologically and epistemologically different viewpoints (e.g., Wuttiprom, 2008; Mannila et al., 2002).

Theme B: Matter (Matter waves involving the de Broglie wavelength, wave–particle duality, analysis of the double-slit experiment with quantum entities and Uncertainty principle) (see Table 3.1).

Theme B-B1 (Matter waves): Exploring into the nature of the depictions which the students had of matter waves, the set of interview questions include: a schematic representation of the double-slit experiment set-up with monochromatic electron gun which set to fire thousands of electrons per second; the interpretation of double-slit experiment for electrons and using the concept of de Broglie wavelength to explain the interference phenomena. The interviews were initiated with introductory question such as:

1. In your quantum mechanics courses we say electrons, protons and photons behave like waves, as well as like particles. What would you say are the simplest 'particle-like' and 'wave-like' properties that one of these things could show?

Following this introductory question, students were shown a schematic representation of the double-slit experiment set-up with monochromatic electron gun which set to fire thousands of electrons per second (see the full set of questions in Appendix I) and they were asked, for example:

1. If only the second slit (S2) is blocked off and if the electron gun is fired for hours; what will the pattern look like? How does this pattern compare to the previous one?

2. When both slits are uncovered and if the electron gun is fired for hours; how does this pattern compare to the two single slit patterns? How does this pattern compare to the single slit patterns?

3. When the intensity is reduced so that there will only be one electron going through the slits at a time, predict where the next electron will hit the screen?

4. When the intensity of the gun is altered so that only one electron is travelling at a time, what will the pattern look like?

The students were then asked to predict how a single change to the original set-up in the double-slit experiment with electron interference shown in Figure 5.1 (see Chapter 5). A similar type of questions has been used in previous studies and found effective since it covers a variety of ontologically and epistemologically different viewpoints (e.g., Ambrose, 1999; Vokos et al., 2000).

Theme B-B2 (Uncertainty principle): Insight into the nature of physics students' conceptual understanding of quantum uncertainty and/or indeterminacy were obtained by analyzing students' qualitative answers and reasoning of the specific interview questions, such as:

1. If you exactly identify the initial condition (say, for example, you do measure the position of an electron and you find it to be at a certain point P) can you determine where was the electron just before you made the measurement? Can you predict with 'certainty' the future states resulting from it?

2. In quantum mechanics, the degree to which a physical variable can be precisely measured is subject to some uncertainty. What does this meant to you? Do you think that repeated errorless measurements of the variable will always give precisely the same value? Why? Can you describe mathematically the Heisenberg uncertainty relations? What is the meaning of Δx and Δp?

3. Do you think that the Heisenberg Uncertainty Principle is generally applied to macroscopic objects such as electrons, photons, cars and tennis balls? If not, why don't we see the uncertainty principle on larger objects such as cars and tennis balls?

In both themes, all necessary situations were represented pictorially. During the interview sessions, students had their own copy of the full set of questions with necessary drawing of the situation, simulated figures presenting the specific situation, a written initial explanation of the situation and the questions. As discussed in section 3.4.3, besides to verbal responses, students were encouraged to give written explanations, draw pictures, diagrams and/or graphs while explaining their answers. Written explanations and drawings were often combined with verbal responses that, together, elicit the students' descriptions of the quantum phenomenon and their organizing constructs in accounting for different phenomena. Uncovering the same information from more than one vantage point helped us describe how the findings occurred under different circumstances and assisted us to confirm the validity of the findings.

3.4.4 Data analysis

The interview data analysis is an extensive task that begins by transcribing all the interviews verbatim. In this phenomenographic study, all the interviews were typically audio taped and transcribed verbatim, making the transcripts and written explanations the focus of the analysis. During the interview, it has explained that participant students were also encouraged to give written explanations, draw pictures, diagrams and/or graphs while explaining their answers with verbal descriptions. Thus, in the study, the interview recordings were transcribed by matching verbal responses and nonverbal descriptions, including written explanations, drawings of pictures, diagrams and/or graphs. These verbal and nonverbal responses were, then, analyzed using the developmental phenomenographic analysis where a picture of physics students' depictions of a quantum concept is built by interpreting the given verbal responses, written explanations, drawings and their associated meaning.

According to most phenomenographers, the whole process of phenomenographic analysis is generally iterative and comparative and involves the continual sorting and resorting of data and ongoing comparisons between data and the constructing categories, as well as between the categories themselves (Marton & Booth, 1997; Bowden & Walsh, 2000); Bowden & Green, 2005 Åkerlind, 2005). The present study followed these phenomenographers, according to which repetitive reading of data, sorting and resorting of data and ongoing comparisons between data and the constructing categories are necessary for the exploration of all possible perspectives to be found from the data. In the process of phenomenographic research, an important consideration during the analysis is identifying appropriate ways of managing the large amount of data involved (Åkerlind, 2005). According to Marton (1981), the phenomenographic context analysis starts from the formation of the pool of meanings. In this study, before attempting to analyze any of the interview responses, all information from the transcripts and from the nonverbal descriptions (e.g., written explanations and drawings) were sorted into one of the five basic quantum concepts covered in the interviews, creating five different pools of understanding. Table 3.2 lists the five basic concepts of quantum mechanics under the two themes, which are simply an expansion of the list given in Section 3.4.1. After the data was organized into these five quantum concepts, the researcher would read repeatedly through all of the data in a given quantum concept (e.g., Quantization of energy) and try to map different dimensions of variation in ways of depicting about a certain aspect of quantum mechanics within that pool of data. At this point, the main purpose was to find out what different dimensions of variation could possibly emerge from the given pool of data. In this early phase of analysis, any predetermined ideas were dropped as much as it is possible to do so and reading through transcripts was done with a high degree of openness for different interpretations.

Table 3.2: Basic concepts of quantum mechanics: the five concepts in the data

Themes	Basic concepts of Quantum Mechanics
Theme A1:	Quantization of energy
Theme A2:	The photon concept
Theme A3:	Light quanta interference
Theme B1:	Matter waves
Theme B2:	Uncertainty principle

Once the overall picture of dimensions of variation began to emerge from that pool of data, notes were taken regarding any descriptions which form the basis for students' depictions of a given concept (e.g., quantization) that were identified. But the formation of the categories of description to characterize the students' depictions of the given concept originally required the use of a set of relevant transcripts, written explanations and drawings cut up into pieces and sub-pieces of description. The process involved searching for comprehensive frames of explanation. The whole analysis process was also highly iterative and had to be done many times from different perspectives, because there were so many aspects present at the same time that looking at them all at once would have been impossible. During this iterative process, in order to categorize students' depictions a given quantum concept, the relevant transcripts, written explanations and drawings were coded. These were then cut up into pieces and gathered into individual "themes of description". Each theme of description characterized a preliminary category of description. A tentative title was given to each of the themes of description. Throughout this analytical process, the themes of description did not remain static. They were continuously rearranged or refined and the wording of their titles was changed to give the best picture of students' depictions. After condensing and organizing of the extracts into these themes of description, a decision was made to begin again using a complete set of transcripts, written explanation and drawings within that given pool of data. The early phase of the analytical process was, however, considered very important even at this later stage, as it now guided the second attempt. Thus, the whole set of transcripts, written explanations and drawings were subsequently categorized and cross-referenced with notes. As it has been common in most phenomenographic analysis, this process also involved thorough reading and rereading of the transcripts, written explanations and drawings. Finally the description categories which form the basis for students' depictions of the given quantum concept began to emerge from explanatory key facets of description which were constructed by reducing irrelevant dissimilarities and the integration and synthesizing of important similarities which make up the content and structure of a given category of description (Linder, 1989). According to Linder (1989) each category of description depicted a detailed structure with individual student's depictions and reasoning as subsets of it. Figure 3.1 graphically shows the steps taken in the analysis process for achieving these analytical outcomes.

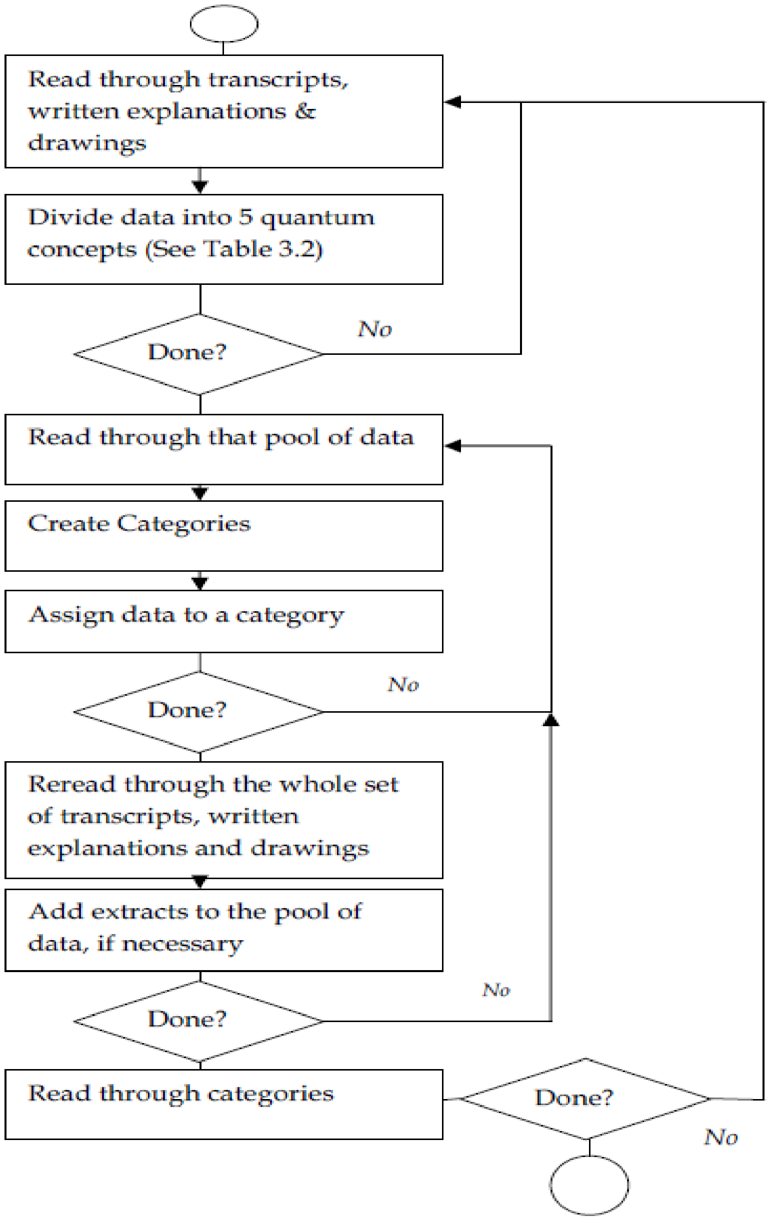


Figure 3.1: A flowchart depicting the iterative analysis process

As can be seen in Figure 3.1, the major analysis process was repeated in an effort to validate the interpretations that had been made. This second phase of analytic path led to some restructuring of the categories of description already evolved, by comparing and contrasting it with newly emerging understandings found in the data, towards a more refined, more complete and more consistent formulations of categories. The phenomenographic perspective used in this research was discussed in Chapter 2 and additional data analysis for this part of the study is also provided in Chapters 4 and 5.

3.4.4.1 Organization of Categories of Description into an Outcome Space

In the study, the ways of depicting each of the five basic concepts of quantum mechanics were presented in categories of description, which were drawn from the interview transcripts, written explanations and drawings of physics students (see Part I; Chapters 4 and 5). The categories were based on the most distinctive features that differentiate one way of depicting of, for example, quantization of energy from another in the hierarchical system called outcome space. The different ways of depicting are represented in the form of categories of description, which are further analyzed with reference to their logical relations in constructing a hierarchical system outcome space (Marton & Booth, 1997). The category of description denotes to those ways of depicting or understanding which have the most important structure and content in common. According to Hella (2007), in phenomenographic perspective, it is widely common to illustrate the categories with their subcategories. In this study, the main categories which depicted the basis for students' ideas of, for example, quantization of energy were described in terms of key facets of description and their constituent aspects without labeling the subcategories. The logical relationships between the categories constitute the outcome space that represents the variation of different ways of understanding each of the five basic concepts of quantum mechanics. It is also important to note that all five of the basic quantum concepts are interconnected. Thus, the outcome space is a representation of the dynamics of the collective awareness of quantum mechanical concepts within a research group at a particular point in time and space (Marton & Booth, 1997). The outcome spaces that are presented here may not be, of course, the full range of all possible categories of description of the phenomena in question, but there is enough variation to make some useful conclusions. According to Bowden's (2000) view of developmental phenomenography, the outcome space illustrates the relation between different ways of understanding the subject matter or concept under study and thus provides a basis for decisions about teaching and assessment. Furthermore, identifying students' ways of understanding of the concept under study provides a basis for devising ways of helping students change their understanding (Bowden, 2000). In general, the developmental phenomenographic research tool guided the analysis of the data in this study. In line with Bowden's (2000) view of developmental phenomenography, this study has yielded a limited set of descriptive categories in accounting for physics students' depictions of each of the basic concepts of quantum mechanics (see Part I; Chapters 4 and 5). With regard to learning quantum mechanics, these limited set of descriptive categories made clear issues, for example: (a) physics students' explanations of quantum phenomena were bounded by their naïve perceptions and (b) they extended classical attributes in making explanations related to the quantum objects or (c) to diffuse uncritically the classical mode of thinking and reasoning into quantum mechanics setting. These findings were used to guide the design of instructional materials that have been shown to address difficulties identified in the principal study (see Part II; Chapter 6).

3.5 TRUSTWORTHINESS IN THE STUDY

The quality criteria of research and its trustworthiness depend on the research paradigm used. This is due to the reason that different paradigms have different knowledge demands (Lincoln & Guba, 1985). The trustworthiness criteria of the conventional paradigm are often presented in terms of "validity" and "reliability". Consequently, researchers using qualitative approaches are still traditionally expected to address issues of the validity and reliability of their research. This is true even though the notions of validity and reliability derive from a positivist method that tries to study an objective reality, rather than the more intersubjective reality that most qualitative research is trying to investigate (Kvale, 1996; Åkerlind, 2005). Within qualitative research, the researcher seeks understanding not 'facts' and thus alternative constructs are needed. Consequently, Lincoln and Guba (1985) have offered equivalent terms to communicate the same meaning, which may be more suitable for qualitative research. They have claimed that interpretive researchers are focused on (a) the credibility of their findings, (b) the transferability or how well their working hypotheses would fit in a similar context, (c) the dependability (reliability) or testing for consistency and (d) the conformability of the data.

As with any kind of qualitative research, within phenomenographic research, validity and reliability are also prime concerns. However, these concepts need to be framed within the context of the ontological and epistemological beliefs of the research method being employed. The criteria for authenticating phenomenographic research are, thus, comparable to that of other qualitative research approaches in which validity and reliability must be confirmed. More specifically, the following sections presented how issues of validity and reliability can be considered in relation to phenomenographic research within the context of this study.

3.5.1 Validity

In phenomenographic studies, Sandberg (2000) claims three criteria to justify the researcher's interpretations: communicative validity, pragmatic validity, and reliability as interpretative awareness. Thus, in phenomenographic studies, validity is based on the researcher's reasoning for presenting the results and the conceptions based on those results as credible and trustworthy (Sandberg, 2000). As this investigation uses the phenomenographic perspective, the same criteria were employed. In general, considering communicative validity in phenomenographic research includes ongoing dialogue between the researcher and the participants in which alternative knowledge claims are debated and also providing adequate quotes to illustrate the meanings of the categories of description. Whereas pragmatic validity involves evaluating the knowledge claims in action. Reliability in this phenomenographic study revolved around the researcher's interpretive awareness, or how interpretations have been controlled and checked throughout the research process (Bowden et al., 1992; Sandberg, 1997).

3.5.1.1 Communicative Validity

In this study, communicative validity was used both during the data collection and analysis phases as well as after a study is complete. In the data collection stage, communicative validity was achieved by using open-ended interview questions that encouraged the student participants to depict and explain to the researcher what they understood as pedagogic connectedness. Impromptu questions and/or prompts such as “What do you mean by that?” throughout the interviews ensured that the researcher understood the ways in which the participants depicted the basic concepts of quantum mechanics. These prompts were also used, as crucial, to orient physics students toward the basic quantum concepts, while further allowing maximum freedom for students to depict their understanding. In the data analysis phase, communicative validity was accomplished as suggested by Sandberg (2000) by making interpretations of students' interviews, written explanations and drawings about the basic concepts of quantum mechanics that were "consistent with both the immediate context of surrounding statements and with the transcript as a whole" (p. 14). Adhering further to the criterion, tentative interpretations were checked and questioned against several alternative interpretations until a basic meaning structure had been established. The final categories of description were further verified on the basis that they identified the key features of student depictions and the object of focal awareness, and, the categories were logically related (Marton & Booth, 1997). These are also supported by student quotes, selected because they illuminated a particular way of depicting the basic concepts of quantum mechanics. As Marton and Booth (1997) suggested, this strategy has the further benefit of allowing the students' 'voices' to be heard in the categories of description. Communicative validity was also sought by publishing the findings in peer-reviewed journal, presenting conference papers (Ayene et al, 2011; 2013) and seminars and through discussions with supervisors.

3.5.1.2 Pragmatic Validity

According to Kvale (1996), pragmatic validity is evaluated by looking at whether interpretations are accompanied by action or lead to future action, or innovations based on them lead to desired results. In the teaching and learning contexts of a particular topic validity can be evaluated by researchers using the results in their own teaching and learning contexts and evaluating the outcomes. The present study is consistent with the developmental interest of phenomenography (Bowden, 2000) and results from this research were applied to develop instructional strategies to improve students' understanding of quantum mechanics. The preliminary assessment shows that the new instructional strategies are helpful in improving students' understanding of the basic concepts of quantum mechanics (see Part II; Chapter 6).

3.5.2 Reliability

The question of reliability in phenomenographic research is typically addressed in one of three different methods (Mckenzie, 2003). On one hand, an individual researcher may develop the categories of description and then be questioned by others and required to argue for the constitution in relation to the evidence in the transcripts (Dunkin, 2000). On the other hand, many researchers involved in a study may independently construct the categories of description from same pool of data, compare their categorization and argue for their description and then reconstruct the categories collectively or independently until agreement is reached (Trigwell, 2000b). On this way of addressing the issues of reliability, Marton (1986) argues that it is possible that different researchers may discover different set of categories while working on the same pool of data individually. But once the set of categories have been found, the researchers must be described in such a way that all researchers can understand and use them. The third way raised in this regard by Marton (1986) involves independent judges categorizing transcripts with reference to the categories of description.

For many researchers (e.g., Sandberg, 1997; Kvale, 1996; Åkerlind, 2005), a better alternative to these particular forms of reliability checks is for the phenomenographic researcher to make their interpretive steps clear to readers by fully detailing the steps, and presenting examples that illustrate them. The question of reliability in phenomenographic perspective is addressed thoroughly by Sandberg (1997) who suggests reliability as interpretative awareness is more appropriate than reliability as replicability. Sandberg (1997) argues that interjudge reliability is incompatible with relational aspect of phenomenographic perspective and claims interpretive awareness as a possible alternative. He described that it is more attuned to phenomenographic tradition, where the researcher is seen to be intentionally related to the object of research (Sandberg, 1997). According to Sandberg (1997), in maintaining interpretive awareness, "the researcher must demonstrate how he/she has controlled and checked his/her interpretations throughout the research process: from formulating the research question, selecting individuals to be investigated, obtaining data from those individuals, analyzing the data obtained and reporting the results." (p. 209)

This suggests that one can strive to maintain a critical perspective of how their subjectivity may influence the research and ensure reliability by applying what Sandberg (1997) refers to as interpretive awareness. According to Sandberg (1997) applying interpretive awareness involves five steps. This involves:

1. Remaining "oriented to the phenomenon as and how it appears throughout the research process";
2. Describing experience rather than explaining it;
3. Treating all aspects of individuals' descriptions as equally important;
4. Searching for the meaning structure of the experience, using "free imaginative variation";
5. Focusing on the what and how of the individuals experiences as well as on the relationship between the what and how.

Finding such arguments to be persuasive, in this study, it was decided against interjudge reliability as a criterion of reliability. Instead, reliability is conceptualized in terms of defensible knowledge claims as the main criterion for the acceptability of the study outcomes. According to Bowden (2000) phenomenographic research should be planned, collected and analyzed around a specific purpose, which provides the focus that guides the action. To this effect, a range of strategies was implemented, throughout the research process, to ensure that the physics students' depictions of quantum mechanics were represented as faithfully as possible. These strategies involve: the internal relationship between the researcher (i.e., a quantum mechanics lecturer at university) and the object of study; the relationship between the participants and the basic concepts of quantum mechanics; and methods and process of data collection and analysis in relation to the outcomes. As in any area of phenomenographic research, in this study, reliability was thus ensured by detailing the interpretive steps of the study and presenting examples to illustrate those. This chapter attempted to demonstrate how the research has applied these criteria, in each part of the research process, to support validity and reliability in researching the physics students' depictions, and thereby, to justify the outcomes of the study. Also, the use of numerous quotes in the text was seen important for reliability reasons in this study; to give the readers steps in the interpretation process in a detailed form and to present examples that illustrate them. In Chapters 4 and 5, a sufficiently 'thick description' including, for example, lengthy excerpts from the interviews together with full details of the process, was involved thereby making it possible for the readers to judge whether they agree with the categories of description or not.

3.6 ETHICAL CONSIDERATIONS

Major ethical protocols required as common practice and by the participating institutions in qualitative studies involving human participants were followed in planning, carrying out and reporting of the present research (Maxwell, 2005). In complying with the University's Ethical Review Committee guidelines, all those involved in the research were informed, verbally and later in writing, prior to the interview, about the purpose of the research, the process, why their participation was necessary, how it would be used, and how and to whom it would be reported. Furthermore, before each interview began, the interviewee was asked to read and sign a consent form (see Appendix II). Besides, the interviewees were told that what was interesting was their quantum mechanical thinking and their depicting of the basic concepts and that the aim of the research was to find ways of improving quantum mechanics teaching based on better knowledge of physics student depicting. The interviewees were also informed that their participation in the study was voluntary and that they could withdraw from the interview at any point or choose not to answer certain questions. All interviewees agreed both to participation in the study and to the audio-recording. All participants were offered the opportunity to remain anonymous when the outcomes of the research are published. Fortunately, no participant withdrew, nor were there any other problems for the participants in this study. Additionally, approval to conduct the research was granted from the Institute for Science and Technology Education, UNISA Ethics Review Committee (see Appendix III).

PART I: ANALYSIS OF STUDENTS' DEPICTIONS OF QUANTUM MECHANICS

The main results and findings of this thesis are divided into two parts. Part I, which consists of Chapters 4 and 5, presents the description categories which form the basis for physics students' depictions of the basic concepts of quantum mechanics. The main emphasis in Chapter 4 is on students' depictions of quantization, the photon concept and light quanta interference. The students' depictions were elicited by having students respond to the semi-structured interview questions about these concepts. The data thus obtained were analyzed using developmental phenomenographic analysis where a picture of students' depictions for each quantum concept was constructed by expounding the given responses and their implications. A similar kind of approach has been used in Chapter 5. However, the main emphasis in Chapter 5 is on students' depictions of matter waves and the uncertainty principle. For each concept, the categories of description that can be considered to reflect the students' conceptual understanding were constructed by analyzing the data obtained from the semi-structured interviews.

In both chapters, in the construction of the categories of description, only the explanations of students related to each quantum concept were taken into consideration. With regard to learning quantum mechanics, the categories of description for each quantum concept made clear several issues. Overall, it was found that naive, quasi-classical ontology and/or variants of classical ways of visualization are dominant in the majority of students' responses. These findings are supported by the findings of previous studies in the similar domain: suggesting that traditional presentations of quantum mechanics seem not only ineffective, but detrimental for student learning. Using this background, multiple representations-based instructions and interactive quantum learning tutorials were developed to teach the basic concepts of quantum mechanics. The preliminary evaluation showed that these strategies are helpful in improving students' conceptual understanding of quantum mechanics. The multiple representations-based instructions and interactive quantum learning tutorials are discussed in the second part of this thesis (Part II; Chapter 6).

CHAPTER 4

PHYSICS STUDENTS’ DEPICTIONS OF QUANTIZATION, THE PHOTON CONCEPT AND LIGHT QUANTA INTERFRENCE

4.1 INTRODUCTION

The developmental phenomenographic perspective used in this thesis and the methods of data analysis for Part I of this study was provided in Chapter 3. The qualitative data analysis has been carried out by first transcribing all the interviews, written explanations and drawings. Before attempting to answer any of the research questions, the interviews, written explanations and drawings were read and listened repeatedly to obtain an overall insight into the substance of the students' depictions of quantum mechanics. These interview responses, written explanations and drawings (graphical, pictorial and verbal) from the transcripts were then organized and sorted under the two themes and associated five basic quantum concepts covered in the interviews creating five different pools of understanding. The generation of the categories of description to characterize the students' depictions of matter waves and the uncertainty principle is available in Chapter 5. This chapter discusses physics students' depictions of energy quantization, the photon concept and the light quanta interference as it pertains to the following three questions:

1. How do undergraduate physics students depict energy quantization, the photon concept and the quantum model of radiation?
2. Do students use a consistent depiction of one key quantum concept when presented with different physical situations?
3. Do students with inappropriate depictions of one concept also give inappropriate depictions of other concept in quantum mechanics?

In order to answer these research questions, the information gleaned from the transcripts of interviews and written explanations about the basic features of the quantum model of light was further sorted and grouped together into the three basic quantum concepts creating three different pools of understanding. Table 4.1 lists the three basic quantum concepts associated with quantum model of light covered in the interviews with their associated qualitative quantum problems.

Table 4.1: Quantum concepts and phenomena associated with the quantum model of light

No.	Quantum Concepts	Quantum Problems Consisting of Open-Ended Interview questions
Concept 1	Quantization	Blackbody Radiation (BBR) spectrum
Concept 2	The concept of photon	Photoelectric effect and Compton scattering
Concept 3	Light quanta interference	Double-slit experiment: The gradual formation of an interference pattern in different cases of low-intensity light

After the interview responses and written explanations (both pictorial and verbal) were coded and organized into concepts shown in Table 4.1, data was again considered this time in each given concept separately to identify different dimensions of variation within that pool of data. Further analysis followed in each concept category by selecting segments of text which were regarded as relevant to the basic concerns of the study. This selection process involves recording key words, phrases, and passages, which the participants themselves had repeated or had indicated as being important. A set of theme of description was developed which paraphrased or generalized the text itself and contained the key characteristics of each theme. The themes of description were organized into the final principal categories. In each category a variation existed in the way it is described, and thus, by identifying the variations assisted in identifying the categories of description. After the variations were found, the categories of description could be determined. Chapter 3 has documented the detail iterative and comparative phenomenographic analysis in constructing the categories of description from the given pool of data.

The data analysis revealed three distinct models of description categories of quantization. These categories of description that can then be considered to reflect the students' conceptual understanding of energy quantization are:

I. Energy in BBR as a factor of "square of frequency"
II. Hybrid description of energy in BBR
III. Energy in BBR as "quanta" of energy size E = hv.

It has suggested that students' depictions of the photon concept can be described with three other distinct models of description categories, which are:

I. Classical intuitive model description
II. Mixed model description
III. Quasi-quantum model description

And, finally, the students' depictions related with light quanta interference were gathered under three different categories of description, namely:

I. Classical wavy and intuitive model description
II. Mixed model description
III. Incipient quantum model description

A graphical layout representing the outcome space and a hierarchy of the categories of description is presented in Figure 4.1. The categories of description are structured logically and hierarchically to visualize their internal relationship to the given aspect of the quantum phenomenon and to each other (see sections 4.2 to 4.4). Relatively, completeness of the categories within the outcome space increased from the top to the bottom of the diagram for every quantum concept. Thus, the hierarchical arrangement used completeness as the organizing criteria to allocate some categories higher on the outcome space than other categories. Categories at the bottom of the outcome space also represent broader or more encompassing ways to think about the quantum concepts. The general features of the outcome space in each typified quantum concept are discussed and how it relates to the discerned categories visualized.

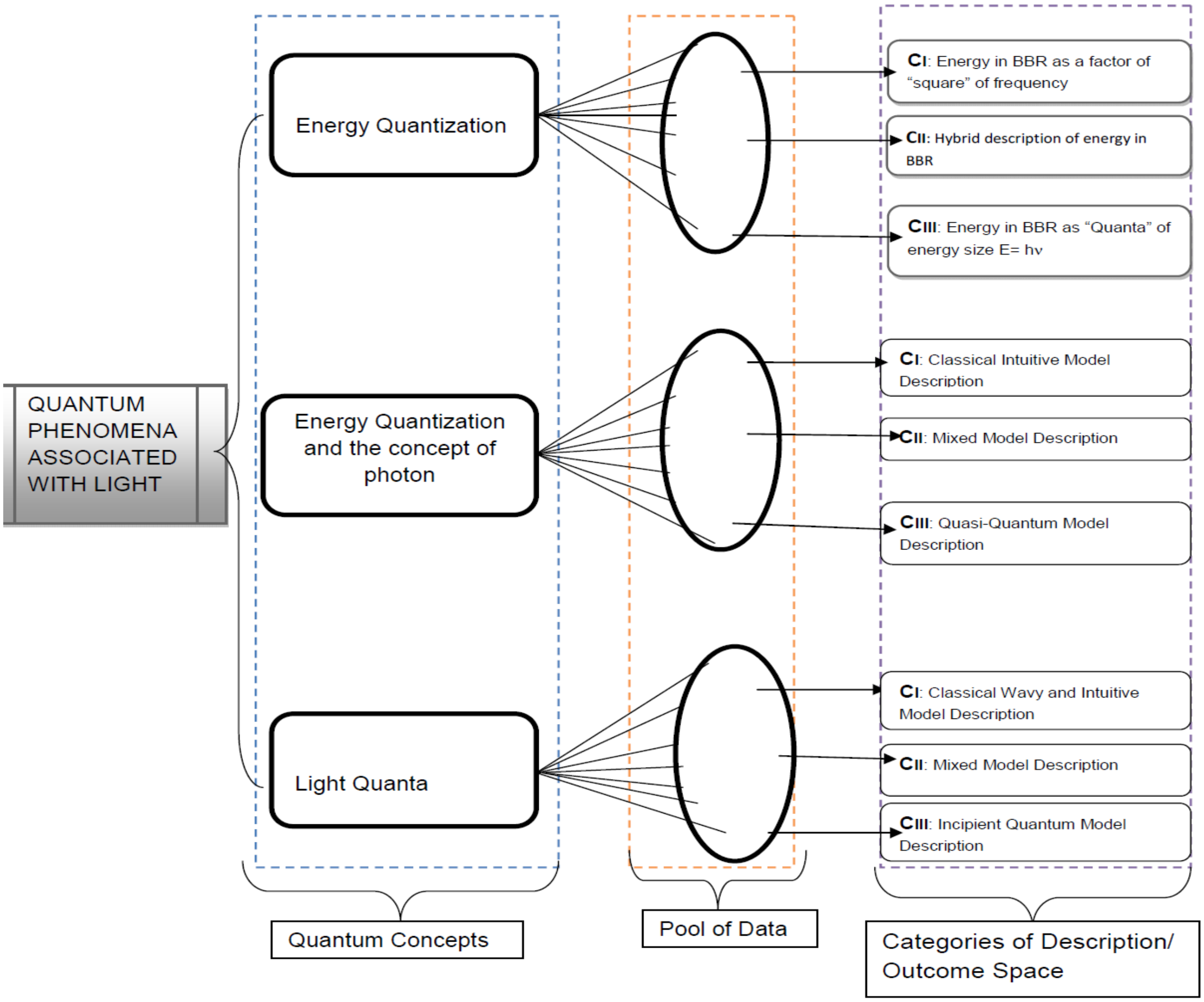


Figure 4.1: A graphical layout of the three quantum concepts and applicable outcome spaces

For each quantum concept, the qualitatively distinct categories of description were drawn from students' interview responses, written explanations and drawings to associated qualitative quantum problems. Exploring into the nature of the depictions which the students had of energy quantization, the first set of interview questions cover the concept of the quantum of energy to explain the phenomenon of blackbody radiation. First, the students were asked to explain the relationship between the total energy radiated (particularly the observed color change) with rising temperatures. This was initiated with a question such as:

> When a solid object is heated, it glows and emits heat radiation. As the temperature increases, the object becomes red, then yellow, then white. What underlying reason do you think is behind the change in color of a heated object as its temperature increases?

Then, students were shown two figures presenting the blackbody spectrum (i.e., radiation energy versus wavelength at different temperatures) and blackbody spectrum (i.e., radiation energy versus frequency at different temperatures) and they were asked to give answers in words and written (pictorial and graphical) explanations to the questions (the full set of interview questions with necessary figures is given on Appendix I), for example:

3. In the BBR spectrum versus wavelength curve, how do you describe the blackbody curve in each region of spectrum as a function temperature?
4. In a BBR versus frequency curve, how do you describe the blackbody curve in each region of spectrum with temperature?
5. What major effects do you expect that governs the distribution of BBR?
6. In a BBR versus Wavelength curve, as temperature is increased, intensity of emission increases, and peak wavelength λ shifts to smaller λs. But why does emission go to zero at very short wavelengths?
7. In a BBR versus frequency curve, you found that at a given temperature the energy radiated at given frequencies increased as the frequency was raised, reached a peak, and then why began to decrease as the frequency was raised still further? Why blackbody radiation should be distributed in the manner as actually observed over the entire range of frequencies?
8. Why new peak radiation would move into higher and higher frequencies as the temperature went up? Or why the new peak is at higher frequency than the previous one in the in a BBR vs frequency curve?
9. How do you account for the fact that the probability of radiation decreased as frequency increased in the blackbody spectrum?

Thus, the interpretations for the categories of description are grounded in students' responses to these questions. For each category of description, therefore, key facets of depictions which appear illustrative of a particular kind of depiction (see Table 4.2) and exemplary excerpts of the interview responses from students are included. Students' depictions are compared and contrasted and, in some cases, possible source(s) for students' depictions are traced.

4.2 PHYSICS STUDENTS’ DEPICTIONS OF THE QUANTIZATION OF ENERGY

As presented in section 4.1, the analysis of students’ responses revealed three set of categories that describes their depictions related to the concepts of quantization, namely: energy in BBR as a factor of “square of frequency”; hybrid description; Energy in BBR as “quanta” of energy size E = hν. These categories are expanded upon with the aid of key facets of students’ depictions (see Table 4.2) and excerpts of interview alongside each category of description to illustrate that the data analysis reflects the students’ depictions as accurately as possible.

Table 4.2: Categories of description representing aspect of students’ ways of depictions of energy quantization

Categories of Description	Key Facets of Students’ depictions
Category I Energy in BBR as a factor of “square of frequency”	Assuming that an electromagnetic radiation emitted from a blackbody can have any energy value in the continuum from zero to infinity Assuming that light waves can exchange any amount of energy interacting with matter Randomly relating the temperature corresponding to the red and blue curve in the BBR spectrum Assuming that all frequencies could be radiated with equal probability Expecting that energy radiated increase as we decrease wavelength Indicating that the energy emitted should be a monotonically increasing function of frequency, diverging as frequency increases without bound Predicting that the intensity of light emitted by a blackbody would increase to infinity as the wavelength decreased or as the frequency increased Thinking that all materials should radiate infinite energy per unit time Assuming that as the frequency ν becomes large, the predicted intensity increases without limit, even for objects at modest temperature. Emphasizing on the continuous nature of energy and assuming that the energy in BBR can have any value
Category II Hybrid description of energy in BBR	Assuming that energy is in quanta form only when it is radiated and absorbed continuously The higher the temperature means the higher the intensity of the emitted radiation with limit. Light is continuously absorbed by the blackbody and the energy radiated is quantized consisted of a series of "packets" of energy Depicting in the way that what the correct interpretations looks like but don’t explain the correct relation between the elements inside the interpretation Assuming that as a piece of object (e.g., iron) is heated, it emits more energy over all but with no shift in its predominant wavelengths Mixing the principle of energy quantization with the ultraviolet catastrophe

Categories of Description	Key Facets of Students' depictions
	of blackbody radiation
Category III Energy in BBR as "Quanta" of energy size E = hν	The idea that the energy in EMR is quantized in discrete bundles was put forwarded in the context of their depictions of the BBR Assuming that the exchange of light radiation is done in finite amounts, called quanta High frequency radiation could only be emitted or absorbed in events involving a single quantum of significantly high energy Microscopic processes occur in discrete or quantized steps Describing that the smallest unit of light radiation that can be emitted or absorbed is $E=h\nu$ where E is the energy of the *"quantum"*, ν is the frequency of radiation, and h is a constant (fundamental constant) Energy must vary directly with the frequency of the light in which it was radiated Radiation of a given frequency ν could only be emitted and absorbed in "quanta" of energy $E=h\nu$ Assuming that the energy spectrum within the blackbody cavity is not continuous, but discrete. For any given temperature T, each curve in the blackbody radiation spectrum peaks at a most probable value.

4.2.1 Category I: Energy in BBR as a factor of "Square" of the frequency ν

For this first category, it is difficult to find specific patterns in the students' responses in many cases. However, as a common element inside their overall depictions, students understood that the energy radiated from a blackbody would increase without limit as the frequency increases. This depiction is appeared to have been framed by a mixture of classical theory of electromagnetic radiation and retention of naïve ideas. For example, concerning the introductory interview question (i.e., to expound the underlying reason behind the change in color of a heated object as its temperature increases), the students seemed to have assumed that the classical theory of radiation, which is working in the macro-scale, was also valid at the microscopic level, these oscillating charges would radiate, presumably giving off the heat and different color light observed. Consider the following illustrative examples:

> **S$_4$:** When a body is heated atoms vibrate. Charge particle in the atom also start oscillation. I think I can say heat radiations are electromagnetic waves. […] is that not? […] if so charged particle in heated body may produce different color light radiation

> **S$_{11}$:** […] different colors may be related to vibration of atoms.

> **S$_{20}$:** For me the different color relates to oscillation of charged particle because of continuous increasing of temperature on the solid

As a follow-up to this question, students were asked: to predict and point out, in general, the BBR curve in each region of spectrum as a function temperature; to explain why at a given temperature the energy radiated at given frequencies increased as the frequency was raised, reached a peak, and then began to decrease as the frequency was raised still further; and why does the intensity of emission go to zero at very short wavelengths.

In fact, their responses held no deeper meaning other than the generalization that virtually all the energy of a radiating body is radiated very rapidly in the violet light and far more still is radiated in the ultraviolet. The following two excerpts manifest this understanding. Excerpts from student S$_4$:

> **S$_4$:** […] temperature is the factor in the BBR phenomena. The total energy radiated from heated body is proportional to the fourth power of temperature. Temperature increase means more and more energy is radiated from heated body.
>
> **S$_4$:** […] the distribution of energy radiated varies with frequency and wavelength. It increases in some wavelength and it decreases in another wavelength and frequency.
>
> **S$_4$:** From the BBR versus frequency curve, an increase in frequency forces the energy to radiate very rapidly. […] I don't understand why further increase in frequency increases a further more rapid energy radiation. But temperature is a factor. […] In the BBR versus wavelength curve the total energy is decreasing and decreasing to zero with wavelength.
>
> **S$_4$:** At a very high frequency the energy radiated is very high. Since wavelength is inversely proportional to frequency then at zero wavelengths, mathematically the total energy radiated becomes very great and increases to infinity.

Excerpts from student S$_{20}$

> **S$_{20}$:** […] temperature increases the energy radiated.
>
> **S$_{20}$:** […] the relationship between the energy radiated and the frequency and wavelength is not consistent. It varies here and there with no pattern. […] in the energy versus frequency as well as energy versus frequency graph, the total energy emitted increase at some point and decrease in another point.
>
> **S$_{20}$:** For the BBR versus frequency curve, the figure indicates energy radiates rapidly at high frequency. That means in the BBR spectrum increasing frequency implies further emission of energy. […] further increase in wavelength resulted further decrease in emissions of energy.

> **S_{20}:** […] as I can see when wavelength is zero energy is very large. Again frequency is very large at this point. […] wavelength is inversely proportional to energy radiated and frequency.

Notice that students are failed to appropriately explain why the blackbody radiation should be distributed in the manner observed by expert physicists. Rather it seems that students used the classical theories of electromagnetism and thermodynamics to show that the amount of energy radiated over a particular range of frequencies should vary as the square of the frequency. Under this category, it is proposed that the energy in blackbody radiation is determined both by the amplitude of the oscillator and frequency. In addition, students' interpretations of the BBR spectrum of the heat radiation emitted by an object at different temperatures are depicted as a function of wavelength or frequency and its explanations showed no nexus. For example, students thought that an infinite amount of energy is being radiated by a blackbody at high frequencies or short wavelengths (i.e., Applying Wiens' displacement law and Rayleigh-Jeans Law to predict the characteristics of the energy emitted from a blackbody as a function of temperature and wavelength of the radiation). Students also considered that the high frequencies are operative, the systems energy is equipartitioned between all its frequencies; but in the blackbody radiation spectrum, students described that the shorter the wavelength, the higher the frequency and the higher frequency is related to the higher temperature. In explaining their reasons for the maximum intensity shifts with wavelengths as the BBR temperature increases in the case of infrared, visible and ultraviolet regions of spectrums, students (e.g., S_4, S_7 and S_{12}) invariably described their answers as [the intensity curve just grew and expanded with increasing temperature but without specifying the actual shape]. To further expose students' thinking, more in-depth questions were raised and students were encouraged to be more specific in explaining what will happen to the peak in radiation intensity for a range of temperatures between 300K and 7,000K in each region of spectrum. They (e.g., S_9, S_{11} and S_{20}) predicted that the blackbody peak intensity curve shifts from the infrared region into the visible spectrum region as the temperatures increases and any further increase will increase the intensity peak within this visible spectrum region without limit. Considering that the higher frequency is related to the higher temperature, two students (e.g., S_{13} and S_{19}) predicted as [the blackbody radiation always exhibits its maximum intensity at the high frequency end in each region of spectrum].

4.2.2 Category II: Hybrid Description of Energy in BBR

The description category in this class of responses seems to be slightly different from the previous category. It permits to include aspects of the quantization idea into an explanation for the intensity spectrum of the radiation emitted by a blackbody. But the basis of this category still depends on intuitive, classical reasoning and repeated definitions presented during the classes and/or from the textbooks. Students in this category depicted that light is continuously absorbed by the blackbody and they no longer thought of radiation from a blackbody as continuous. They argued that this radiation is emitted in small packets, each containing hν: depicting that radiation emitted from the blackbody is being thought of as a "packet of energy". The description category is constructed through restructuring of one's thinking orientation by combining some elements of the classical understanding with some newly incorporated elements of the correct understanding of energy in BBR spectrum. Responses have incorporated some of the main concepts "quantization of energy, E=hν "which are mostly blurred and unspecified by their meaning. These responses do not correctly describe the quantization of energy and E=hν, as explored in their responses and in the fact that, in any case, these concepts appear related to the light quantum hypothesis; most importantly with the quantum model of blackbody radiation. For instance, students (e.g., S_2, S_{10} and S_{18}) predicted that the intensity emitted by blackbody radiation would increase without limit as the frequency increases. It is explored from their responses that students' thinking seems to go back to the familiar classical kinetic theory (by Rayleigh and Jeans) which predicts the energy radiated will increase as the square of the frequency increases. The following excerpts are some illustrative examples of how students were responding to depict why at a given temperature the energy radiated at given frequencies increased as the frequency was raised, reached a peak, and then began to decrease as the frequency was raised still further; and why does intensity of emission go to zero at very short wavelengths:

> **S_2:** […] off course I understand […] at a given temperature, the energy radiated at given frequencies increased as the frequency raise. This because energy emitted is the fourth power of temperature. It means the amount of energy radiated over a particular range of frequencies should vary as the forth power of frequency. At high frequency the intensity of emission goes to very high. […] but from the experimental finding the energy decreases although the frequency is increasing. […] from quantum mechanics energy is quantized.

> And it is emitted in discreet form although the absorption is still continuous. That means $E = h\nu$ so radiation of a given frequency ν could only be emitted in "quanta" of energy $E=h\nu$. […] this reduces the effect of ultraviolet catastrophe. I am […] sorry I don't understand it but I remembered quantization forbid this catastrophe. The reason for the emission go to zero for short wavelength is still because high frequency.

> **S_{18}:** as the temperature and frequency increases the emission of energy further increases. I think this is central fact in the BBR versus frequency curve. According Planck's theory again energy is quantized into discrete packets energy (photons) and the total energy is a multiple of this energy E= hν and this might be the reason […] I mean at high frequency one can also see low energy emission. But from the mathematical relationship the energy emitted is always goes to infinity as the frequency further increases. That is the ultraviolet catastrophe. I expect […] the same phenomena in the short wavelength but the effect is indirectly proportional to energy in this case.

Students' depictions are characterized by a prevalent classical perception of quantum phenomena. They (e.g., S_2 and S_{10}) thought that energy of EM radiation cannot have just any values (continuous), but is in fact quantized. Furthermore, in their responses (e.g., S_2 and S_{10}) energy in BBR is radiated as little discrete packets of energy (photons), whose energy depends on the frequency of the radiation: E=hν. In general, however naively and classically perceived, their description in this category reflected some sensible depictions for the quantum phenomenon they were dealing with.

4.2.3 Category III: Energy in BBR as "Quanta" of Energy size $E = h\nu$

In this category of description most features of energy quantization are discerned. The interaction of radiation with matter, explanation of blackbody radiation and the quantization of electromagnetic radiation are described based on the quantum mechanics formalism. The underlying reason behind the change in color of a heated object is seen in terms of the energy density that shows a pronounced maximum at a given frequency, which increases with temperature; that is, the peak of the radiation spectrum occurs at a frequency that is proportional to the temperature. S_{15}, for example, interpreted the change in color of a heated object as its temperature increases as follows:

> **S_{15}:** […] from Planck's formula radiation from a heated object is not continuous. […]so it is quantized with $E= h\nu$. $E= h\nu$ implies energy is emitted and absorbed in small packets or photons of a definite energy with frequencyν. In BBR case for a body is heated […], maximum energy is at a certain frequency with the temperature. The different colors correspond to different frequencies again that mean it emits at radiation of oneλ. […] so the color change from red to yellow to white with increase temperature.

It seems evident that to S_{15} the energy density which shows a pronounced maximum at a given frequency, which increases with temperature is the underlying reason behind the change in color notably from red to yellow to white. The basic quantity of energy $h\nu$ is associated with the notion of the photon, the quantum of energy. The idea of radiation in the form of energy quanta of size $h\nu$ is discerned to explain the radiation energy emitted by a blackbody as a function of frequency ν and temperature T. Though it is only for one student (S_{15}), the observed BBR spectrums are understood from quantum mechanics perspective underlying Planck's theory of radiation. S_{15} succeeded in understanding the idea of quantization by postulating that energy exchanges between matter and radiation do not take place in a continuous manner but by discrete and indivisible quantities, or quanta of energy. He showed that by assuming that the quantum of energy was proportional to the frequency, $E = h\nu$. In the later interview, S_{15} also relied upon the Planck's theory of radiation to make sense of the BBR versus frequency and the BBR versus wavelength curves. In understanding why at a given temperature the energy radiated at given frequencies increased as the frequency was raised, reached a peak, and then began to decrease as the frequency was raised still further, S_{15} pointed out the following reasons:

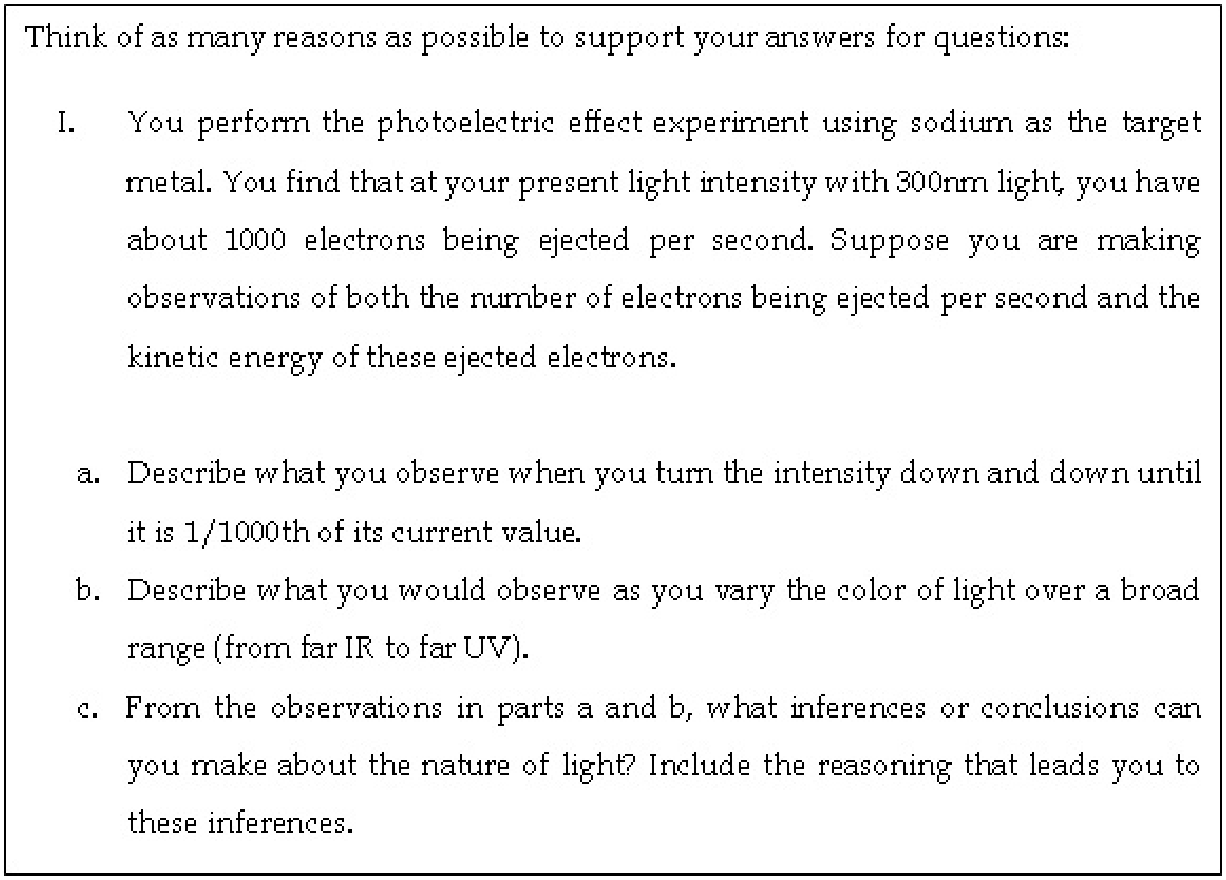
> S_{15}: As I understand from Planck's low this radiation emitted or absorbed in packets of energy. As I learned it is called quanta and it is proportional to the frequency. […] from my knowledge and also I see in a BBR versus frequency curve, at smaller frequencyν or high wavelength, and $\nu \uparrow$ means radiation$\uparrow$. But if ν continue like this […] energy increases but not similar to ν and reach maximum value then decreases. If temperature increases at the same time the peak or maximum value increases with large frequencies.

> S_{15}: I understand this behavior […] from quantum view or Planck's low it is because energy is quantized which is proportional to the frequency. […] again from this course I understand high frequency BBR is emitted in multiple of a single quantum of high energy $E=h\nu$. It implies at high frequency no infinity energy or no ultraviolet catastrophe. In classical case there is infinite energy but in quantum not happened because light and energy is in quantized or photons.

In the foregoing excerpts, an aspect of reasoning, not found in other categories, is the understanding of energy changes in the radiation spectrum by jumps of integral multiples of $h\nu$ that cleared up the ultra-violet catastrophe. Furthermore, the idea of the ultra-violet catastrophe is discerned as one of the key features in which quantum mechanics differs from classical interpretation of radiation emitted by a blackbody. In conclusion, this is the only category that S_{15}'s depictions indicated a relatively better understanding of the phenomena under investigation.

4.3 PHYSICS STUDENTS' DEPICTIONS OF THE PHOTON CONCEPT

The second context, quantum phenomena associated with light quanta, selected for in-depth interviews were the qualitative analysis of the photoelectric effect and Compton scattering experiments. These concepts are powerful tools to help students build an understanding of the photon model of light, and to probe their understanding of the photon model. Students were, therefore, asked to describe the critical features of these experiments, for example, how would students predict the results of these quantum experiments, and describe how these results lead to the photon model of light. These semi-structured interview questions were designed to provide various contexts that might trigger a variety of student descriptions that was observed in this part of analysis. Parts of the interview questions that have been used extensively on this section of the analysis are presented on the Figure 4.2 (see Appendix I for the full set of questions). By analyzing students' responses on these questions, three categories of description which form the basis for students' depictions of the photon concept were identified (see Table 4.3).



Think of as many reasons as possible to support your answers for questions:

I. You perform the photoelectric effect experiment using sodium as the target metal. You find that at your present light intensity with 300nm light, you have about 1000 electrons being ejected per second. Suppose you are making observations of both the number of electrons being ejected per second and the kinetic energy of these ejected electrons.

   a. Describe what you observe when you turn the intensity down and down until it is 1/1000th of its current value.
   b. Describe what you would observe as you vary the color of light over a broad range (from far IR to far UV).
   c. From the observations in parts a and b, what inferences or conclusions can you make about the nature of light? Include the reasoning that leads you to these inferences.

Figure 4.2: Semi-structured interview questions on the photoelectric effect and Compton scattering experiment given to students

Table 4.3: Categories of description representing aspects of students' depiction the photon concept

Categories of Description	Key Facets of Depictions
Category I Classical Intuitive Model Description	Assuming that the intensity of the light would imply larger amplitude of the light waves, which would result in larger energy transfer to electrons when the light hit the atoms of the surface; Assuming that the energy available in light is proportional to the intensity and independent of frequency, ν The phenomenon of photoelectric effect and Compton scattering are depicted in terms of wave model of radiation. Discerning that the kinetic energy of ejected electron should depend on the intensity of the radiation Assuming that the existence of threshold frequency has no explanation and/or physical meaning

Categories of Description	Key Facets of Depictions
	Predicting that there should considerable time lag between the arrival of the radiation and the ejection of electron Expecting the presence of only unmodified radiation in the Compton experiment
<u>Category II</u> Mixed Model Description	Light is radiated in quanta and if the first quantum is insufficient to liberate electrons from the metal surface multiplying the numbers of quantum will do the job The energy available in light is proportional to both the intensity and frequency, ν Predicating that brighter lights produce more photoelectrons with more energy photoelectrons An extremely intense light with any value of frequency would bring about the emission of electrons Understanding, if the intensity is low, although electrons might still be ejected, a measurable time lag and the low number of electrons should be evident The photon is discerned as the smallest possible packet (quantum) of light; but it has both mass and definite energy; The electron's kinetic energy should depend on both on the energy a photon (frequency) and on how many strike the metal per unit time (intensity) The ejection of a given electron is accomplished by multiple of photons expecting that these multiple photons could strike the electron simultaneously Any value of frequency of light will produce electrons but energy of electron increases with the increase of light frequency The billiard ball type conception of photons is commonly applied to describe momentum transfers and the Compton effect.
<u>Category III</u> Quasi-Quantum Model Description	Assuming that the incident light is composed of quanta of energy The number of electrons emitted would vary with the total energy of the light, but again all would have the kinetic energy An intense light would bring about the emission of many low-energy electrons Proposing that radiation is not only absorbed and emitted in quanta but that it also propagates as such An extremely intense light with a frequency below the threshold value would bring about the emission of no electrons The size of the light quantum increases as frequency increases As the frequency increases further, more and more energy will be left over to be applied as kinetic energy of the electron A light beam is discerned to be a stream of particles, light quanta or photons, each of energy $E_{photon} = h\nu$ Discerning that the more intense beam just contains more photons and *can* liberate more photoelectrons from the metal plate. The presence of radiation of longer wavelength, called modified radiation, in the scattered radiation can be understood

4.3.1 Category I: Classical Intuitive Model Description

In this category, students' emphasized the wave model of radiation to predict and explain the effects of making qualitative changes in the experimental parameters of the photoelectric effect and Compton scattering experiments. Students' responses held the depictions that the kinetic energy of an ejected electron (photoelectrons) is dependent on the intensity of the radiation. Their description of radiation in the Compton scattering experiment predicted the presence of only unmodified radiation. The presence of radiation of longer wavelengths, called modified radiation, in the scattered radiation is understood on the basis of the wave model of radiation. For example, students were asked if they had heard of the photoelectric effect, and whether they could describe and sketch the effect of varying the intensity of the incident radiation on the number of the photoelectrons and the kinetic energy of each electron when the other variables were held constant. Student (e.g., S_1, S_1 and S_1) in this category replied:

> **S_1:** The photoelectric effect occurs when light hit a metal surface and causes electrons to be ejected from that surface.
>
> **S_6:** […] high intensity light energy liberate electron from metal. When intensity of light high means high light energy hit the metal and then electrons ejected faster and faster from metal.
>
> **S_{25}:** […] photoelectric effect is a process of emitting electrons by a very high beam of light radiation. […] in the photoelectric experiment very high intensity light produce electric current. […] when our light source is powerful the electrons emitted from the metal and then move faster and have more energy.

From the forgoing responses it seems that as light is made more intense, more and more energy could be transferred to the metal surface. Students expected that not only would the electrons then be set free, but considerable kinetic energy would be available to them, so they would dart off at great velocities. Clearly supporting the classical hypothesis that [the more intense the light, the greater the velocities]. As part of their interview responses, students also sketched the effect of varying the intensity of the incident radiation on the number of photoelectrons and the kinetic energy of it as visualized in Figure 4.3 by student S_1. The student (S_1) was asked to explain his graphs. He gave reasons supporting his sketch:

S_1: I think intensity increase results electrons increase and also intensity increase, increases the energy.

According to his sketch and reasoning, the degree to which this happened would be anticipated to depend upon the intensity of the light beam, since this determined its energy, but he would not expect any dependence on the frequency of the incident light. It seemed fair to assume that he replied by simply memorizing the textbook and classroom diagrams of the variation of photoelectric current with intensity.

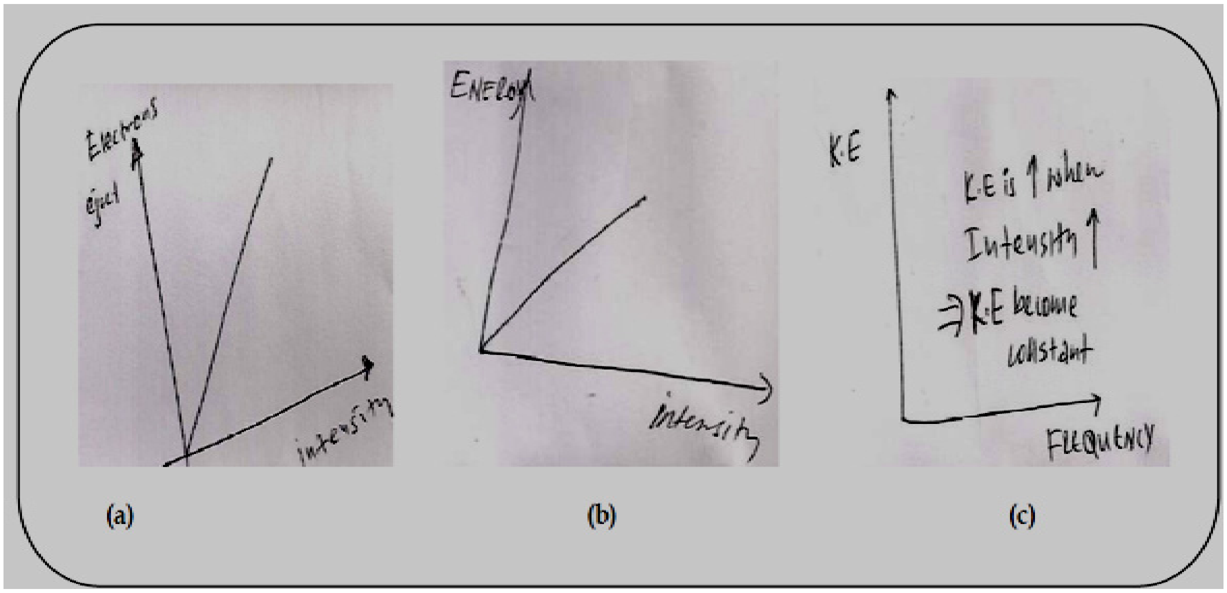


Figure 4.3: Student S_1's graphical descriptions of the photoelectric effect ((a) the number of electrons ejected versus light intensity (b) the kinetic energy versus light intensity and (c) the kinetic energy with the frequency of light)

Student S_1 was further asked about these sketches during the interview. The following dialogue visualized a further evidence of his picture.

I: So what do affect the number of photoelectrons ejected from the metal surface?

S_1: I think the intensity.

I: What will happen if we changed the target metal keeping the same value for the intensity of incident light?

S_1: Umm [….] I understand electrons eject is proportional to intensity so [….] I think the same.

I: You observed that 1000 electrons are ejected from the target in your hypothetical light intensity with 300nm. What will happen if we changed the present light intensity with an ultraviolet light with very weak intensity?

S_1: As I said number will be less. I mean below 1000.

I: What will happen to the kinetic energy of the photoelectrons?

S_1: Intensity is small so electron ejected is small energy is small. Intensity weak means small energy.

I: What is meant by "intensity"?

S_1: Energy. It is the energy of light

It is obvious that the student used naïve and classical reasoning to account for the quantum phenomena on the photoelectric experiment instead of the photon model of light. As in the photoelectric effect description, students' depiction of Compton scattering was without incorporating the quantum principles into the concept of photon. The classical perceptions of the scattering process form the dominant pattern of students' explanations in this category. The majority of the students thought that the incident and scattered radiation should have the same wavelength. In the following excerpts it is interesting to note how S_1 had made sense of the scattering of light radiation by electrons.

I: In the Compton scattering problem (see in Figure 4.2), what changes if it exists do you notice when the yellow light is replaced with an infrared (IR) light radiation?

S_1: If the color of yellow light does not change […] I am not sure. Not changed if you replaced by IR radiation.

I: What do you think of this?

S_1: I think IR radiation is scattered and there is no variation in intensity to that of yellow.

I: What do you think if you replaced it with X-ray photons or gamma ray light radiation?

S_1: The same. I mean no change in color. The same to that of it.

I: What is the relation between frequency and color of light?

S_1: I do not know. Frequency is inversely proportional to wave length.

I: Do you think that changing the intensity of the yellow light may change the color after it is scattered?

S_1: I think so, because electrons may be ejected.

> I: Do you think that the free electrons should take up any energy from the incident radiation?
>
> **S_1**: I do not think so. Umm[…] yes if intensity is high. High intensity light causes electrons to move.

As can be seen in the foregoing excerpts, the student expected that the incident and scattered radiation should have the same wavelength. It appeared as though this student has been unable to change the naïve and classical background of scattering of radiation by a quantum model because he was unable to incorporate the quantum principles into the concept of photon.

4.3.2 Category II: Mixed Model Description

In this category, students used multiple reasoning simultaneously about the photon concept and its implications about the quantum model of light. In their prediction and reasoning process, quantum mechanical aspects and aspects based on classical ideas coexisted at the same time. Aspects of conflict of thinking is seen in explaining the photoelectric effect, for example, [There were limiting threshold intensity and frequency of light above which, and only above which, the effect of photoelectric was to be observed], [The number of electrons emitted varies with the total energy of the light but they would have different kinetic energy] and [As the light frequency rises further, it doesn't matter how intense the light is, more and more electrons begin to be ejected with greater kinetic energy]. Aspects of conflicting thinking of the scattering of radiation by matter are also prevalent as [A 'billiard ball' kind of collision would be involved between an electron and a photon, in the course of which the photon would lose some of its energy to the electron] and [The wavelength shift of the scattering rays depends on the scattering angle and on the frequency of the incident photons]. This may suggest that students' depictions of how the results of the photoelectric effect and Compton scattering experiments lead the photon model of light are particularly context sensitive. Exemplary responses are explored in the photoelectric and Compton scattering problems. For example, students' responses held the correct relation between the intensity of the incident radiation and the number of photoelectrons ejected. When applied in other contexts, students thought that at low intensity although electrons might still be ejected, a measurable time lag and a low number of electrons should be evident; as a wave being diffuse, considerable time may be required for enough energy to accumulate in the electron's vicinity. For example, S_{10} described that for fixed incident intensity the maximum kinetic energy of the photoelectron is directly proportional to the frequency of incident radiation. S_{10}'s figures visualized his conflicting view that the emission of photoelectrons occurs up to a definite minimum frequency of the incident light (Figure 4.4 (a)). However, as it has been depicted the maximum kinetic energy of the photoelectrons goes to infinity without end. Some further typical responses from this student are:

> S_{10}: […] for fixed frequency, decreasing intensity decreases the electrons ejected. I am clear with number photon […] and intensity. So for a very, very low intensity, electrons become lower and lower. In this case liberating electrons may not be quick. I mean they may ejected after time taking to and energy getting from the light.

Figure 4.4 (b), (c), (d) and (e) visualized other students (S_{11}, S_{16}, S_{27}, and S_{28} respectively) sketch for the effect of varying intensity on the number of photons ejected at a fixed frequency. As it can be seen in the sketch shown in Figure 4.4, students who did not understand the correct relation between the graph of the maximum kinetic energy and the frequency at a fixed intensity are often confused on the relation between the kinetic energy and frequency.

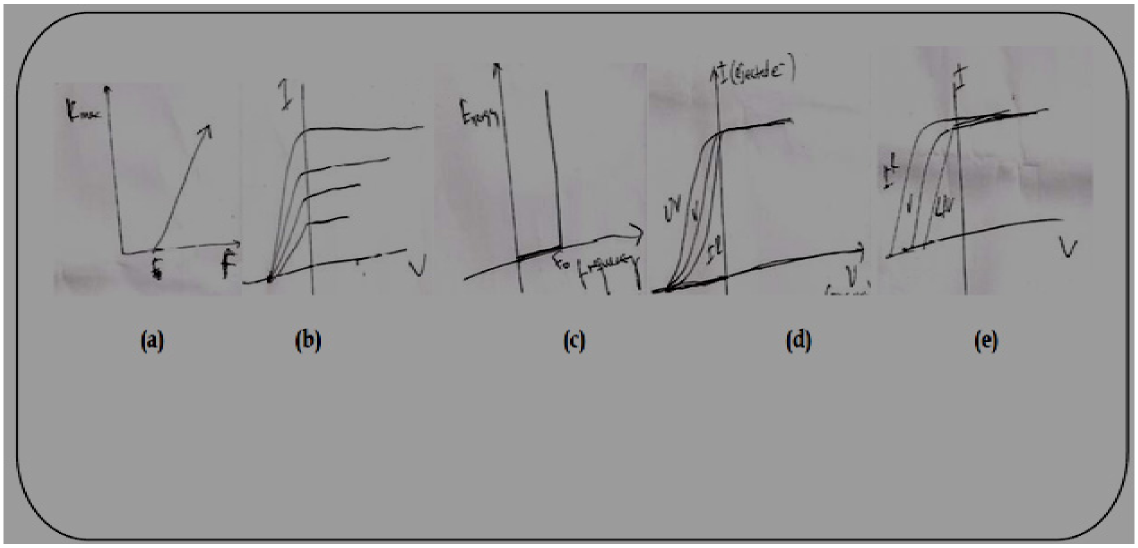


Figure 4.4: Students' sketch of the photoelectric effect ((a) S_{10}'s kinetic energy versus frequency graph (b) S_{11}'s current versus voltage (c) S_{16}'s kinetic energy versus frequency graph (d) S_{27}'s number of ejected electrons (current) versus voltage graph)

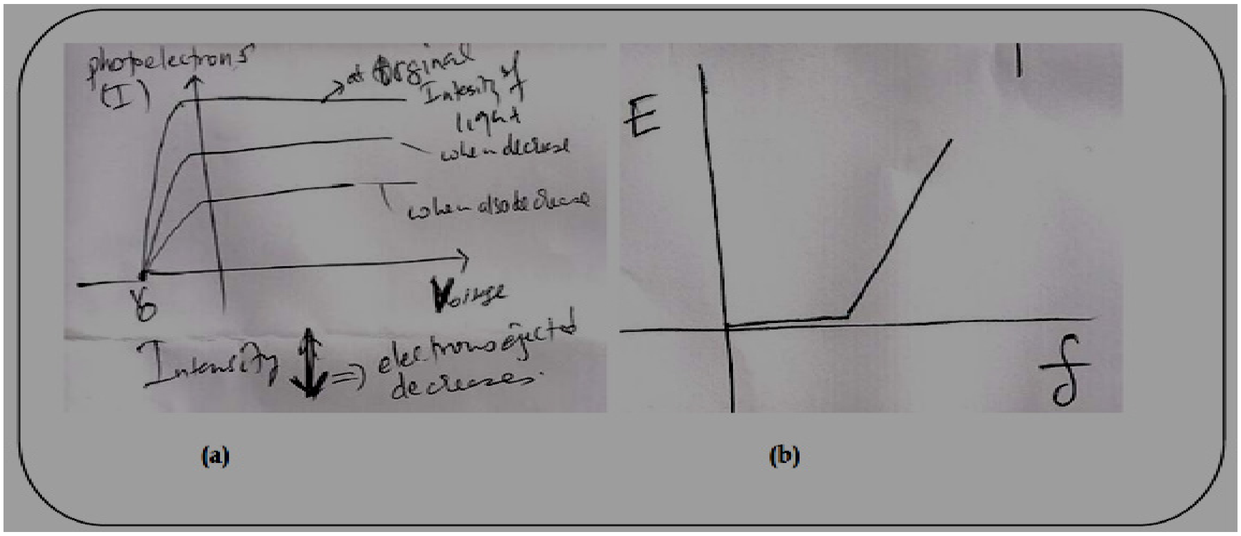
As shown in Figure 4.4 (b), S_{11} correctly indicated the effect of varying the incident intensity on the number of photoelectrons. That is, when the intensity of radiation is decreased at constant frequency saturation photoelectrons is also decreased, but he then related the intensity of the incident radiation with the maximum kinetic energy of the emitted photoelectrons. In explaining how the intensity of the incident radiation associated with the maximum kinetic energy, S_{11} gave the following explanation

> S_{11}: […] when we decrease the intensity, the electrons also decreased. Intensity is directly proportional to electrons. Energy is directly proportional to frequency because of the Einstein equation. In my I-V graph, lower intensity means lower voltage also works.

Therefore, any attempt to explain the photoelectric effect only within the framework of quantum mechanics is an impossible task for the students in this category. Thus the intermixing of descriptions clearly demonstrates that in the one hand students held strong classical and naïve perceptions about light quanta manifested in the photoelectric and Compton scattering experiments. On the other hand their descriptions are based on memorizing the correct quantum mechanical predications and results.

4.3.3 Category III: Quasi-Quantum Model Description

In this category, students held a similar viewpoint to the investigated concepts shared by experts. It is particularly depicted that radiation is not only absorbed and emitted in quanta but that it also propagates as such. In students responses, it is observed that a light beam is discerned to be a stream of particles, light quanta or photons, each of energy $E_{photon} = h\nu$. Unlike the previous categories of description, the presence of radiation of longer wavelength, called modified radiation, in the Compton scattered radiation is discerned. Responses positioned in this category reflected that when a beam of X-rays of frequency ν passes through a medium containing free electrons, X-rays of lower frequencies, $\nu' < \nu$ and higher wavelengths$\lambda' > \lambda$, are detected in the emergent beam and as a result a color change in the scattered radiation will be evident. However, their reasoning did not fully rest on treating the X-rays as collections of photons each with a discrete energy. Although this is the only category that includes the correct understanding of the quantum phenomena, students quoted, without conceptual details, several examples from textbooks and classroom discussions to reinforce their reasoning and explanations. Particularly, when logical reasoning is needed, the students went back to search for a textbook and classroom interpretation of the effect of varying intensity and frequency of the incident radiation on the number of photoelectrons and the maximum kinetic energy of the photoelectrons. For example, a student (e.g., S_{15}) positioned in this category gave a correct sketch of the effect of varying the intensity of the incident radiation in I-V graph and the effect of frequency of incident radiation on the maximum kinetic energy of the photoelectrons (See Figure 4.5 (a) and (b)).



(a) (b)

Figure 4.5: Photoelectric experiment graphs drawn by S_{15} (a) a qualitatively appropriate I-V (current versus voltage) graph and (b) the kinetic energy versus frequency graph

Although the graphs drawn by the student revealed how he correctly represented the photoelectric effect, his reasoning depicted that the understanding of the critical features of the photoelectric experiment is slightly flawed. The following responses illustrate that S_{15} had not completely settled the question of his preferred explanation:

> What do you think that in you figure 4.5 (a) all the three lines are starting from a single stopping potential point?
>
> S_{15}: the I-V graph shows when intensity decreases the electrons ejected decreases. As we discussed the three lines starts at one stopping potential. The I-V graph is presented always like this.
>
> I: In you I-V graph of figure 4.5 (a) for the photoelectric experiment, what changes do you expect if the frequency of the incident light increased or decreased?
>
> S_{15}: In the photoelectric experiment, the number of electrons is ejected directly proportional to intensity, the energy of the electron is proportional to frequency. So the graph not changed.
>
> I: What is the kinetic energy of the electron?
>
> S_{15}: according to the equation it is $KE_{electron}=hf-W$.
>
> I: How do you explain figure 4.5 (b)?
>
> S_{15}: Frequency increasing is proportional to energy increasing.

> I: What happen to figure 4.5 (b) if you change the metal?
>
> S_{15}: I don't understand better […] I think as I told you energy is preoperational to frequency so the same thing I expect.
>
> I: What will happen to figure 4.5 (b) if the work function is increased or decreased?
>
> S_{15}: I think it is the same.
>
> I: What inferences or conclusions can you make about the nature of light?
>
> S_{15}: light radiation is a dual nature of both the wave and particle.

From the above dialogue, the student often memorized the basic points but failed sometimes to understand the terms correctly and to apply it in new contexts. The responses of other students in this category also indicated that they recognized the effect of varying intensity and frequency of incident radiation but often confused how to describe the photoelectric effect that leads to the photon model of light. When asked to sketch the effect of varying intensity and frequency of incident radiation, S_{18} for example gave the correct sketch as seen in Figure 4.6 (a) and (b).

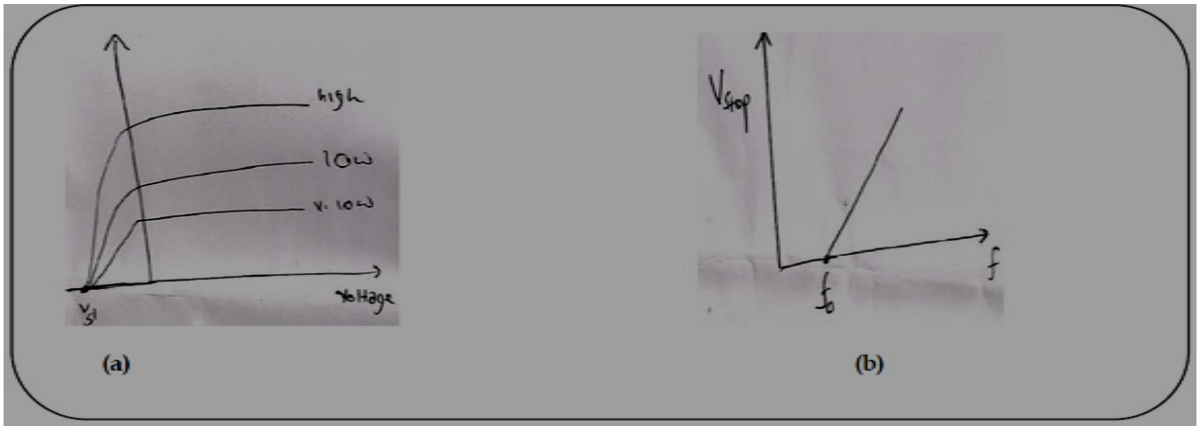


Figure 4.6: S_{18}'s graphs of the photoelectric experiment

For example, when asked to give physical explanations, S_{18} claimed:

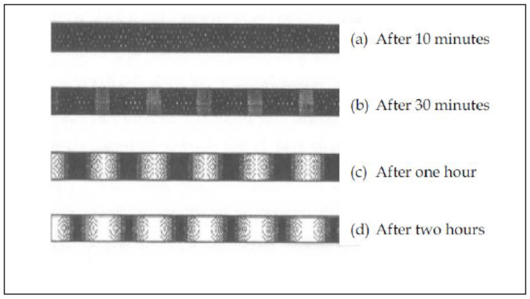
> S_{18}: […] in our modern physics and quantum I we discuss the photoelectric figure. As I understand current is proportional to intensity, kinetic energy is proportional to frequency. Current is not related with frequency […] energy is not related with intensity because of the Planck's hypothesis E = hν and in Einstein's equation KE = hν- w.

More in-depth questions about student thinking were further probed concerning the experimental results of the photoelectric effect and Compton scattering experiments. This student could not come up with anything more than simply restating an observation of the photoelectric experiment as a reason for an inference. Student responses in this category didn't reflect a deep sequence of reasoning that could lead to a qualitative understanding of why description based on classical models is inconsistent with the experimental observations and why a photon model is consistent.

4.4 PHYSICS STUDENTS' DEPICTIONS OF LIGHT QUANTA INTERFERENCE

Like other basic quantum mechanics experiments such as the photoelectric effect and Compton scattering, the double-slit experiment is pedagogically more direct and compelling to study students' depictions of the concept of light quanta. The concept of light quanta to explain, among other observations, light quanta interference in the double-slit experiment is a basic ingredient in many quantum mechanics courses and in any case evidence for light quanta has been used to introduce undergraduate students to quantum physics. At this stage, in order to construct a picture of students' depictions of the concept of light quanta to explain the light quanta interference in the double-slit experiment, the gradual formation of an interference pattern in the cases of low-intensity light beam was used as a basis for the semi-structured interview questions. A similar kind of interview questions has been used in previous studies and found advantages since it covers a variety of ontologically and epistemologically different viewpoints (e.g., Wuttiprom, 2008; Mannila et al., 2002). Thus, in the same way, physics students were shown a series of figures presenting the gradual formation of an interference pattern, and they were asked to give responses in words, written explanations, pictures and graphs (see Figure 4.7 and Appendix I for the full set of questions).

The patterns that appear in photographs of a-d are the typical interference pattern that appear after different periods of time, from a few minutes (the top pattern) to a few hours (the bottom one) obtained in double slit experiment when monochromatic light is projected through two adjacent narrow slits. Based on this figure answer the questions raised below. Explain your reasoning in each case. If you feel you would like to draw anything to briefly explain every-any of your answers feel free to do so.



1. Explain briefly what is discovered in figure (*a*), and how the occurrence of white 'dots' in it can be explained. What can you say about the behavior of light on the basis of this situation?
2. Explain briefly what is discovered in figure (*d*), and how the occurrence of white 'stripes' in it can be explained. What is the process or course of events that causes the phenomenon?
3. What can you say about the light on the basis of this situation?
4. Why the shape and form of a typical interference pattern began to emerge in the distribution of the dots after longer periods of time? (see Appendix I for more questions)

Figure 4.7: The interference patterns of the double-slit experiment that appears in the photographic images after different periods of time

By analyzing the data obtained from the interviews responses it was able to identify three distinct categories of description, i.e. general structures behind the depictions used in explaining the formation of a light quanta interference pattern. These categories are (a) Classical wavy and intuitive model description, (b) mixed model description and (c) Incipient quantum model description (see Table 4.4). In the construction of these categories, only the explanations of students related to the concepts of light quanta to explain the light quanta interference in the double-slit experiment were taken into consideration.

Table 4.4: Categories of description representing aspect of students' depictions of light quanta

Categories of Description	**Key Facets of Students' Depictions**
Category I Classical Wavy and Intuitive Model Description	Expecting light falling on photographic film (screen) to expose it uniformly along its entire wave front Understanding weak intensity radiation implied no constructive interference of light waves or weak interference of waves from two slits. Understanding the role of the two slits in the production of the interference pattern for getting coherent sources of secondary light waves. Conception of interference phenomenon as an outcome of collective behavior of several photons Assuming that photons following certain trajectories in the double-slit experiment
Category II Mixed Model Description	Quantum mechanical aspects and aspects based on classical ideas coexist at the same time. The photon is discerned as the smallest possible packet (quantum) of light; but it has both mass and definite energy. Light quanta, photons are seen as objects simultaneously having properties of classical particles and waves A classical wave model is used for the light, interference and/or diffraction is discussed in the explanation Depicting that a photon is detected as particles and can be predicted with certainty where a give photon will be found in a given region on the screen. Particle nature of light is basically material particles, with some properties, in particular mass, and describes definite trajectories. Interpreting the duality light photons as particles moving along sinusoidal trajectories
Category III Incipient Quantum Model Description	Understanding that at a very low intensity light radiation, the dots indicating that the light is one photon (as one particle) at a time. Describing wave-particle duality is an essential property of photons. Depicting light as a collection of particles-photons having the particle properties of discrete energy and momentum related to the wave properties of frequency and wavelength via $E=h\nu$ and $p=h/\lambda$ Explicating that through which slit the photon passed cannot be determined. a light beam is discerned to be a stream of particles, *light quanta* or *photons* Photons are used as terms referring to broad class of properties observed in the double-slit experiment Assuming the probabilistic nature of single event

4.4.1 Category I: Classical Wavy and Intuitive Model Description

For this category the nature of light are basically classical wavy ones. As explored in the interviews, it is quite natural for the students in this category to use classical wavy and intuitive ideas in describing the quantum aspects of radiation. Students thought of light as a wave, and then when it falls on photographic film (screen) they often likened it to an ocean wave hitting the beach. By such classical water wave analogy, they expected light falling on film to expose it uniformly along its entire wave front. In opening interview for this concept, for example, students were asked what would they say are the simplest 'wave -like' and 'particle -like' properties that light radiation could show. Consider the following excerpts this category:

> **S$_{1}$**: Waves are [...] it can be reflected from boundary. Wave is […] a disturbance transmitted from one place to other place. It is also a diffraction phenomena if we add two waves it also interference phenomena occur etc.
>
> **S$_{8}$**: Wave is a disturbance. But particle […] I think a particle is an object like ball, stone and the like.
>
> **S$_{12}$**: Like water wave it is…I mean light wave disturbs […] light wave is not mechanical wave. It has crest and trough. It is an example of longitudinal […] umm no it is transverse wave. When I mean particle-like […] particle property means it has mass and position. So light has wave and particle property it is called dual nature.
>
> **S$_{20}$**: Light is both a wave and a particle. I think a wave like property of light means it is a disturbance, it has frequency and wavelength, it also interferes if we add to waves. The particle like behavior is […] I think a particle is like an object which has mass, velocity, position and the like.

As can be seen in the forgoing excerpts, students depicted the particle-like properties of light as localized position, compact, hard, and massive objects that carry energy and momentum. The wave-like properties of light is also characterized by classical wave properties as a simple disturbance, like water wave moving in an extended medium and as a diffusing of object in space and time which has wavelengths and frequencies. A similar classical and intuitive reasoning often incorrect explanation is seen in students' responses to account for the gradual formation of a light quantum interference pattern in the double slit experiment:

> **S$_{8}$**: I think in Young's experiment, we know waves from slit 1 combine with 2 so interference and diffraction appear. But for me I think in figure 4.7(a) light waves from 1 and 2 mostly distract to each other when the two waves hitting the screen. So the dots created may be weak interference of waves from slit 1 and 2 when the two waves hit the screen. About the nature of light as I said light is a dual nature of wave and particle. But in figure (d) that bright bands appear when waves from slit 1 and 2 interfere constructively and dark bands when waves interfere destructively. In the figure (d) case I think when time increase light

> waves from slit 1 combine with 2 increases. Since wave is a dual nature the interference and diffraction phenomena show the wave and particle nature of light.

> **S$_{12}$**: Umm[…] I am not clear about figure 4.7 (a) and (b).I think it is a wave and so […] this wave is passing across the slits and finally interacting with the screen. But figure 4.7 (c) and (d) shows interference and diffraction phenomena. According to the experiment light show interference and diffraction. Since it is a wave interference and diffraction occur in all cases. […] The bright fringes indicate high intensity light but not the dark once. We discussed light has a dual nature.

> **S$_{20}$**: In quantum physics light is photons of energy hν and so light is energy and figure 4.7 (a), (b) and (c)show light energy on the screen which is passing through slit 1 and 2. Umm […] about figure 4.7 (d), as I understand the interference pattern is the addition of waves from slit 1 and 2. When added constructively the pattern becomes bright and when add destructively it forms black pattern. When it is single slit [….] As I remembered the interference also appear in the screen on the screen because light behave like a wave in this case. But when light is passing from the source to the screen, I think […] it is particle-like. So to my understanding light is behaving both wave-like and particle-like.

The students expected that a quantum entity (light radiation in the double-slit experiment) sometimes behaves like a (classical) wave and at other times like a (classical) particle. Moreover, excerpts visualized that students in this category were not able to differentiate between classical wave conceptions and common intuitions (naïve ideas) and were not sure when it is appropriate to apply them for depicting physical phenomena. For example, they mentioned that the interference and diffraction patterns appearing in this experiment is evidence of light acting as a wave and particle. In general, students in this category characterized the wave- and particle-like properties light as a classical particle or a classical wave as if they were mutually exclusive. Such an understanding of the concept of light quanta to explain the light quanta interference in the double-slit experiment was also found in the other categories of description. Nevertheless, the extent to which it was used decreased going down the hierarchical structure of categories from classical to incipient quantum categories of description.

4.4.2 Category II: Mixed Model Description

In this category, students' depictions are characterized as a mixture of the quantum description with the dominant classical pictures of description, resulting in confused mental images. Most students' descriptions in this category, reflecting that light have a dual nature, were not able to give answers that explicitly addressed the nature of this dualism. In characterizing the simplest 'wave -like' and 'particle -like' properties that light radiation could show, students described the observation of the phenomena of interference and diffraction as wave-like properties of radiation; and regarding light radiation as a stream of photons possessing energy and linear momentum with mv (mass x velocity) as particle-like properties of light radiation.

> S_{10}: […] light radiation is both wave and particle. Wave means a disturbance. It has frequency and wavelength. Waves show interference and diffraction in experiment... Particle means Umm [...] umm […] I mean it has energy, mass, position, also momentum, […] Yeah, […] which means light composed of particles and this particle is photons. The photon is very small particle,[…] Can I say a small spherical object? […] I think so. This photon has energy $h\nu$ (h is Planck's constant) and also the other particle nature. But it is also a wave at the same time.
>
> S_{24}: […] light is quantized as Einstein proved. So light is quantized means it has photons and photons are particles. I think this is particle nature. Wave nature of light means it has wave properties like interference, diffraction etc.

Apparently, the particle-like property of light radiations are described in terms of a stream of photons, but photons are depicted as particles whose behavior is very similar from what classical physics would have led us to expect. For example, when the students were asked what made them to say photons are particles, S_{24} vacillated:

> S_{24}: Like all other particles. For example like small balls. But it is very small, [...] light is stream of photon, […] so that is particle nature. I think it is like electrons but smaller mass. By the way electrons are also wave and particle nature. Umm […] I am not sure about charge of a photon. Is it like electrons? Is that […]?

S_{24} generalized that photons can be thought of in the same way as electrons, with a well-defined position and size (presumably small compared with electrons or small balls). His responses provided a further important indication that students depicted photons as having juxtaposed wave and particle properties. For answering interview questions that used the gradual formation of an interference pattern, students thought that light is made of photons but describing those bright bands (intensity maxima) and dark bands (intensity minima) appeared in the interference pattern (see Figure 4.7) as a positive and negative resultant of waves at each point on the screen coming from the two slits. Students consistently stated that light is a stream of particles, light quanta or photons. However, to briefly explain what is discovered in Figure 4.7 (a), these students characterized light as a wave, and then when it falls on photographic film (screen) they often anticipated it to form a spherical wave, in congruence to what we might expect from classical physics. Typical responses drawn from S_{10} and S_{24} are:

> S_{10}: […] as I said light has dual nature the particle nature I think the stream photons and the wave nature. Umm [...] Ok. Light intensity is weak means less energy so I don't say about Figure 4.7 (a). But Figure 4.7 (d) is light interference. I mean light from the source pass through slit 1 and slit 2 so […] when it is added constructively it form maxima intensity. When added negatively the dark once formed. I mean destructed wave.

> S_{24}: I understand that light has duality nature. Stream of photons as a particle nature and […] interference as a wave nature. As I understanding the light intensity is weak in the first case. This means in figure (a) the light is spreading out from slit 1 and 2 and collide to the screen but the energy is weak interference don't occur. In figure (d) [...] it is clear that light waves are constructively interfering and destructively interfere. Therefore light and black fringe occur.

It can be seen in the forgoing excerpts, students depicted the interference pattern emerged in the later images in the double-slit experiment in terms of the constructive and destructive combination of light (or stream photons). Thus, there was a subsumption of the classical interpretation of the interference of light into students' cognitive structure though the concept of duality is linked to their perception. In order to illustrate once again this conceptual picture about the concept of light quanta, consider the following excerpts from students' responses to the same double-slit experiment problems involving very weak light:

> **S_{13}**: In the previous I told that light are composed photons. […] photon through slit 1 reach on the screen or photon follows slit 2 and reaches the screen form dots. The dots in figure 4.7 (a) implies […] I guess it is that photons from slit 1 and slit 2 because photons are particles. But Figure 4.7 (d) shows […] the bright and dark brands Umm […] it clear that the result of

> constructive and destructive interference of light waves from slit 1 and 2. That bright related with constructive. Dark related with destructive.

> **S₂₈**: In my opinion dots are particle nature of light. […] photons from the source pass in slit 1 or in slit 2 like particle. So they form dots at the screen like but I do not know the reason. The interference phenomena in figure 4.7 (d) is the constructive interference of light was coming from slit 1and slit 2 which is bright. Again the dark is destructive interference of the light waves from slit 1 and slit 2.

Students associated the occurrence of white 'dots' in Figure 4.7 (a) to the incidence of a single photon click at specific detector position only. However, both interpreted the occurrence of bright and dark bands in Figure 4.7 (d) as the outcome of the constructive or destructive combination of waves from the two slits. The particle characteristic of the light would be depicted by the students as a new property additional to the wave view characteristic that light is forming an interference on the screen resulted from the superposition of waves. It is illustrative that this conceptual picture as outlined by the students (e.g., S_{13} and S_{28}) is consistent with the idea that light quanta is simultaneously both wave and localized particles following trajectories. According the students' predictions, the position of each dot in Figure 4.7(a) is objectively real and predetermined based on unknowable initial conditions. Aspects of students' conceptual understanding about light quanta can be generalized by: first, a remarkable confusion created by the intermixture of intuitive, classical wavy and quantum models/theories, and, second, the indisputable domination of classical reasoning imposed by classical ontology.

4.4.3 Category III: Incipient Quantum Model Description

In this category, the central idea of students' responses seemed to be that the microscopic objects has not the same nature as the macroscopic world. However, their description took things even further by suggesting that this wave-particle duality is not restricted to light quanta, photons, but must be universal: all material particles should also display dual wave-particle behavior. Students' responses on these interviews showed that they conceived light as having a wave-and particle-like nature; depicting that light is either waves or particles depending on which experiments were presented. In describing the simplest 'wave -like' and 'particle -like' properties that light radiation could show and in explaining briefly what are discovered in the series of figure from Figure 4.7(a) to 4.7(d), S_{15} gave the following explanations:

> S_{15}: Quantum mechanically light and matter show wave-particle nature. […] but wave-particle is true in electrons and photons. […] light is quantized. It is multiples of photons and this photon show particle-like nature e.g., with no mass photon has momentum, energy and position [...] photon energy $E=h\nu$ or hc/λ and photon momentum, $p=h/\lambda$ or $p = h\nu/c$ […] as I remember the position and momentum of photon and electron isn't simultaneously measured because it is the problem of the uncertainty principle. Because of uncertainty, the wave and particle nature of photon is not predetermined […] it is known after that.

> S_{15}: […] Figure 4.7 (a) the dots indicate each photons representing particle nature of light. After some time in Figure 4.7(d) light is wave. After randomly photons distributed by inference with itself produce figure (d) […] Photons pass like particles or electrons through slits and also like waves. Bright fringe is I think more photons more probability density to get photon. Dark fringe means in quantum case small photons strike it […] less probability point. That is the idea of duality.

In this category, the depiction of interference is understood to be a result of the repeated occurrence of hits or connected to multi-photon light beams in the double-slit experiment. Descriptions were starting to incorporate some of the basic concepts to explain the quantum interference phenomenon of light, for instance, by introducing physically meaningful conception of photon, probability density, indeterminacy and superposition principles. It is also seen that students depicted the uncertainty principle as an important consequence of the wave-particle duality of light radiation and matter and was inherent to the quantum description of nature. Even if it is possible to find evidence of correct models to understand light quanta, it looked obvious that to most of them the concepts were fragmentary or mere mathematical expressions. It is also seen that students' depictions were simply memorization of the textbook definitions, repeating some phrase they have heard in class or read in the textbooks, or it might also be that students with this descriptions do not have the scientific language skills necessary to depict their ideas. It is also found that quanta are something that is poorly conceptualized. However, compared to the previous two categories, this is the only category that reflects most of the quantum mechanical aspect of light quanta.

4.5 DESCUSSION OF THE DESCRIPTION CATEGORIES

The developmental phenomenographic research approach guided the analysis of the data in this section. Consistent with findings of previous studies (e.g., Mannila et al., 2002; Domert et al., 2005) that have used this approach, this study has generated a limited set of descriptive categories in accounting for physics students' depictions of each quantum phenomenon (concept) associated with light quanta. The outcome space for each quantum concept (Concept 1, 2 and 3) was comprised of three qualitatively different ways of depictions (see Figure 4.1). In general, the three descriptive categories were roughly widened from strongly classical intuitive thinking to quantum-like descriptions. These categories with their key aspects of depictions, that is, for Concept 1, 2 and 3 are summarized in Tables 4.2, 4.3 and 4.4 respectively. A paradigmatic description of the categories with excerpts from both the interviews and the written explanations was presented to illustrate the findings under each concept. For each concept the first two descriptive categories (e.g., Energy in BBR as a factor of "square of frequency" and Hybrid descriptions in Concept 1; Classical Intuitive and Mixed Model Descriptions in Concept 2 and; Classical Wavy and Intuitive Model and Mixed Model Descriptions in Concept 3) correspond to inadequate and intermixed descriptions based on naïve and classical understandings. These insufficient and intermixed descriptions based on naïve and/or classical depictions uncover some of the most basic alternative conceptions of physics students regarding the quantum rule of energy quantization, the concept of photon and the light quanta interference. Firstly students did not take quanta into account in their explanations of microscopic phenomena but assume both energy and light to be continuous. They were not aware of the fact that there are quanta of energy and that a radiating body could give off one quantum of energy or two quanta of energy, but never one and a half quanta of energy or anything but an integral number of such entities. As a result, these students failed to go on to suppose that the energy content of such a quantum of energy must vary directly with the frequency of the light in which it was radiated. Secondly, students extended classical and macroscopic explanations to a microscopic level for depicting quantum phenomena associated with light. These descriptive categories visualized examples of explanations of the light quanta interference which consisted of students attributing classical wave properties to the photon model of light. Illustrating this point are two examples: Some of the students' ideas were that in a double-slit experiment with very weak light beam, the interference pattern that emerged in the later images can be seen as outcome of an interaction between the photons. This explanation is parallel to classical (i.e., Maxwellian) theory of waves: in Young's experiment the interference pattern results from the constructive or destructive combination of waves or the superposition of these secondary waves on the screen. Another aspect of physics students' depictions of the concept of light quanta was: light consists of a stream of particles called photons which are classically localized particles with mass, energy and momentum. In their descriptions, these photons or particles of light can be thought of in the same way as bullets, with a well-defined position, momentum, and then trajectory and size (presumably small compared with the bullet). Students, in general, exhibited confusion between pairs of concepts and quantum phenomena such as wave- and particle-like properties, continuous and discrete enteritis, deterministic trajectories and probabilistic predictions, and classical fringe pattern and quantum interference. Thus, many of the students in these description categories are still struggling with the notion of abandoning classical conceptions. The remaining others held some type of mixed view on the interpretation of the quantization and the photon model of light, or saw little distinction between the classical and quantum mechanical worldviews. While for two or three students (i.e., in Category III) we could see evidences of formation of quasi-quantum models to depict quantum phenomena and concepts associated with light, detailed explanations and predictions that result from them were not adequate from an accepted understanding of quanta. It seems evident that when logical reasoning is needed, most of them will go back to search for both a quantum and classical interpretation of the photon model of light. These findings are in line with the previous studies (e.g., Ireson, 2002; Singh et al., 2006; Baily & Finkelstein, 2010) regarding student conceptions with quantum phenomena, suggesting that most physics undergraduates do not, even after two semesters of undergraduate quantum mechanics courses, have an understanding of quanta which approximates to the accepted interpretation. Further discussions are given in Section 4.7. In the next section (i.e., Section 4.6) the consistencies and/or conceptual shifts of the students' depictions as the contexts of explaining changes are considered.

4.6 PHYSICS STUDENTS' WAYS OF DEPICTIONS OF QUANTA AS THE CONTEXT OF EXPLAINING CHANGES

The study presented in this chapter aimed among other things, to identify the description categories which form the basis of physics students' depicting of quanta. It is now completed by combining the results of energy quantization, the concept of photon and the quantum interference in the double slit experiment. The essential explanations students used to depict these quantum phenomena were discerned and discussed in previous sections. Attention must now be brought back to the other research sub-questions of the thesis: do students use a consistent depiction of quantum concepts when presented with different physical situations? and do students with inappropriate depictions of one concept (quantum phenomena) also give inappropriate depictions of other concept in quantum mechanics?

The nexus between students' models of description that can be applied for depicting a particular quantum idea with other quantum phenomena have not be been investigated extensively. Therefore, investigating how students' reasoning transit between categories as the context of explaining changes is a key to understanding the coherence of students inappropriate and/ or appropriate depictions that appear in describing quantum concepts. For this purpose, the data analysis for these questions was slightly deviated from the phenomenographic approach. The result of a phenomenographic perspective is the outcome space which represents a set of descriptive categories (i.e., constituted in relation to the collective pool of conceptions) and the relation between them. However, according to Ingerman (2002) and Adawi (2002) what happens after the arrival of the outcome space depends on the formulation of the research question and further analysis can be carried out at an individual, collective or researcher level as they applied in their study. In phenomenographic studies, the researcher can turn the outcome space back on the transcripts of the interviews and use it to illuminate the individual (Ingerman, 2002; Adawi, 2002). Other researchers suggested that since phenomenographic perspective aims on different ways experiencing a phenomenon and the relations between them, it provides an important framework for studying changes between ways of understanding (Johansson, Marton and Svensson, 1985). According to McKenzie (2003), this framework can also be used for analyzing individual students' ways of experiencing a phenomenon and how these changes over time and contexts. As it has been argued in Chapter 3, the aim of the research was both to understand the variation in the ways that student depict key aspects of quantum mechanics and to inform teaching development practices, intentionally data analysis in this section was slightly departed from the pure phenomenographic approach. Thus, individual student patterns of depictions in each and across quantum contexts were related to the categories of description at a collective level with the aim of identifying whether their ways of depicting quantum phenomenon had changed over contexts. Below in section 4.6.1, frequencies of student's responses falling into the different categories of description of the concept of quantization and the photon concept are obtained and compared.

4.6.1 Students ways of Depictions of Quanta as the Context Changes from BBR to Photoelectric Effect

Student depictions of the quantum rules of energy quantization and the photon concept were monitored through the descriptions they have given for the interview questions. The context of explaining was different in concept 1 and concept 2. The qualitative problems involved in the former were about interpretation of BBR, whereas the qualitative problems in the latter were about photoelectric and Compton scattering experiments. The qualitatively different ways in which the students had depicted illustrate much of their conceptual understanding progress across contexts. To investigate how students' depictions transit between categories as the context of explaining changes, each of the student responses was allocated to one of the three main categories in each quantum concept. Here, as it has been discussed by Marton and Booth (1997), this does not imply that all students themselves completely fall into one of these three categories but rather only that almost all of their responses have a maximum (95% and above) tendency toward one of the three categories in this particular quantum concept. In this sense each student belongs to one main category in energy quantization (i.e., in BBR) and potentially to the same and/or another description category in the photon concept. The comparison of analysis was demonstrated first in Table 4.5, where students' depictions of the phenomena of quantization and the photon concept as a function of the quantum contexts was presented; and second, in Table 4.6, where cross-correlation of depictions by 35 physics students (identified by numbers ***S_1-S_{35}*** i.e., numbers from ***S_1- S_{17}*** represent students from BDU and ***S_{18}-S_{35}*** from WU) was displayed.

Table 4.5: Description perspectives as a function of quantum contexts

	QUANTUM CONTEXTS	
Categories of Description	Context I: Blackbody Radiation	Context II: Photoelectric and Compton Scattering Experiments
Category I	S_1, S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{11}, S_{12}, S_{13}, S_{14}, S_{17}, S_{19}, S_{20}, S_{21}, S_{22}, S_{23}, S_{25}, S_{26}, S_{29}, S_{30}, S_{32}, S_{33}, S_{34}, S_{35}	S_1, S_3, S_4, S_5, S_6, S_8, S_9, S_{12}, S_{14}, S_{17}, S_{19}, S_{20}, S_{21}, S_{22}, S_{23}, S_{25}, S_{26}, S_{29}, S_{30}, S_{32}, S_{33}, S_{35}
Category II	S_2, S_{10}, S_{16}, S_{18}, S_{24}, S_{27}, S_{28}, S_{31}	S_7, S_{10}, S_{11}, S_{13}, S_{16}, S_{24}, S_{27}, S_{28}, S_{31}, S_{34}
Category III	S_{15}	S_2, S_{15}, S_{18}

Table 4.5 showed the distribution of the students' responses in each category for the quantum contexts: BBR and the photoelectric and Compton scattering experiments. In the

context of the BBR, it was noticed that 97.1% of the participant students'responses were derived by utilizing meanings associated with Category I and Category II. This would suggest that these students were not recognizing the concept of quantization as a new concept but instead they take their prior conceptions and simply apply them to explain the features in BBR curve.provided explanations by referring to the text book answer. Only one student's responses gave explanations that close to Category III (Table 4.5). Under the basic aspects of the photoelectric and Compton effects, the first two categories (Category I and Category II) accounted for 91.4% of the participant students' responses. These students did not understand how the concept photon is used to describe quantum phenomena associated with light. The analysis revealed that only 8.6% of the participant students have adopted Category III. The analysis revealed that the majority of students are indeed having great difficulty in both topics. Their responses were strongly influenced by the perspective of classical physics in making explanations related to the quantization of energy and the nature of the photon and the concept of duality.

The sorting of students' depictions to different descriptive categories and the shifts in their usage was also presented in Table 4.6 in order to visualize consistency (i.e., appropriate and/or inappropriate) and the progress of the categories in the case of each student. Consistent and stable use of descriptive categories (potentially based on the conception of classical waves and/or variants of classical ways of visualization) in both quantum contexts was taken as a sign of unsuccessful qualitative understanding, whereas unstable and inconsistent use of categories is taken as a sign of shallow (intermixed) understanding of quantum phenomena. Use of correct categories (based on quasi-quantum worldview) is taken as simply a sign of incipient understanding of quantum phenomena. In general, most students expressed understandings of the two concepts in corresponding categories. If a student for example expressed an understanding of quantization corresponding to the first category, he or she also expressed an understanding of the concept of photon corresponding to the first category (see Table 4.6). For example, out of the 26 students who were in Category I of the BBR context about 22 were still placed into Category I of the photoelectric and Compton scattering experiments.

Table 4.6: The cross-correlations of descriptive categories in the context of the blackbody radiation and the photoelectric effect

		Context II: Photoelectric and Compton Scattering Experiments			
	Descriptive Categories ⇒ ⇓	Classical Wavy and Intuitive Model Description	Mixed-Model Description	Quasi-Quantum Model Description	Total
Context I: Blackbody Radiation	Energy in BBR as a factor of “square of frequency”	22(62.9%) S_1, S_3, S_4 , S_5, S_6 , S_8 , S_9, S_{12} , S_{14} , S_{17}, S_{19}, S_{20}, S_{21} , S_{22}, S_{23} , S_{25} , S_{26} , S_{29} , S_{30}, S_{32}, S_{33}, S_{35}	4(11.4%) S_7, S_{11} , S_{13}, S_{34},		26 (74.3 %)
	Hybrid description of energy in BBR		6(17.1%) S_{10}, S_{16}, S_{24}, S_{27}, S_{28}, S_{31}	2(5.7%) S_2, S_{18}	22.8 %
	Energy in BBR as “Quanta” of energy size E = hν			2.9 % S_{15}	2.9%
	Total	22(62.9%)	10(28.5%)	3(8.6%)	35(100%)

However, out of 26 such students only 4 students were managed to make the shift from the strongly classical-like descriptive categories (i.e., Category I) of the BBR context into mixed model (i.e., Category II). About 8 students were categorized to Category II in the case of the BBR, and remain in mixed Category II of photoelectric and Compton scattering experiments. Out of 8 such students only 2 were able to transfer from hybrid description to more coherent quasi-quantum perspective. There are no, in general, conditions where students showed an advanced understanding of quantization in explaining the basic features of the BBR curves, and a poor understanding of the photon model of light in the basic aspects of the photoelectric and Compton effects. Table 4.6, shows that a student (e.g.,

S_{15}) in advanced category of the BBR, are also classified into advanced subcategory in the case of the photoelectric and Compton effects.

These transition can be seen that if energy quantization was a relatively trouble-some concept for the majority of the students, the concept of photon in the photoelectric and Compton scattering problems are poorly understood. In the examples of the BBR interview problems, for example students often assumed that an electromagnetic radiation emitted from a blackbody can have any energy value in the continuum from zero to infinity. Emphasizing on this continuous nature of energy, students frequently used the classical theories of electromagnetism and thermodynamics to show that the amount of energy radiated over a particular range of frequencies should vary as the square of the frequency. It seems that such usage of classical ideas can strongly interfere with these students' understanding of quantum phenomena such as photoelectric effect, Compton scattering experiments, etc.

4.6.2 Students ways of Depictions of Light Quanta as the Context Changes from Photoelectric Effect into Double-slit Experiments

In section 4.6.1, by monitoring the descriptive categories students' have given for quantum contexts of the BBR and the photoelectric effect, a physics student's transit between categories were explored. There is a close relationship between the concepts quantization and the photon model of light and Table 4.6 shows similar patterns for the physics students' inappropriate and/or appropriate understanding of these concepts. The description categories which form the basis of students' ideas of light quanta were examined through the depictions students have given for the light quanta interference in double-slit experiment. Likewise, depictions of light quanta interference held by the participant students' have included a three set of categories that captures the variation in the understanding of the quantum model of light. Analyses of data suggest that 60% (21) of the participant students transformed the classical particle and wave properties into the properties of photons without essential changes. 11 students' responses were more or less simple extensions of classical pictures of quantum entities or simple mixtures of classical and quantum pictures. It is only in three students' responses, an incipient quantum pictures were observed.

Table 4.7: The cross-correlations of descriptive categories in the context of the photoelectric and Compton scattering experiments and light quanta interference in the double-slit experiment

		Context III: Light Quanta Interference in the Double-slit Experiment			
	Descriptive Categories ⇒ ⇓	Classical Intuitive Model Description	Mixed-Model Description	Incipient Quantum Model Description	Total
Context II: Photoelectric and Compton Scattering Experiments	Classical Wavy and Intuitive Model Description”	21(60%) S_1, S_3, S_4, S_5, S_6, S_8, S_9, S_{12}, S_{14}, S_{17}, S_{20}, S_{21}, S_{22}, S_{23}, S_{25}, S_{26}, S_{29}, S_{30}, S_{32}, S_{33}, S_{35}	1(2.9%) S_{19},		22(62.9%)
	Mixed-Model Description		10(28.5%) S_7, S_{11}, S_{13}, S_{34}, S_{10}, S_{16}, S_{24}, S_{27}, S_{28}, S_{31}		10(28.5%)
	Quasi-Quantum Model Description			3(8.6%) S_2, S_{15}, S_{18}	3(8.6%)
	Total	21(60%)	11(31.4%)	3(8.6%)	35(100%)

As can be seen in Table 4.7, the majority of students were consistently applying a classical intuitive model of description in their explanations as the contexts moves from the basic aspects of the photoelectric effect to the double-slit interference pattern in the cases of low-intensity light. In the photoelectric effect context, for instance, the most common classical-like responses were that the proposed change in intensity of light beam would provide enough energy for the release of electrons. Students were not able to differentiate between the effect of changing the intensity of the light beam (the photon flux) and the effect of changing the frequency of the light beam (the photon energy). As a result, these students could not be expected to identify the role of the photoelectric and Compton scattering experiments for depicting the photon model for light.

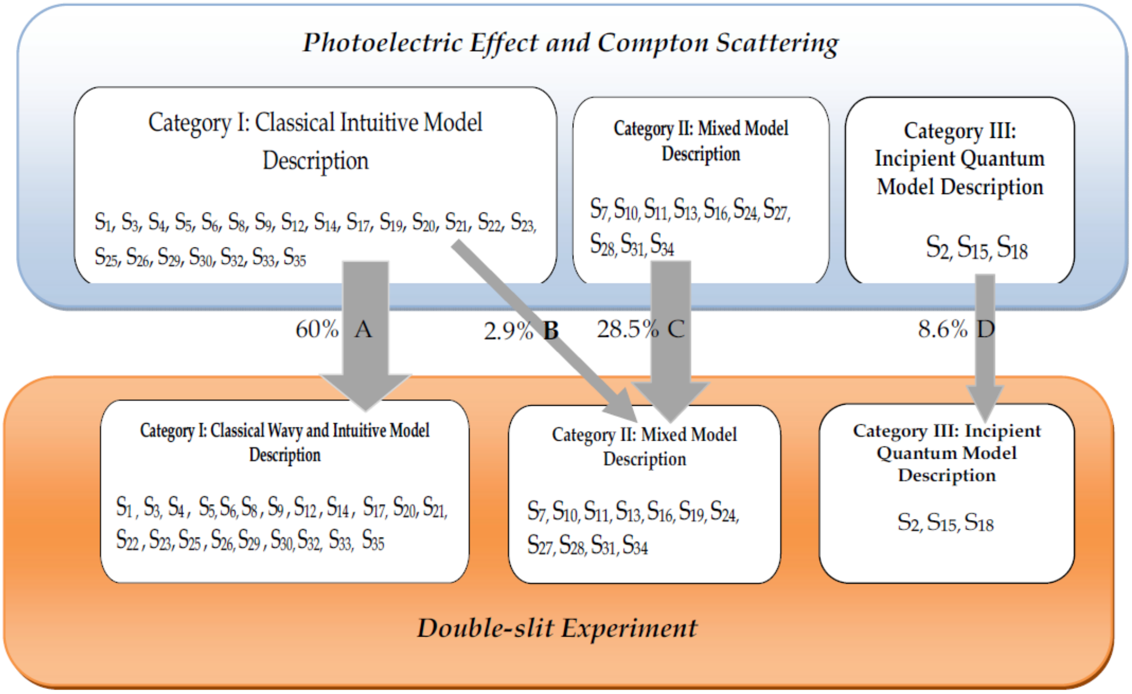


Figure 4.8: The classification of students' descriptions into different categories as the context of the phenomena changes from the photoelectric effect to light quanta interference

In the consecutive light quanta interference questions, 21 (out of the 22) students used a classical intuitive and naïve description to explain about the properties of the observed quantum phenomena, such as, [Weak intensity light beam implied no constructive interference of light waves] and [Photons are particles of light; they can be thought of in the same way as small bullets, with a well-defined position and size (small compared with bullets)]. Such classical and naïve (often incorrect) explanations suggest that these students could spontaneously extend their classical worldviews of the photoelectric experiment to the new context of light quanta (see Figure 4.8). 28.5% of the students, in an effort to explain the basic aspects of the photoelectric effect, such as experimental results, and implications about the nature of light, tended to assimilate the quantum mechanical ideas into categories and modes of thinking that are deeply rooted into classical physics worldview (Table 4.7). In the context of double-slit interference with low-intensity light, these students expressed understanding of light quanta in corresponding categories (see Figure 4.8 and Table 4.7). It was found that mixed-based descriptions of light quanta are dominant in these students' responses.

In general, when looking for the different understanding of the concept light quanta within the context of double-slit interference experiment, a pattern similar to the understanding of the photon model of light expressed in the photoelectric and Compton effects is found. This implies that students participating in the study were consistent in their intuitive and classical-like views about light quanta across the consecutive contexts. In the light of these findings, it seems fact that students' classical-based reasoning of energy quantization and the photon model guided how they understand features of the light quanta. In that sense, it seems also reasonable to infer that the inappropriate and/or appropriate understanding of features of the light quanta interference stems from the inappropriate and/or appropriate understanding of the quantum rule of energy quantization.

4.7 CHAPTER SUMMARY, CONCLUSIONS AND IMPLICATIONS

The phenomenographic analysis of physics students' responses revealed a set of descriptive categories that represents the participants' depictions related to the quantum rules of energy quantization, the photon concept and the light quanta interference in the double-slit experiment. Considering the three quantum contexts together, an interpretation of students' depictions of quanta could be that most undergraduate physics students' conceptual understanding was strongly mediated by the perspective of classical physics and also by naïve and primitive intuitions. Such naïve and quasi-classical thinking is typified by, for example, in the case energy quantization [Radiation emitted from a blackbody can have any energy value in the continuum zero to infinity] and in the case the photon model of light [the intensity of the light would imply larger amplitude of the light waves, which would result in larger energy transfer to electrons when the light hit the atoms of the surface]. Again in the case of light quanta interference [interference phenomenon is an outcome of the constructive and destructive interference of classical waves]. The quantization of energy and the photon model of light were also depicted by some other students from an intricately intertwined quasi-classical and quasi-quantum descriptive model, and were thus considered to represent a qualitatively different depiction which could not be specifically framed by either of the categories. Only few physics students who participated in the study made quantum-like explanations by memorizing simple examples frequently used in classrooms and quantum physics textbooks.

The participant physics students share common difficulties with concepts related to energy quantization and light quanta. In particular, they were unclear about the relation between the energy content of a quantum of radiation with the frequency of that radiation and why the violet catastrophe did not happen and why, in actual, fact, light was radiated chiefly at low frequencies and more slowly at high frequencies. Students also had difficulty in distinguishing between the intensity and frequency of light, and the wave-and particle-like properties photons. These findings extend previous studies (e.g., by Mannila et al., 2002; Müller & Wiesner, 2002; Ayene et al., 2011; Zhu & Singh, 2012), confirming that after a traditional quantum mechanics instruction many undergraduate physics students were unable to relinquish their initial knowledge stated based on classical physics instruction and adopt the quantum mechanical framework in describing atomic and subatomic phenomena. In general, physics students struggled with issues related to the principle of quantization and the photon model of light after a traditional quantum physics courses in their undergraduate program.

The findings presented in section 4.6.1 and 4.6.2 are also able to map how students transit between categories as the context of explaining changes and highlight some particular features of the students' depictions a quantum context and the way they accessed them in the other quantum settings. As presented earlier there was no major difference to be seen in the majority of the participant physics students' depictions of the concepts for three consecutive contexts. For example, most students were consistent in their intuitive and classical-based views about quanta across contexts. Most notably, among the physics students who participated in this study, relations between depictions of energy quantization and the photon model of light was found that:

1. not understanding the Planck's assumption that the energy content of a quantum of radiation is proportional to the frequency of that radiation may prevent students comparing the effect of changing the intensity of the light (the photon flux) and the effect of changing the frequency of the light (the photon energy); this may again prevent students recognizing the significance of the photoelectric experiment for the development of the photon model for light; again this may further prevent seeing photons as non-localized or extended objects obeying the linear superposition principle;
2. holding an intuitive classical physics perspective, for example, [radiation emitted from a blackbody can have any energy value in the continuum zero to infinity], [light waves can exchange any amount of energy interacting with matter] and [the energy emitted should be a monotonically increasing function of frequency, diverging as frequency increases without bound] may lead to a student depicting that the intensity of the light would imply larger amplitude of the light waves, which would result in larger energy transfer to electrons when the light hit the atoms of the surface; or it may lead a student depicting an intense (bright) light radiation would provide enough energy for the release of electrons; In turn this may further lead this student to note that the gradual formation of an interference pattern in the cases of low-intensity light created by superimposing classical (i.e. Maxwellian) waves; or results from the superposition of these secondary waves on the screen.

While it should not be assumed that this small group of undergraduate physics students can be considered to be typical of all students at the university level, nevertheless, the findings can provide useful indication that depictions of quantization and the photon concept may be a key to understanding inappropriate and/or appropriate understandings of the concept of light quanta. It appeared that inappropriate understanding of photons to describe spatially and temporally localized interaction event was found to follow from inappropriate understanding of the quantized energy exchange mechanism which was constructed in the case of blackbody radiation.

CHAPTER 5

PHYSICS STUDENTS' DEPICTIONS OF MATTER WAVES AND THE UNCERTAINTY PRINCIPLE

5.1 INTRODUCTION

This chapter discusses physics students' depictions of matter waves and the uncertainty principle as it pertains to the following research question:

> How do physics students depict the quantum model of matter waves and the uncertainty principle?

As discussed in Chapter 3, thirty-five undergraduate students were interviewed for two interview themes on quantum mechanics. The analysis of the first theme was described in Chapter 4 and aspects of students' depictions of light quanta in quantum mechanics were identified. The phenomenographic perspective on the second theme has incorporated a broad questioning approach to explore students' depictions of matter waves and the uncertainty principle, briefly discussing it in several aspects and contexts. The procedure of data analysis was described in detail in Chapter 3. Interview responses related to matter waves and the uncertainty principle were read and reread to obtain an overall insight into the substance of the students' responses. The information gleaned from the interviews was, then, further sorted and grouped together into two concepts such as matter waves and the uncertainty principle. Responses under each concept were then analyzed using developmental phenomenographic analysis where a picture of students' depictions of matter waves and the uncertainty principle was separately developed.

The analysis of students' responses revealed three set of categories that describes their depictions related to the concepts of matter waves. These categories are (a) classical intuitive and trajectory-based model, (b) an intricate blend of classical and quantum model description and (c) incipient quantum model descriptions. Similarly, it is suggested that students' depictions of the uncertainty principle can be described with three distinct models of description categories, which are (a) uncertainty as a classical ignorance, (b) uncertainty as a measurement disturbance and (d) uncertainty as a quasi-quantum uncertainty principle.

5.2 PHYSICS STUDENTS' DEPICTIONS OF THE QUANTUM MODEL OF MATTER WAVES

As introduced, in this section, the analysis was carried out and a picture of students' conceptual understanding of matter waves was constructed. This was done by analyzing students' responses to the set of interview questions. The interview questions are based on an example of the gradual formation of interference pattern for electron beam passing through a double-slit experiment. The concept of de Broglie wavelength to explain and account for the double-slit electron interference was also part of the interview questions. The full set of questions is given in Appendix I.

During the interview, the students were first asked to explain about the simplest 'particle-like' and 'wave-like' properties that microscopic objects such as electrons and protons could show. This was initiated with questions such as:

> In your quantum mechanics courses we say electrons, protons and photons behave like waves, as well as like particles. What would you say are the simplest 'particle-like' and 'wave-like' properties that one of these things could show?

Following this question, students were shown a schematic representation of the double-slit experiment set-up with monochromatic electron gun which set to fire thousands of electrons per second (see Appendix I). Soon the students were asked to predict what will happen on the screen for any possible change on the experimental setup and also to explain their reasoning and/or sketch the result in each case. This was initiated with questions such as:

> If only the first slit (S1) is blocked off and if the electron gun is fired for hours, what will the pattern look like? Sketch and explain the reason.

If only the second slit (S2) is blocked off and if the electron gun is fired for hours; what will the pattern look like? How does this pattern compare to the previous one?

When both slits are uncovered and if the electron gun is fired for hours; how does this pattern compare to the two single slit patterns? How does this pattern compare to the single slit patterns?

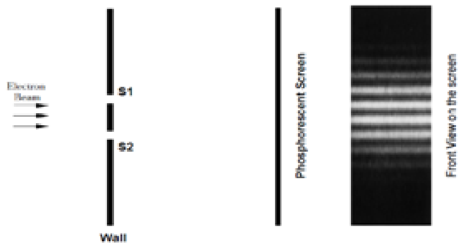
When the intensity is reduced so that there will only be one electron going through the slits at a time, predict where the next electron will hit the screen?

When the intensity of the gun is altered so that only one electron is travelling at a time, what will the pattern look like?

A detector is added to the left slit. This will be able to detect whether the electrons went through the left silt or the right slit. It will not block the electrons. What will the pattern look like? How does this pattern compare to the two single slit patterns?

The students were then asked to predict how a single change to the original set-up in the double-slit experiment with electron interference shown in Figure 5.1 would affect the nature observed phenomena on the screen and to explain their reasoning in each case. Sample interview questions are presented below (i.e., adapted from Vokos et al., 2000 and Ambrose, 1999) in Figure 5.1.

Please have a look at a simulated -A beam of electrons is incident on a wall that contains two narrow slits. The simulated photograph shows the pattern seen on a phosphorescent screen placed at a distance from the slits. The brighter regions indicate the concentrations of electrons hitting the screen.



Assume this experiment was repeated with one change made at a time with the original setup. For any possible change mentioned below predict what will happen on the screen. Explain your reasoning in each case

- The speed of electrons increased
- If the electrons are replaced with elementary particles, with each particle having the same kinetic energy as each of that the original electrons but a higher mass.

Figure 5.1: Typical interview questions on double-slit interference of electrons

Therefore, the interpretations for the categories of description were grounded in students' responses to all these questions. For each category of description, key facets of depictions which appear illustrative of a particular kind of depiction (see Table 5.1) and exemplary excerpts of the interview responses from students were included. Students' depictions were compared and contrasted and, in some cases, possible source(s) for students' depictions were traced.

Table 5.1: Categories of description representing aspect of physics students' depictions of matter waves

Categories of Description	**Key Facets of Students' depictions**
Category I Classical and Trajectory-based Model Description	Ascribing a precise trajectory to a moving electron implies absolute certainty as to its position at any moment Expecting that the quantum world is as objective, mechanistic, solid firm, predictable and certain as it is considered in the classical manner When both slits are open, the resulting curve is the sum of the individual curves The electrons go either through slit 1 or through slit 2, because that is what particles would do We can predict the definite measurement outcome for a specific particle, where it is localized at a certain time, thus we can assign a path to the particle. Position and momentum of a particle evolve in a deterministic manner based upon the interactions
Category II An Intricate Blend of Classical and Quantum Model Description	An electron sometimes behaves like a (classical) wave and at other times like a (classical) particle Corresponding matter waves into vibrations in an underlying physical medium or it is the result of particle vibrations The electron is described as a delocalized probability wave that takes a well-defined path (trajectory) In the context of the double-slit electron interference experiment associating the idea of a superposition state into a simple sum of components Realizing that a quantum corpuscular phenomenon does refer to a classical particle property
Category III Incipient Quantum Model Description	The electrons behave either like particles or like waves, depending on what it is that is being observed Assuming that the exchange of light radiation is done in finite amounts, called quanta Single electron events build up to from an interference pattern in the double-slit experiments When both slits are open, we do not speak about the electron as following a distinct path since we have no such information

Categories of Description	Key Facets of Students’ depictions
	Gaining path information destroys the wave like behavior
	Whenever an electron is detected at any position behind the double-slit it is always the whole electron and not part of it
	The physics of the microscopic world is intrinsically random at a fundamental level
	Larger momentum means a smaller de Broglie wavelength, which corresponds to a smaller distance between bright fringes

5.2.1 Category I: Classical and Trajectory-based Model Description

The main idea implied in this category is that objects (such as, electrons) from the microscopic world are basically material particles, with classical properties, in particular mass, momentum, kinetic energy, definite speed and position. This is evident in the following quotes from the students in the first interview question, when they discussed the contrast between the simplest “wave-like” and “particle-like” properties that electron and other microscopic objects could show:

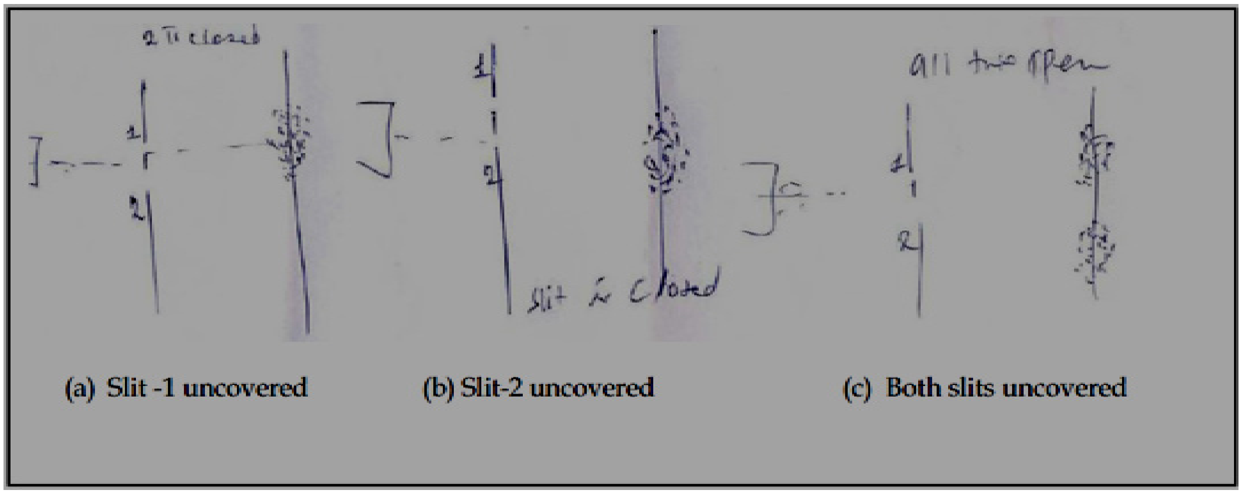
> **S$_3$**: Ideally yes […] in quantum mechanics electrons show wave property. A wave means I think a wave disturbance [...] ideally a disturbance between electrons. […] electrons as a particle-like means […] of course electrons are small particles. So an electron has small mass, high speed, momentum and energy. From Newton’s second law […] it is possible to determine its speed acceleration and position vector. An electron has a small charge. So wave particle duality is a property of small materials.

> **S$_{17}$**: wave-particle is a quantum mechanics idea. Umm […] normally electrons are materials occupying space. But it is smaller in nature with small mass and charge. Like all matter its mass, momentum and energy and position can be determined. So this is its particle nature. […] umm the wave nature is that […] wave is a disturbance. So if electron is a wave it shows disturbance it has wave properties wavelength frequency amplitude and the like.

> **S$_{23}$**: […] particle-like property of electron is a small object but small mass and small charge $e=1x10^{-16}$. Wave nature of electrons means a disturbance of electrons, like any waves in nature waves interfere constructively and destructively. Waves also show diffraction. So electrons always show this particle nature i.e. it has momentum, it has energy, it has specific position it has specific speed. Again electrons show wave disturbance. So electrons show wave-particle nature.

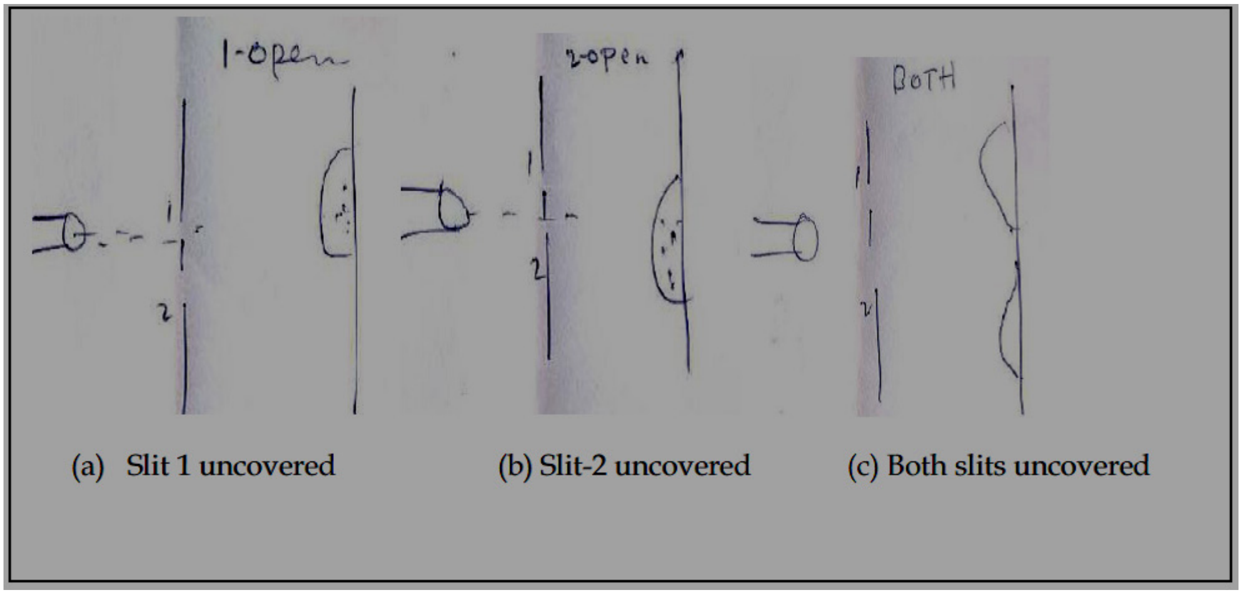
The foregoing responses convey that physics students' descriptions seemed to be that the microscopic world has the same characteristics as the macroscopic world. As a result they constantly applied the classical method for describing the entire physical world. For example, microscopic particles appeared in students' depictions as tiny material objects possessing intrinsic properties, which remain unalterable even when they move or interact with other particles. Electrons and other elementary particles are also considered to possess certain physical quantities (localized, definite position, momentum, kinetic energy and soon confined in space) that can be precisely determined at any moment. Students often mentioned wave-like properties as simple wave disturbance and the concept of duality but they did not understand the scientific meaning behind and hence failed to apply it properly in quantum contexts.

Furthermore, students could not find a single explanation that could relate wave-like properties of microscopic objects to the behavior of electrons in the double-slit experiment. Their prediction of the properties of the observed phenomena visualized that students seem to be locked into the classical conceptions where electrons have definite locations and moves along definite paths. For example, Figure 5.2 and 5.3 visualize that students' thinking of electrons in the double-slit experiments are based on the classical theory and naive idea that the electrons are like small balls. In the figures (5.2 & 5.3) below, in the double-slit experiment (a) is when only the first slit is uncovered (b) when only the second slit is uncovered and (c) when both slits are uncovered.



(a) Slit -1 uncovered (b) Slit-2 uncovered (c) Both slits uncovered

Figure 5.2: S₃'s prediction of the double-slit experiment with electrons



(a) Slit 1 uncovered (b) Slit-2 uncovered (c) Both slits uncovered

Figure 5.3: S₂₃'s prediction of the double-slit experiment with electrons

In their figures the electrons are assumed to be indestructible and hence arrived on the screen in identical lumps (see Figure 5.2 and 5.3). the students expected that the position of a microscopic particle is objectively real and predetermined based on unknowable initial conditions as if they were macroscopic objects such as bullets. They thought that the electrons would sometimes come through slit 1 and sometimes through slit 2 – varying between the two possibilities in a random way – producing two piles behind each slit in a way that is simply the sum of the results that would be observed with one or the other slit opened. Such a classical and trajectory-based description is also found in their responses when they were asked to predict what would happen when the intensity of the electron beam is altered so that only one electron passes through the apparatus at a time. The following excerpts are presented to illustrate this description as S_3 and S_{23} attempted to predict the observed phenomena in the case of a low intensity electron beam:

> **S_3**: If one electron going through the slits at a time, the same thing happens. I mean when an electron get to slit 1 it pass through slit 1 and strike the screen directly in front of slit 1. If it gets to slit 2 the same happens on the screen. So I think the same pattern forms, two spread out regions from two slits.
> I don't see the difference with time. Because nothing is changed in the experiment. So it is the same. If we increase the time I expect many electrons will strike the screen.
>
> **S_{23}**: I am not sure. Uhh […] if only one electron is going through the slits I expect a similar pattern but since the number of electron is small the curve behind the two slits will be small. May be if we let for long time. The electrons striking the screen behind slit 1 and 2 are large. Umm […] I think the curve may be merged as one big curve. A large two merged curve formed.

The foregoing excerpts suggested that the students have the classical particle notion that individual electrons are detected as localized particles on the screen without an interference pattern being developed. They thought that since only a single dot at a time appears on the detecting screen, the electron must have been a small ball, traveling somewhere inside that apparatus, so that the electron went through one slit or the other on its way to the screen where it was detected directly behind each slit. A further illustration of this line of thinking was also evident as these students attempt to predict what change will occur when a detector is placed at one of the slits:

> **S_3**: I don't think there would be a difference. I think the detector never closed the hole so I expect a similar pattern.
>
> **S_{23}**: I am not sure. Uhh […] if only one electron is going through the slits I expect a similar pattern but since the number of electron is small the curve behind the two slits will be small.

The foregoing excerpts suggest that the students' line of thinking was against the very quantum mechanical principle which stated that measurements interfere with the states of microscopic objects. In this category, in general, emphasis has been laid upon the fact that on the one hand, the wave-like properties of electrons are depicted with reference to simple wave phenomena (such as, a disturbance, in space and time which has wavelengths and frequencies, interference, diffraction). On the other hand, the students depicted the particle-like properties that microscopic entities (i.e., electrons) could show, mentioning the fact that electrons have some defining classical properties (e.g. as localized, compact, hard, and massive objects that carry charge, energy and momentum). Students vaguely explained the concept of duality in terms of waves, particles, or both, without clearly conceiving of the nature microscopic entities (i.e., electrons) as having wave-like and particle-like properties. Except for repeating some phrase they have heard in class or read in the quantum mechanics books, students often appeared to cling to the classical ideas associated with a wave-and particle-like properties of electrons. Since the idea of a particle as being localized, compact, hard and massive was at the core of students' conceptual understanding, the concept of trajectory (as electron passes through either the two slit) is heavily depicted just like that of classical picture of the path of a massive particle moving in space-time.

In a similar vein, further naïve and classical thinking is also seen in students' explanations on questions and statements related to the concept de Broglie wavelength and the wave properties of matter (see typical interview questions in Figure 5.1) in the double-slit experiment. The following excerpts help to illustrate this approach as a student attempts to predict how the double-slit pattern would change when, first, the electrons are moving with greater speed and secondly, when replacing electrons with other elementary particles:

> **S_3**: interference is wave nature. Speed is particle nature electrons or the wave speed. Then interference wave nature and particle nature of electrons is the duality property. This is occurring in nature. So […] no change in pattern […] I think so.
>
> **S_3**: replacing the electrons with different particles may lower the interference. […] Wave nature is the property of electrons. May be […] I expected each particle has its own interference
>
> **S_5**: For me interference is not affected by velocity change. Why? it is the same pattern
>
> **S_5**: replacing electron may affect the pattern. Larger objects imply lower constructive and destructive interference. […] when the object is larger than electron how much of this object is passing through slit 1 or slit 2. So the interference is between only those objects passing the slit. For larger objects, low numbers is passing slit 1 and in slit and interfere. I think […] low interference.

> **S$_{30}$**: First, uhh [...] I think. First, is there any relationship between interference and speed? Interference means wave nature. I don't know but velocity doesn't affect interference. So it is the same pattern. The speed of the electron doesn't affect the wave nature.
>
> **S$_{30}$**: if the energy is not changed the pattern is the same.
>
> **S$_{35}$**: I expect if the experiment changed the result changed. For example, […] I guess if velocity increased means electrons are energetic so a big interference may be. I am not sure.
>
> **S$_{35}$**: Mathematically replacing the electrons with massive particle means the speed is smaller. So the dark and bright region will form with less speed in turn less bright. Pattern may totally change into a more dimmer pattern.

These students' explanations illustrate that students thought that changing the velocity of electron would not affect the interference pattern, in turn the wavelength of electrons. Their descriptions demonstrated a lack of understanding that if the velocity increases, the momentum increases and as a result a decrease in the de Broglie wavelength that explains the double-slit electron interference pattern. Students' explanations, for the interview questions in which the electrons are replaced with particles of different mass, were also never relate the interference pattern to de Broglie wavelength. Students seemed to predict correctly that replacing electron with other object would affect the location of interference maxima and minima but used naive reasoning about the relationship between mass and wave property of matter. Students couldn't see that interview contexts referring to the replacement of electrons with a massive particle, velocity and/or kinetic energy of particles were concepts about the de Broglie wavelength of electrons. Other most common types of students' responses in this category were that a change in the velocity of electrons would affect the double-slit interference pattern but they did not have any reasons at all, or, if they did, those were consequences of naïve and/or inappropriate kinds of interpretation and reasoning.

In general, the acquired description category (i.e., which visualize the basis for students' ideas of matter wave and way of using quantum probability concepts in explaining the observed phenomena) reflected insufficient explanatory power, undifferentiated description mainly driven by naive and everyday language and were consistent with the principles taught in some previous courses. For example, the idea of a particle as being localized, compact, hard and massive was at the core of students' conceptual understanding in this category; the concept of trajectory (as electrons or photons pass through the double-slits) is heavily depicted just like that of classical pictures of the path of a massive particle moving in space-time. Evidence from students' explanations confirmed that students, in general, are unable to recognize that changing the momentum of a microscopic particle affect its de Broglie wavelength. It is clear that this conceptual picture as outlined by students in this category is consistent with the mutually exclusive classical wave-and particle-like model of matter waves. These naïve and classical trajectory-based descriptions are also found in the other categories of description. However, the extent to which it was used decreased going down the hierarchical structure of categories from classical to incipient quantum categories of description.

5.2.2 Category II: An Intricate Blend of Classical and Quantum Model Description

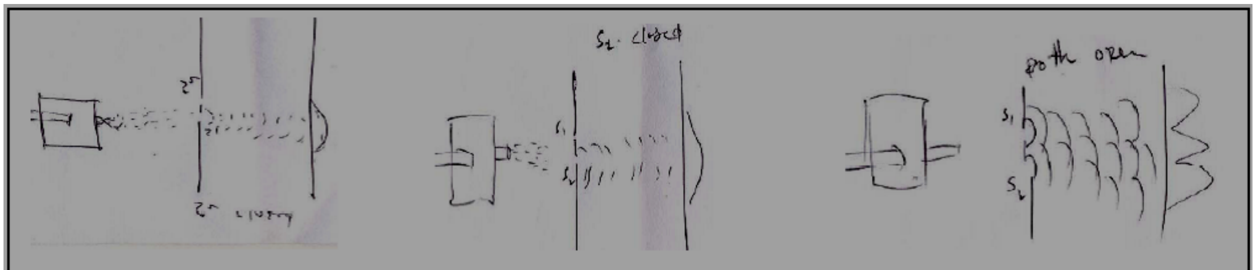
This description category was initially considered to consist of various aspects of depictions. For example, students' depictions of matter waves often included aspects of quantum perspectives but the foundation for their depictions and explanations was still based on classical reasoning; or students applied simultaneously and interchangeably quantum perspective and perspectives based on classical ideas on interpreting the nature of matter waves in similar quantum contexts. Again students in this category also applied a strong classical reasoning with the correct quantum ingredients in depicting the observed quantum phenomena in the double-slit experiment for electrons. This description category can be seen as a model which combines and/or mixes aspects of understanding of matter waves based on classical perspectives and the accepted understanding of quantum phenomena. The students in this category, for example, articulated their understanding of the simplest particle- and wave-like properties that microscopic objects such as electrons could show as:

> **S_{11}**: From wave-particle duality the particle nature of microscopic object or electron is clear. [..] like any object electrons has charge, mass, size, speed, momentum and position calculated by second law of Newton. So […] electron is a single matter. That is particle

> nature at the same time it has wave nature. So small objects show disturbance in space like waves. Electrons also show constructive and destructive interference in the two slit experiment. The wave-particle nature of electrons is […] based quantum theory it is a superposition of the wave and particle behaviors of electron.
>
> **S_{13}**: particle nature of electron is […] mass, charge, speed momentum and position in space. Wave natures of electron are […] frequency, wavelength, and disturbance and […] carry energy and […] show interference of waves. Both property of electron is the dual wave-particle nature.

From the foregoing excerpts, these students seemed to conceive a particle in terms of its charge mass, definite position and momentum. They, most importantly, saw a particle property of electron in the context of quantum mechanics as an isolated entity. They also stated the superposition of states as being a superposition of the wave and particle behaviors of an electron. Again, these students used a variety of words to describe the wave-like property electron in quantum mechanics including: wavelength, disturbance, frequency and interference. Thus, in one hand they believe that an electron sometimes behaves like a (classical) wave and at other times like a (classical) particle and on the other hand their responses include quantum fragments, in the sense that it consisted more of isolated quantum descriptions.

In response to the follow-up interview questions (i.e., predictions and interpretation of double-slit experiment for electrons), students were able to predict the important features and properties of the observed phenomena on the double-slit and provide a likely behaviour scenario for the quantum entity. As can be visualized in Figure 5.4 a student (S_{31}) accepted and established a key quantum principle that when both slits are open the resulting curve is similar to an interference pattern.



(a) Only Slit 1 uncovered (b) Only Slit 2 uncovered (C) Both slits uncovered

Figure 5.4: S_{31} prediction of the double-slit experiment with electrons

It appears that S_{31} understood that the interference curve cannot be obtained by adding the individual curves produced when the slits are opened one at a time. In interpreting the observed phenomena, however, the student appeared to cling to the classical ideas associated with a quantum matter wave model and did not significantly modify his mental models during his studies of quantum mechanics. Some typical responses of this student are:

> S_{31}: off course I understand electrons are particles. But […] in this case it has both particle and wave nature. What […] um […] I understand is that electrons are moving like waves in the two slit experiment. When I say electrons are waves, […] umm […] I know that waves from S 1 and S 2 are constructively or destructively interfere with each other. Which means interference pattern is formed on the screen. In case of only slit 1, diffraction is occurring behind slit 1 and behind slit 2 in case only slit 2. So the two figures show diffraction only […] I expect it is no interference between wave nature electron from slit 1 and slit 2.

As can be seen, the interference phenomena are explained as an outcome of the collective behavior of several electrons (or an outcome of the constructive or destructive combination of electrons). The student did not abandon the classical particle viewpoint, while he did recognize the wave behavior of the electrons. A blended description of this category was typified by, for example, [The electron is described as a delocalized probability wave that takes however a well-defined path (trajectory)]. Similarly when the double-slit context was shifted slightly, students in this category were also unable to construct a coherent and supported argument to explain features and properties of the observed phenomena on the double-slit experiment for electrons. Excerpts from students are presented below. They illustrate how students in this category tended to transfer macroscopic property to the electrons, diffuse the deterministic mode of thinking and reasoning into quantum context and/or blend elements of both mechanistic and quantum ideas with respect to the observed phenomena in the double-slit experiment for single electrons:

> **S_{16}**: When the intensity is reduced so that there will only be one electron going through the slits at a time, I expect electrons behind slit 1 for the one coming through slit 1. I expect on the screen behind slit for an electron following slit 2. Again there is a probability for some electrons reflected back from the slit wall. Regarding the pattern on the screen, since there is no constructive destructive interference between electrons no pattern or electron randomly distributed. […] may because interaction between electrons after some time interference pattern formed. […] I am not sure the reason.
>
> **S_{24}**: when only one electron is going through the slits at a time, I expected individual electron to pass through slit 1 or slit 2 and hit the screen behind the slits. I think […] quantum physics is probabilistic so after some time the electrons distributed randomly on the screen. But some of the electrons coming from slit 1 and the other from slit 2.
>
> Concerning the pattern, […] I as said there is interference probability after some time because random interaction between electrons.

It can be seen that although students have predicted the gradual formation of an interference pattern with only one electron at a time, they have showed a strong tendency to prefer a trajectory-based interpretation (each electron goes through either one slit or the other, but not both) to discern in which slit each electron traversed. It seems that they maintained the classical deterministic mode of thinking and reasoning into quantum mechanics context. In an attempt to map if the students realized that an associated wavelength was assigned to the electron and to all the matter, all the participant students were asked questions listed in Figure 5.1. For example, they were asked to predict how the interference pattern detection for electrons would change if the electrons are moving with greater speed and/or when replacing electrons with other elementary particles with same kinetic energy. Students explicitly predicted that varying the speed of electrons would result in a change in the location of interference maxima. However, they did not support their description with the de Broglie wavelength, but simply guessing that higher speed means higher frequency of interference maxima. When electrons were replaced with relatively heavier particles ($m_p \cong m_e$) of the same kinetic energy, these students correctly related the wavelength is inversely proportional to mass, but they predicted that no clear interference pattern would emerge on the screen. Quantum mechanically based descriptions were framed by an intuitive sense that electrons could usefully be described as the only quantum entity with wave-like property , but no such wave-like nature can be observed in the case other microscopic objects. Consider the following illustrative examples:

> S_{11}: When electrons have large speed, I expect more number of interference maxima will be created on the same screen. I … think more speed is for me I am … saying more frequency. When this is happen the size of the interference maxima is smaller. Not wide as it was. I think this the speed is the reason. When speed decrease the opposite are created. I think so. In quantum case,… umm [...] the Planck equation is E = hf, also E = pc, from this p = hf/c = h/λ. So we learned mass increase means λ become small then wave nature become small. So interference pattern is not created.

> **S_{24}**: I expect … when speed increase the pattern is narrower. But if we decrease the speed the interference become wide. Because the speed is the factor. When the speed high means the interference formation be come fast but when the speed become low so the interference also low. Which means wide. Heaver mass always particle like. The wave nature of matter is possible for electrons. Because the Plank constant is small and as a result λ also small. Again λ small means no wave nature such as interference or it is small.

In most cases, the terms used to describe the wave-like properties of microscopic objects are usually drawn from quantum mechanics-based terminology; however, their meanings are diverse and often inappropriate. Other students (e.g., S_7 and S_{13}) correctly related the de Broglie wavelength of electrons to the velocity and momentum but predicting that no change would occur on the interference pattern despite varying the velocity or replacing electrons with other particles. Such a blend thinking of these students is typified by, for example, [The same interference is seen for speedy electrons because all electrons have same wavelength]. In general, the concept of matter wave was depicted from an intricately intertwined classical and quantum perspective and was thus considered to represent intermixed ideas which could be specifically framed by the blended perspective. This would seem to reflect elements of diverse and often inappropriate intuition in the students' conceptual understanding.

5.2.3 Category III: Incipient Quantum Model Description

The fact that students' depictions of matter wave incorporated ideas of quantum mechanics (e.g., the Planck-de Broglie relations, duality, principle of superposition, probability distribution, the uncertainty principle, the de Broglie wavelength) is one of the remarkable features of this category. For physics students, in this category, quantum phenomena related with matter wave and aspects of microscopic entities are understood nearly based on the 'accepted' quantum physics formalism. They succeeded mostly in answering the interview questions and gave explanations (despite the fact that they have quoted several examples from textbooks and memorized definitions and formulas from lecture notes) for the concepts included in the interviews. Thus, these students' depictions were categorized as incipient quantum model of description since it exhibited a quantum mechanical way of thinking and reasoning with few fragments of alternative ideas in many aspects of the quantum model matter wave.

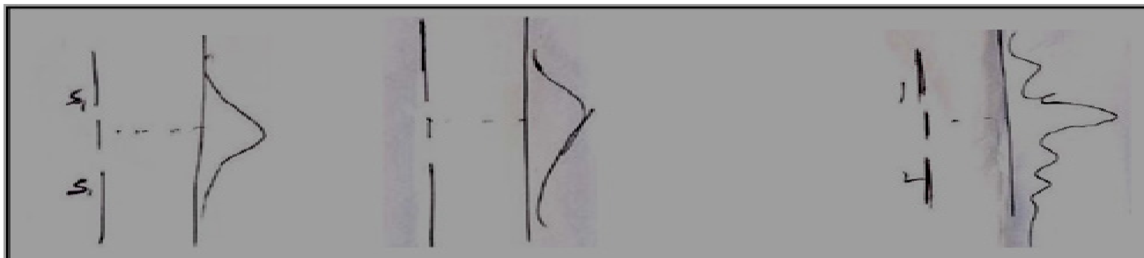
For example, while students in this category made very few metaconceptual statements (i.e., depictions about their own conceptions), they, when asked about the simplest particle- and wave-like properties that microscopic objects such as electrons could show, had the following quantum-like descriptions:

> S_2: Yea […] wave particle duality is true in quantum mechanics. […] microscopic particles show wave nature such as diffraction and interference of electrons in the double-slit. Based on de Broglie, electrons have wavelength, $\lambda = h/p$. so electrons have particle nature and wave nature. Because electrons are atomic objects. […] large objects don't have wavelength. Quantum physics works in smaller objects because Planck proved that the Planck's constant very small and […] not working for large objects. The duality of electrons is particle in one experiment again wave in the other experiment.
>
> S_{15}: […] a body is wave-like when it exhibits interference or diffraction. Everyday objects or microscopic objects don't show wave nature, because according to the de Broglie wavelength i.e., $\lambda = h/p$, the greater an object means great mass and great momentum, so

> the more the object like a particle it behave. The lower the object means low mass, low momentum and the more like a wave it behaves. From our quantum lecture, Plank's constant, h which very small is a factor also why we don't observe wave nature in large objects.

> S_{18}: Umm […] as we learn quantum mechanics is the physics for small or atomic things. So atomic objects show wave-particle nature. Duality is complementary. In quantum physics, electrons show wave and particle properties. De Broglie proved the wave nature of electron. […] firstly it is known energy is quantized, $E = h\nu$ *or* $E = hc/\lambda$, from de Broglie, $\lambda = h/p$, $= h\nu/c$. […] so momentum that is the particle nature of an electron is related to the wavelength of electrons. diffraction of electrons also proved by experiment of electron beam with crystal. Interference electrons also observed in the double-slit experiment.

The key idea in their depictions of the wave- and particle-like properties of microscopic object was that a matter wave associated with a particle has a de Broglie wavelength given by $\lambda = h/p$. It seems that Student S_2's, S_{15}'s and S_{18}'s depictions are quantum-like but their reasoning and thinking of the wave –and particle-like properties of quantum entities were driven by their memorized definitions and formulas from lecture notes and textbooks. In the double-slit experiment interview questions, students in this category were also able to sketch and describe the key aspects and properties of the observed quantum phenomena on the double-slit for electrons and provided a quantum-like scenario for matter wave phenomena (i.e. the interference of electrons at a double slit). For example, S_{15} gave his sketch of matter wave interference in the double-slit experiment for electrons as in Figure 5.5 and provided a plausible explanation for his figures that with either slit open alone, electrons are detected at all points on the screen; but when both are open at the same time, electrons producing a double-slit interference pattern:



(a) Only Slit 1 open **(b) Only Slit 2 open** **(C) Both slits open**

Figure 5.5: S_{15}'s predictions of the double-slit experiment with electrons

> S_{15}: for opening slit 1 or slit 2, no interference. I think it is diffraction of wave or it is particle nature of electrons. When both open electrons randomly distributed and wave interference occur.

When this student was asked to predict what would happen when the intensity of the electron beam is altered so that only one electron passes through the apparatus at a time, he replied the following:

> S_{15}: if only one electron is at once, […] I think in quantum mechanics this unpredictable, or we can know it the place, or it is random. I think we are unable to determine the next electron position.[…] it is not known by scientists or our experiment is unable to determine. But after many time […] as I read interference pattern occur may be because interaction on the screen.
>
> When both slits open and a detector is placed wave interference disappear […] because there is a disturbance of the experiment. Again according to Bohr wave and particle nature is complementary. If I see electron passing in the slit, no interference occur.

Apparently, S_{15} tried to sketch and explain the observed phenomena on the double-slit experiment for electrons, which was relatively successful, but he seemed to treat the workings of the microscopic world in much the same way that classical mechanics treats the workings of the large-scale world. For example, S_{15} seemed to view that we cannot predict the next position of electron because we are simply unable to determine their values (because of some hidden aspect), or control them in any way, and hence give rise to the apparent random behavior of microscopic systems. The remaining two students (e.g., S_{18} and S_2) did not get far enough to be explicitly aware of the few naïve conflicts and just used their intuitive ideas for reasoning but in rare situations. On the follow-up interview questions in which students were asked to predict how an interference pattern would be affected by increasing the speed of electrons; and they were asked how replacing electrons with heavier particles having the same kinetic energy used in the double-slit interference experiment would affect the locations of the interference maxima. All three students (e.g, S_2, S_{18} and S_{15}) grouped in this category, then, seemed to have made sense of the relevance of the de Broglie wavelength in situations in which the wave properties of matter are important. Students correctly predicted that both increasing the speed of electrons and replacing with heavier particles having the same kinetic energy would cause the interference maxima to move closer together. They seemed to recognize that the de Broglie wavelength was the critical concept in answering the two interview questions. However, these students still overstated the mathematical relationships between energy and wavelength and momentum and frequency, which are applicable for electromagnetic radiation (photons), as equivalent for a matter (e.g., electron) with a wave nature. It would seem that the students were not clear about the wave-particle relationships fundamental to all phenomena are between momentum and wavelength and energy and frequency. In general, the first two description categories (Category I and II) are variants of classical-like types of depictions, and only the third description category, identified in three students' responses, could permit an incipient quantum understanding of matter wave phenomena and concepts.

5.3 PHYSICS STUDENTS' DEPICTIONS OF THE UNCERTAINTY PRINCIPLE

It is a common understanding among physicists that some aspects of the wave-like description of atomic and subatomic objects lead to some uncertainties in determining simultaneously pairs of observables like position and momentum, energy and time and other observables. This was formulated by the Heisenberg uncertainty principle which states that the position of a particle and its momentum can never be determined simultaneously with infinite accuracy. The uncertainty principle contributed to the indeterminacy of the quantum world and it is one of the most discussed topics in most undergraduate quantum mechanics courses starting from first year. Thus, much insight into the nature of physics students' conceptual understanding of quantum uncertainty and/or indeterminacy can be obtained by analyzing students' qualitative answers and reasoning of the specific interview questions selected applies to the idea of the uncertainty principle. As explained in Chapter 3 and 5, the interview questions selected applies to the idea of the uncertainty principle were administered to the participant students immediately after an in-depth interview on matter waves had taken place. The set of interview questions are:

1. Is it possible for quantum physics teachers to carefully perform the same experiment (i.e., a quantum experiment) and get two very different results that are both correct? Explain your agreement or disagreement with reasoning.
2. If you know exactly the initial condition (say, for example, you do measure the position of an electron and you find it to be at a certain point P) can you determine where was the electron just before you made the measurement? Can you predict with 'certainty' the future states resulting from it?
3. In quantum mechanics, you cannot predict with certainty the outcome of a simple experiment to measure its position. Is it a peculiarity of microscopic world, a fault in the measuring apparatus, lack sophisticated technology, or what?
4. Recall the simple double-slit electron interference experiment; can you determine the impact point of an electron on the screen before the instant of impact? Can you track the particle position without destroying its interference pattern?
5. In Quantum mechanics, the degree to which a physical variable can be precisely measured is subject to some uncertainty. What does this meant to you? Do you think that repeated errorless measurements of the variable will always give precisely the same value? Why? Can you describe mathematically the Heisenberg uncertainty relations? What is the meaning of Δx and Δp?
6. Do you think that the Heisenberg Uncertainty Principle is generally applied to macroscopic objects such as electrons, photons, cars and tennis balls? If not, why don't we see the uncertainty principle on larger objects such as cars and tennis balls?

As discussed, physics students' responses to these interview questions were separately analyzed using developmental phenomenographic analysis where the description categories which form the basis for students' depictions of the uncertainty principle are identified by interpreting the given responses and their meaning. It is explored that students' depictions of the quantum uncertainty can be described with three distinct types' description categories, namely: quantum uncertainty as a classical ignorance, quantum uncertainty as a measurement disturbance and quantum uncertainty as a quasi-quantum principle. In the construction of these categories, only the explanations of students related to the concepts of uncertainty and/or indeterminacy were taken into consideration. For illustrative purpose, key facets of depictions which appear descriptive of a particular kind of description category (see Table 5.2) and exemplary excerpts of the interview responses from students are included. Students' depictions are compared and contrasted and, in some cases, possible source(s) for students’ depictions are traced.

Except for a few students’ responses, all physics students’ responses can be characterized adequately using the first two simplified models of the discerned categories. It suggests that students participated in this study did not have enough knowledge to define the concepts of quantum uncertainty and they were influenced by the perspective of classical models in making explanations related to the concepts of quantum uncertainty.

Table 5.2: Categories of description representing aspect of physics students’ depictions of the uncertainty principle

Categories of Description	**Key Facets of Students’ depictions**
Category I Uncertainty as Classical Ignorance	The quantum uncertainty can always, in principle, be made smaller by using more sensitive equipment The idea of uncertainty principle is the perfectly normal state of being unsure about things Thinking that the electron has a well-defined position and momentum, but we do not happen to know what it is Measurement is capable, in general, of determining these properties instant by instant to whatever accuracy we wish the uncertainty is related to any technical imperfections of the measurement process Position and momentum of a particle evolve in a deterministic manner based upon the interactions Quantum measurement can be considered as a passive reading of pre-existing values The idea of quantum uncertainty principle could be taken as something like experimental error Electron moves along a well- defined and predictable trajectory Quantum uncertainty is an ambiguity about the position and momentum of electron, created by missing information that is relevant and could be known The quantum world was completely knowable, and it evolved according to laws
Category II Uncertainty as Measurement Disturbance	The quantum uncertainty as a principle that deals with the precision of a measurement and the disturbance it introduces Suggesting that quantum uncertainty were due to discontinuous changes occurring during the process of measurement Position and momentum are in general not well defined for a given state of a quantum system because a measuring apparatus disturbs the quantum system Quantum uncertainty is refereeing for the inaccuracy of a measurement of one of the quantities and the ensuing disturbance in the distribution of the other Macroscopic objects at any instant of time have an exact position and exact

Categories of Description	Key Facets of Students' depictions
	momentum and with sufficient care we can measure both precisely The uncertainty principle is not about the intrinsic uncertainty any quantum state must possess but about a statement of empirical fact of the inevitable and uncontrollable disturbance of a quantum system by the measuring apparatus Microscopic objects obey Newton's laws of motion, to which the quantum uncertainty principle does not apply
Category III Uncertainty as a Quasi-Quantum Principle	The uncertainties in the experiment arise the fact that the position and the momentum of the electron cannot be simultaneously defined in the microscope experiment Position, momentum, and other observables are in general not well defined for a given state of a quantum system The quantum mechanical uncertainty as an inequality relation due to the wave-particle duality inherent in all quantum systems A position measurement is accurate, the information about the momentum is inaccurate and vice versa Uncertainty principle is a statement about the observation produced effect Prediction would thereby be limited because of initial uncertainty Physical theories can do no more than predict the probabilities of the outcome of any measurement

5.3.1 Category I: Uncertainty as a Classical Ignorance

To this category of description, the uncertainty principle is not a characteristic of an intrinsic property of physical phenomena, but a representation of our classical ignorance; and/or an ambiguity created by missing information that is relevant and could be known. Students, in this category, also described uncertainty as a measurement error due to an external effect such as thermal agitation, noise, vibration, the surrounding contacts, etc. Except for some factors associated with the experimental setup and lack of information, mentioned in their reasoning, students expected the results of experimental measurements as an approximation of the true value of the quantity being measured. Extracts of such explanations are found when they were presented with interview question (1) such as:

> Is it possible for quantum physics teachers to carefully perform the same experiment (i.e., a quantum experiment) and get two very different results that are both correct? Explain your agreement or disagreement with reasoning.

> **S_5**: My answer is yes it is possible. My reasoning is if only if the experiment is carefully done. But the difference may be due to heat effect, instrument the lab table movement and the like. I think this is what I can say.
>
> **S_8**: Uhm yes […] I agree. Because I know that I can repeat experimental results if the laboratory materials, the environment is not affecting it. […] But even personal error may vary the results. […] the different may be coming out of the settings of the experiment […] otherwise I agree.
>
> **S_{17}**: I think it is not possible. If they are doing the same experiments, the results will also the same. I mean one correct answer. Why two correct answer for the same two experiments. I do not expect difference. The need of experiment is […] for me, to repeat results for testing.
>
> **S_{20}**: For me […] experimental results must repeatable if they are conducted in the same way. If there is a difference in the outcome, I understand something in the theory or setup should be changed. So […] no two different results will be recorded from the two teachers.
>
> **S_{23}**: Yes […] yeah I agree. But experiments are associated with some errors. I mean, small errors may be created because of the temperature others factors. Again the apparatuses may be differ one from the other. […] In general I expect correct result.

As can be seen in the foregoing excerpts, there is a clear trend in the way that the four students responded to the interview question. The prevailing reasons within them seemed to be insisting upon classical factors and lack of information. In answering interview questions (2) and (3), the students reflected a general idea that indeterminacy is not a fact of microscopic world, but a reflection of our ignorance. Consider the following typical students (S_5 and S_{23}) responses when they were presented with interview question (2):

> **S_5**: […] um […] I think it is possible to predict the future position if you give me the initial points. […] by applying the givens information I can calculate their future states that occupy after some time […] the distance it travels. So it is possible to calculate the position. Umm […] I think so. If I found it at point P, I think […] it was at this point P or the position vector is already determined because it is there already.
>
> **S_{23}**: if I found something somewhere, I expect it was there. So I expect the electron was there at P. To determine future position, […] or during calculating this kind of problems sometimes the theory and the mathematical prediction do not meet. […] using the initial conditions, because of air resistance, the perdition may not be correct. But if it is a vacuum it will be possible to predict its future state from given initial data.

As can be seen in their explanations, students believed that a repetition of the experiment under identical initial conditions may lead to the same possible outcomes. These students' (i.e., S_5 and S_{23}) responses when they were presented with interview question (3) are:

> **S$_5$**: yes in quantum physics […] we cannot predict position. We cannot also predict momentum. […]I expected this is because of sharp technology. If we can get good experimental atmosphere that do not interfere, I think it is possible. It is also because in quantum physics there are some issues that in experiment we do not know the factors for correct prediction because of uncertainty principle.
>
> **S$_{23}$**: not predicting the position measurement is, […] I think, working in only quantum physics. [...] for very small particles yes, I expected it is difficult to predict position measurement. I think it is because of both the particles are very small and lack of microscopic laboratory experiments. So […] the position is unpredictable.

From the foregoing students' responses to the interview questions involving the idea of quantum measurement and indeterminacy, students seemed to conclude that simply by refining the laboratory equipment, the randomness, uncertainty and/or indeterminacy can be reduced, in principle removing it all together if we are clever enough. Likewise, their explanation to the fourth interview question, "In the simple double-slit electron interference experiment; can you determine the impact point of an electron on the screen before the instant of impact? Can you track the particle position without destroying its interference pattern?" was typified by, for example, [Electrons move along a well- defined and predictable trajectory]. Students in this category still maintain a similar classical reasoning to the remaining interview questions (question (4) and (5)). Note these students' responses to interview questions (4 & 5):

> **Q4**: In quantum mechanics, the degree to which a physical variable can be precisely measured is subject to some uncertainty. What does this meant to you? Do you think that repeated errorless measurements of the variable will always give precisely the same value? Why? Can you describe mathematically the Heisenberg uncertainty relations? What is the meaning of Δx and Δp?
>
> **S$_5$**: Uncertainty is an error in the measurement because various reasons. If it is error free yes I expect true value. But there are errors in experiment. Uncertainty means $\Delta x \Delta p \geq \hbar/2$. So Δx is the difference in the position measurement I mean the error and the same for Δp. Uncertainty simply says there is always some error.
>
> **S$_{23}$**: I understand there is no sure result in quantum mechanics. When all error causing problems are controlled, I except precise or exact value. Uncertainty means, there is always doubt or it is always ambiguous in measuring. That is uncertainty. According Heisenberg's relation it is $\Delta x \Delta p \geq \hbar/2$ that is […] I think, it is uncertainty in position and momentum Δx and Δp are values indicating the difference between true and measured value. That is the uncertainty.

> **Q5**: Do you think that the Heisenberg Uncertainty Principle is generally applied to macroscopic objects such as electrons, photons, cars and tennis balls? If not, why don't we see the uncertainty principle on larger objects such as cars and tennis balls?
>
> **S$_5$**: I am not sure but uncertain error is always present. But I expect almost zero for large object.
>
> **S$_{23}$**: for larger object correct measurement is possible. We can measure larger balls but not electron.

In the foregoing excerpts uncertainty usually refers to a situation in which there is ambiguity or error about measurement outcomes and this measurement uncertainty is due to lack of information or inadequacies in our experimental technique. It was also found in the students' responses that experiments on atomic scale systems performed under identical conditions, where everything is as precisely determined as possible, will always, in general, yield results that do not vary in any way from one run of the experiment to the next. In general, students in this category thought of the quantum phenomena as a classical quantity which permits unlimited accuracy in the fixing and predicting the values of physical or dynamical quantities, and our failure to predict with certainty the outcome of a simple experiment that measure electron's position is simply a fault of inadequacies in our experimental technique or because of our ignorance.

5.3.2 Category II: Uncertainty as a Measurement Disturbance

Students' description appeared to use distorted quantum worldview to interpret the concept of quantum uncertainty and/or indeterminacy. As with category I, a significant part of this category is dominated by a classical interpretation of the uncertainty principle. However, the nature of this category was not necessarily of the character we had anticipated from the classical ignorance category. Students' ideas in this category pointed to the contrasting meaning of quantum measurement. This is conveyed in the following statements by students in response to the preliminary interview question (question (1)), "Is it possible for quantum physics teachers to carefully perform the same experiment (i.e., a quantum experiment) and get two very different results that are both correct? Explain your agreement or disagreement with reasoning":

> **S_7**: First I think […] does everything the same? I do not believe similar results. You know experiments are not error less but their error may not be the same for two correct results as far as confirming the reality. Off course our quantum physics also say the same. I mean […] we cannot determine the results beforehand. That is, in quantum case two correct and different values are possible.
>
> **S_{10}**: As you know Quantum physics is unpredicted physics. So for this case I agree it may be possible. As I remember it is also true in all science […] that means, experimental results may interpret based on the setting. For example, the error in case one may be negligible and ignored. In the second the source of error may be explain and consider. So I agree based on the reason.

As can be seen, in a very contrasting form, the students seemed, on the one hand, to reason out experimental results in relation with classical experimental error and hidden variables and on the other hand, they have mentioned that quantum mechanics could allow for two valid, but different, experimental outcomes. When probed again for the role measurement in quantum mechanics using question (2), students in this category also exhibited such a contrasting view:

> **S_7**: before we measured it? […] in quantum physics when we measure position we disturb momentum. Before measurement, I do not know the position of the particle, may be at the same point. But in quantum case, it is not possible to predict before measurement. But […] if the particle is not affected by some external force, I expect exactly at the same place in the future.

It is clear to note how the student (i.e., S_7) drew two different but contrasting pictures of measurement uncertainties. On the one hand, the student seemed to recognize that measurement is not about a passive reading of pre-existing values and on the other hand, the student believed that the future position of a particle can be precisely predicted from knowledge of initial conditions. To a large extent, in this second category of description, uncertainty is characterized by a physical relation that deals with the precision of a measurement and the disturbance it introduces. They have linked the idea of uncertainty principle to the term measurement disturbance. Students had the following explanations when responding to selected questions (5 & 6) about the uncertainty principle:

Q5: In quantum mechanics, the degree to which a physical variable can be precisely measured is subject to some uncertainty. What does this meant to you? Do you think that repeated errorless measurements of the variable will always give precisely the same value? Why? Can you describe mathematically the Heisenberg uncertainty relations? What is the meaning of Δx and Δp?

S$_7$: uncertainty means things are indeterministic. In our case for example, there is uncertainty in position and momentum in measurement. It means the correct measure of position disturbs the value of momentum […] because position measurement influences the momentum and in equation form it is $\Delta x \Delta p \geq \hbar /2$. Δx and Δp is not direct errors I am not sure but I think the uncertainties in position and momentum.

S$_{24}$: Uhmm […] uncertainty means when we measure the position of electron correctly we do not measure momentum correctly because we disturb the momentum or the vise verse. It is impossible to measure without disturbance. One measurement disturbs the other. When momentum defined the position is not defined. Uncertainty is $\Delta x \Delta p \geq \hbar /2$. Both Δx and Δp are uncertainties.

Q6: Do you think that the Heisenberg Uncertainty Principle is generally applied to macroscopic objects such as electrons, photons, cars and tennis balls? If not, why don't we see the uncertainty principle on larger objects such as cars and tennis balls?

S$_7$: uncertainty is for microscopic objects. Uncertainty is an error for larger objects

S$_{24}$: Uhh […] I think there is no disturbance in the large objects. Large objects are the case of classical physics. Uncertainty is a quantum physics principle. It is used for electrons. Umm […] I don't correctly remembered why but the Planck's constant "h" is also another reason for this. I think so. Because uncertainty is $\Delta x \Delta p \geq \hbar /2$.

As noted above, the students gave intuitive explanations of the manifestations of uncertainty principle: the quantum uncertainty representing the inaccuracy of a measurement of one of the quantities and the ensuing disturbance in the distribution of the other and the inaccuracies of any joint measurements of these quantities. Students' explanations of the uncertainty principle as disturbance during measurement: position measurement disturbs the particle's momentum actually reveals a depiction that the observation produced effect. Students, thus, did not appear to have clear understanding of the idea of the quantum uncertainty relation in the sense that it is impossible to detect exactly the values of conjugate observables simultaneously, that these relations manifest an inner indeterminism inherent to quantum states. As can be seen in the excerpts taken from the interviews, the students mentioned about the correct mathematical expression of the quantum uncertainty but it seems reasonable to conclude that students in this category still followed incomplete and classical-like interpretations of its physical meaning. They did not understand that the uncertainty principle is deeply rooted in the wave-mechanical description of particles; once we represent a particle by a wave then it is inevitable that we should allow for some kind of a distribution of the values of its position and momentum. Students claimed that, in principle, the quantum uncertainty principle is valid for only small particles such as electrons, but for macroscopic objects, they followed ideas of classical experimental errors due to some technical imperfections of the measurement process.

5.3.3 Category III: Uncertainty as a Quasi-Quantum Principle

In this category, while students' responses to most interview questions exhibited some degree of ambiguities in their own explanations, they were inclined to focus on the quantum model of the uncertainty principle in their reasoning. For instance, in response to the first interview question, "is it possible for quantum physics teachers to carefully perform the same experiment (i.e., a quantum experiment) and get two very different results that are both correct? Explain your agreement or disagreement with reasoning", students referred quantum-like justification for agreeing with the idea that quantum phenomena could allow for two valid, but different, experimental results. S_{15}, for example, responded as followed:

> **S_{15}**: I agree. The two teachers get two very different results that are both correct. The question is on quantum not classical experiment. Uhh […] my reason is the uncertainty relation in measuring quantum phenomena. If we measure the electron's position once and get a value and if we measure in the same experiment again and again, the result is different […] that means position of electron don't equal but correct in quantum case. I understand umm [...] the measured positions aren't wrong because of quantum uncertainty.

Indeed, the foregoing explanations indicate that students inclined to focus on the quantum perspectives for agreeing with the possibility of two valid, but different, experimental results. In the consecutive position measurement questions (see question Q2), this student followed a quantum perspective to answer the questions about the position of a particle. S_{15} gave the following explanation:

> **S_{15}**: […] uncertainty principle doesn't allow certainty before the measurement is conducted. Again […] I see in this modern physics, there is no experiment that can be performed in order to predict certainly the future state even if as you said initial conditions are known. I think in general repeated measurement on quantum case does not give the same value. It is always random.

S_{15} seemed to have got the general quantum principle that experiments on atomic scale systems performed under identical conditions, where everything is as precisely determined as possible, will always, in general, yield results that vary in a random way from one run of the experiment to the next. He also started recognizing that the quantum mechanical uncertainty is not associated with the precision of a measurement and the disturbance it introduces, but with the intrinsic uncertainty any quantum state must possess. For instance, in explaining why we cannot predict with certainty the outcome of a simple experiment to measure microscopic object's position, S_{15} stated:

> I understand in quantum mechanics the future is indeterministic. No definite value for position and momentum in quantum case. It is uncertain. It is not because of measuring instruments or personal error. It is because of the uncertainty relations, $\Delta x \Delta p \geq \hbar /2$, uncertainty reflects that it is impossible to determine correctly both the position and the momentum for microscopic object at the same time or simultaneously.

In the foregoing excerpt, the student demonstrated an understanding of the uncertainty principle in the context of quantum mechanics by indicating that it would not be possible to know the values of both position and momentum with arbitrary accuracy. His responses asserted that a quantum system simply does not possess a definite value for its position and momentum at the same time. However, when the student was asked questions about the mathematical expressions of the Heisenberg uncertainty relations and the physical interpretations of Δx and Δp in his equations of uncertainty relation $\Delta x \Delta p \geq \hbar /2$, the student was unsure. The following is an example of an explanation that Student S_{15} stated:

> **S_{15}**: There are two uncertainty mathematical equations for the dynamical variables position and time, and also energy and time. $\Delta x \Delta p \geq \hbar /2$ and $\Delta E \Delta t \geq \hbar /2$. I think

> Δx and Δp is uncertainties. […] may be the quantum errors in position and in momentum. In quantum case uncertainty is intrinsic and is not because experimental setup or something else. […] when Δx is very, very small […] then Δp is very, very large. The more one can accurately determined x, less accurately determine p at the same time. I am not sure may be the mean uncertainty for position and for momentum.

Indeed, the use of the sloppy expression "position uncertainty and momentum uncertainty" was regularly found in Student S_{15}'s explanation, yet this students demonstrated no clear understanding that Δx (position uncertainty) is the standard deviation in x, and Δp (momentum uncertainty) is the standard deviation in p in the results of repeated measurements on identically prepared systems. He also considered time (i.e., the independent variable of which the dynamical quantities are functions) as a dynamical variable, measurable characteristics of the system, at any given time. In the last uncertainty question (Q6), while students argued that quantum mechanics allows to associate quantum uncertainties as much to the macroscopic particles as to the microscopic ones, the underlying reasoning that they gave for why don't we use the uncertainty principle on larger objects such as tennis balls was: "Because quantum uncertainty is intrinsic for all object, it does apply to larger object." For these students, the nonobservability of quantum uncertainties in the classical world is not associated to the smallness of Planck's constant and therefore to the de Broglie wavelength of a macroscopic object. Despite this, the interview responses confirmed that students in this category are started recognizing uncertainty as a quantum mechanical uncertainty which is different from our classical ignorance; however, it seems that students simply memorize the textbook definition or teachers' lecture notes and apply this understand to the world of quantum phenomena.

5.4 DISCUSSION OF THE DESCRIPTION CATEGORIES

The developmental phenomenographic analysis of physics students' responses revealed a set of categories that qualitatively describes the participants' depictions related to the concepts of matter waves and the uncertainty principle. The physics students' ways of describing about matter waves were divided in three distinct categories of description. Table 5.1 presented an overview of the resulting phenomenographic categories of description with key facets of depictions that emerged from the phenomenographic analysis. In section 5.2.1, 5.2.2 and 5.2.3, the categories of descriptions are extensively described using quotes and interpretations. The first category, classical and trajectory-based model description, corresponds to the inadequate and intuitive descriptions based on classical ontology and/or the classical concept of path conceptions. Mainly, in this category, the representation that students succeed in treating microscopic particles from the undergraduate quantum classroom contexts corresponds to material objects of everyday experience. It is typified by, for example, [The position of an electron is objectively real and precisely predetermined based on unknowable initial conditions as if they were bullets], [Electron moves along a well- defined and predictable trajectory] and [In a double-slit experiment with high intensity electrons, when both slits are open, the resulting curve is the sum of the individual curves]. Except for few participants, it was found that the classical and trajectory-based model of description is dominant in the majority of physics students' responses who participated in the study (see Figure 5.6).

The next category, an intricate blend of classical and quantum model, represented that students' depictions contain certain quantum-like description of matter wave, but the foundation for their reasoning was still based on classical and trajectory-based conceptions. In describing one or more quantum features associated with matter waves, students often followed a quantum-like description and descriptions based on classical ontology at the same time. It is indicating that after traditional quantum mechanics instruction, physics students are found to be in a state where multiple descriptions coexist in depicting quantum phenomena associated with matter waves. As discussed above, the first two description categories (Category I and II) are variants of classical-like types of depictions, and only the third description category, identified in only three physics students' responses, could permit an incipient quantum understanding of matter wave (see Figure 5.6).

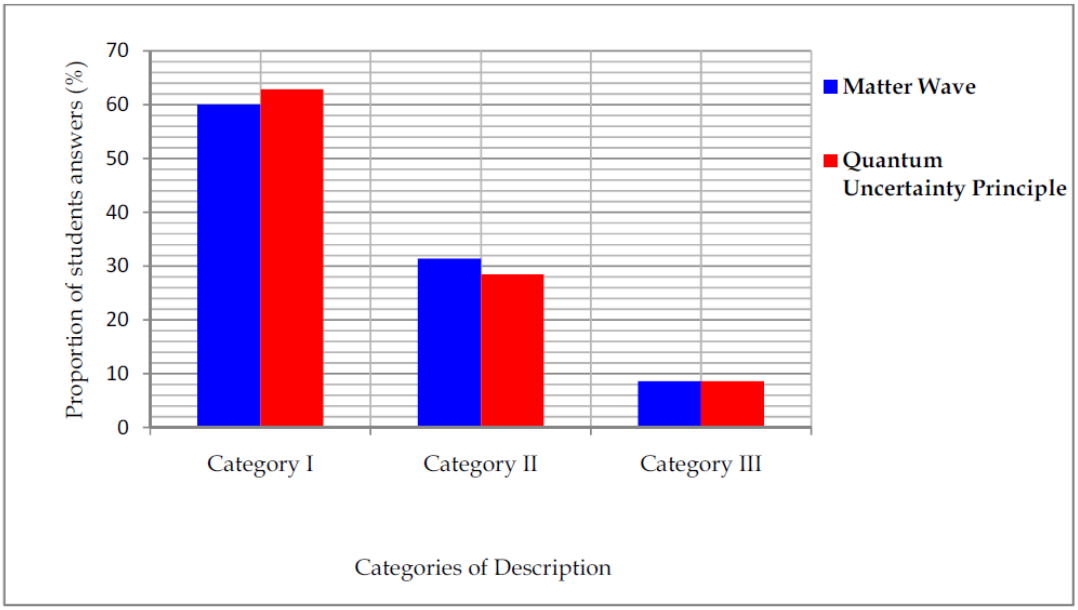


Figure 5.6: Frequency distribution of physics students' answers for interview questions on the matter waves and the quantum uncertainty principle

Physics students' ways of depicting about the uncertainty principle was also divided into three distinct categories of description (see Table 5.2). The first qualitative understanding of the uncertainty principle among most physics students (62.9%) is seeing quantum uncertainty as a classical ignorance (i.e., Category I). These students characterized quantum uncertainty as a representation of our classical ignorance; and/or an ambiguity created by missing information that is relevant and could be known. Students, in this first category, also described uncertainty as a measurement error due to an external effect such as thermal agitation, noise, vibration, the surrounding contacts, etc. In general, 22 (22.9%) students in this category used the idea of classical ignorance in their responses when making explanations about the uncertainty principle. In other words, students thought of the uncertainty principle in quantum mechanics as if it were the measurement error obtained due to technical imperfections of the measurement apparatus. The next level (i.e., Category II: quantum uncertainty as measurement disturbance) responses included the understanding that uncertainty principle prohibits the possibility of precisely measuring both the position and the momentum for microscopic object at the same time. However, the foundation for these understanding is based on the fact that precisely measuring the position disturbs momentum measurement. In the last category (Category III), while students' responses to most interview questions exhibited some degree of ambiguities in their own explanations, they were inclined to focus on the quantum version of the uncertainty principle in their reasoning. For three physics students quantum uncertainty is about the prediction of a state given the current position and momentum. They were the only physics students to attribute appropriate depictions, from the viewpoint shared by most physicists' community, to the idea of the uncertainty principle.

As is evident from the distribution of students' responses shown in Figure 5.6 only a few student responses can be represented by the third category, which confirms the conclusion that little advancement in conceptual understanding may take place during the traditional teaching of quantum mechanics. It is clearly shown that the two concepts (matter waves and the uncertainty principle) usually considered essential to describe microscopic world did not seem to be understood by the majority of physics students. Figure 5.6 also clearly has demonstrated that in the empirical data, most physics students expressed understanding of the concepts in corresponding categories (see also Table 5.1 and 5.2). The finding confirmed that if a physics student for example expressed an understanding of matter wave corresponding to the first category in Table 5.1, he or she also expressed an understanding of uncertainty principle corresponding to the first category in Table 5.2 (see also Figure 5.6). There are very few, if any examples where physics students show a better understanding of the concept matter waves, and a poor understanding of the uncertainty principle and the vice versa (Figure 5.6). It is well known that the uncertainty principle is deeply rooted in the quantum mechanical description of microscopic particles; once we represent a microscopic particle by a wave-like property then it is inevitable that we should allow for some kind of distribution of the values of its position and momentum. It is therefore viable to conclude that an appropriate and/or inappropriate interpretation of the quantum mechanical description of microscopic particles might leave ineradicable traces in student mental model about the uncertainty principle.

5.5 CHAPTER SUMMARY AND CONCLUSIONS

This chapter presents students' depictions of matter waves and the uncertainty principle. The data of the study were collected by semi-structured interviews with 35 undergraduate physics students and analyzed by using the developmental phenomenographic analysis method. As a result of analysis, different distinct categories of description were determined towards the students' depictions of matter waves and the uncertainty principle. In addition to presenting students' perspectives of reasoning by means of a collective map, these distinct categories of description have shown that the quantum mechanical description of matter waves and the uncertainty principle are difficult concepts to grasp, even after two years of undergraduate quantum mechanics studies. For, example, it was revealed that many physics students did not understand the quantum mechanical description of microscopic particles and the interpretation of the uncertainty principle as an inherent indeterminacy in microscopic events. In particular, they did not show an understanding of the incompatibility between the concept of trajectory and the principle of uncertainty. Students also had difficulty in distinguishing between the probabilities in the quantum world, the measurement disturbance and our classical ignorance. Most physics students did not give appropriate answers indicating their conceptual understanding of the wave-like properties (i.e., interference and diffraction of matter waves) of quantum entities such as electrons. It appeared that, in general, the description ways of the physics students who participated in this study when depicting the quantum mechanical description of microscopic objects and the uncertainty principle can be summarized as: (a) students depictions were bounded by their naïve perceptions and thus, they did not have enough knowledge to depict the fundamental concepts of quantum mechanics, (b) students were influenced by the perspective of classical physics in making explanations related to the concepts of quantum mechanics and/or they tried to understand the concepts of quantum mechanics by making reasoning from classical mechanics and (c) students made inappropriate links to previous classical and quantum mechanics learning.

These conclusive results are consistent with previous studies in different countries and contexts, confirming that after the traditional quantum mechanics instruction students' difficulties are real, stable over time and cross-cultural (e.g., Mashhadi, 1993; Ambrose, 1999; Vokos et al., 2000; Olsen, 2002; Ireson, 2002; Kalkanis et al., 2002; Singh et al.,2006; Ayene et al., 2011). These findings, together with previous related projects (Mashhadi, 1993; Olsen, 2002; Ireson, 2002; Singh et al., 2006; Ayene et al., 2011), indicated that the majority of physics students do not, even after two years of quantum mechanics study, have a conceptual understanding of quantum mechanics. In this study, the students' difficulties seemed to be quite severe and to persist beyond the first or later exposure to more advanced quantum mechanics courses. The difficulties documented here support to frame better curricula and pedagogies for teaching undergraduates and even postgraduate quantum mechanics in Ethiopian contexts. One of the most important objectives for the research in this thesis is to apply the findings in designing learning strategies and learning tools that are effective in improving students' understanding of quantum mechanics. The results from the findings were, therefore, used to develop the design of instructional materials based on multiple representations and interactive quantum learning tutorials. The interactive learning tutorials often use computer-based visualization tools to help physics students build their intuition about quantum concepts and keep them engaged in the learning process (Singh, 2008). They also incorporated computer simulations which are developed by the PhET team at the University of Colorado (McKagan et al., 2009) and a computational simulation of the Mach–Zehnder interferometer, developed by Pereira et al (2009). The preliminary evaluation showed that the research-based learning strategies and interactive tutorials are helpful in improving our physics students' conceptual understanding of quantum mechanics (see Part II; Chapter 6).

PART II: IMPROVING PHYSICS STUDENTS' CONCEPTUAL UNDERSTANDING OF QUANTUM MECHANICS

CHAPTER 6

ADDRESSING CONCEPTUAL DIFFICULTIES BY INTRODUCING MULTIPLE REPRESENTATIONS OF QUANTUM PHENOMENA AND USING INTERACTIVE TUTORIALS

6.1 INTRODUCTION

Part I of this thesis explored that after traditional quantum mechanics instructions, physics students' depictions were both naive, simple extensions of classical views and/or quasi-classical views of quantum phenomena and exhibited a number of qualitative differences (often inappropriate). The traditional instructional approach does not favor students learning the quantum mechanical way of perceiving microscopic phenomena; and according to Greca and Freire (2003) latter advanced quantum mechanics courses, more abstract and technical ones, also do not seem to succeed in the conceptual understanding either. However, these highly technical and mathematical courses reinforce the descriptions used by students – to depict quantum phenomena from classical frameworks previously learnt – by way of using classical and quasi-classical views (Greca & Freire, 2003; Ayene et al., 2013). McKagan et al (2008c) argued that the main issue at the center of physics student difficulties in learning quantum mechanics is the struggle to develop the quantum models that are implicit in physicist' understanding but often not explicitly addressed in traditional instruction. The conceptual complexity of the quantum phenomenon is exacerbated by the traditionally rapid lecture of increasingly abstract and counterintuitive concepts. In Chapters 4 and 5, for example, by the end of the traditional instruction, even better physics students' depictions of quantum phenomena were characterized by a rather classical model of quantum mechanics that illustrates aspects of both classical-deterministic and quantum models.

The detailed analysis of students' depicting of quantum phenomena gives another type of result, which may help in designing domain specific pedagogies for teaching quantum mechanics. Hadzidaki (2008) claimed that an in-depth understanding of both the difficulties and the possible conceptual directions students may take in trying to depict quantum ideas has significant implications for creating research informed teaching instructional environments. Currently there is growing evidence that the implementation of research informed instructional approach will enhance students' learning of quantum mechanical concepts (Singh, 2008). In line with these claims, the findings of Part I of this thesis into physics students' depictions of quantum mechanics were extrapolated to scaffold possible changes to instructional practices at the site that provided the context for the study. In other words, the findings from the preliminary investigation were used to guide the design of instructional strategies (i.e. based on multiple representations coupled with interactive quantum learning tutorials) that have been shown to address difficulties identified in this study.

Thus, with the aid of previous studies in effective instruction and the findings from the study of student conceptual difficulties in learning quantum mechanics in our contexts, instructional designs (i.e. based on multiple representations and interactive quantum learning tutorials) were developed and implemented. The choice of the multiple representations-based instructions were based on the fact that studies have shown it to be an effective approach that enhances students' conceptual understanding across physics topics, including some of the basic quantum mechanical concepts (Ainsworth, 1999; Gunel et al., 2006; Abdurrhaman, 2010). In this part of the study, the context of the multiple representations and interactive quantum learning tutorials, which was based on an earlier studies (e.g., Muller & Wiesner, 2002; Singh, 2008; Pereira et al., 2009; Abdurrahman, 2010), was only on the conceptual issues of the undergraduate quantum mechanics course (Quantum Mechanics I) at Wollo University, Ethiopia. Thus, instructional units were emphasizing first the photon model of light that includes the photoelectric effect, the Compton scattering, wave particle behavior light in the Mach-Zehnder experiment and the light quanta interference in the double-slit experiment. The second part was devoted to the quantum model of matter waves and included de Broglie hypothesis and the wave particle aspect of microscopic objects, the double-slit experiment with electrons and the Heisenberg uncertainty principle and quantum probability. The spiral progression of the quantum mechanics topics embedded within the multiple representation-based instructions and the interactive quantum learning tutorials were presented later in section 6.3. The general aim was to provide multiple ways of a quantum phenomenon to help undergraduate physics students to: (a) develop basic quantum mechanical concepts and use these concepts to interpret different quantum ideas and (b) practice required formalism in the subject and relate and use multiple representations in describing quantum phenomena. The details of such instructional materials were discussed in sections 6. 4.1 and 6.4.2.

6.2 THE CASE STUDY

This part of the study was conducted to identify and describe undergraduate physics students' conceptual pathways of the basic concepts of quantum mechanical from pre- to post-instruction to seven weeks after the research-based instructions (i.e. based on multiple representations complimented with interactive learning tutorials) on topics of quantum mechanics. The subsequent purpose of the study was to explore the efficacy of the instructions on promoting change in physics students' conceptual understanding of quantum mechanical concepts. For this purpose, the following research questions have found important to guide a single case study:

- How do physics students' depictions of the fundamental concepts of quantum mechanics differ from pre- to post-instruction and from post- to seven weeks after completion of the instructions on the topics of quantum mechanics?
- What are the patterns of physics students' conceptual pathways of the basic quantum mechanical concepts from pre- to post-instruction to seven weeks after completion of the instructions on the topics quantum mechanics

The research questions guided the choice of the approaches used in this part of the investigation. Thus, given the nature of the research questions, an in-depth qualitative case study was found most suitable for this study. Since an interpretive research approach allows the researcher to explore research questions about the complexity of instructional sequences and classroom learning processes that cannot be answered fully or satisfactorily using other research approaches (Erickson, 1998). According to Merriam (1998), interpretative case study is relatively different from other kinds of interpretative research because it uses intensive description to analyze programs, events, groups, interventions, communities or individuals. As a result, Merriam (1998) describes to three special features of case studies: Particularistic, descriptive, and heuristic. According to Merriam (1998), a case study is particularistic in that it focuses on a particular situation, event, program, or phenomenon. Secondly, a case study is descriptive in that its end product is a rich, thick description of the phenomenon being studied. The description is often qualitative, that is, instead of reporting information in quantitative form, case studies use prose to describe and analyze situations. Finally, a case study is heuristic in that it informs readers' understanding of the phenomenon under study by providing new insights or extending their experience about the phenomenon being studied. The qualitative case study to inquiry used in this study means that the nature and progress of the physics students' conceptual understanding about the basic concepts of quantum mechanics was explored in depth and described in detail. This case study will provide the opportunity for heuristic learning regarding conceptual change of quantum mechanical concepts, and contribute to a broader conceptualization and understanding of the development of these quantum concepts in the undergraduate physics students.

As discussed above, the aim was to provide rich and detailed information about the physics students' depictions of quantum phenomena without constraining their responses to predetermined categories. Thus, a variety of data sources were used to characterize students' progress and conceptual understanding of quantum mechanics, including written explanations and drawings. The data were, therefore, collected from open-ended conceptual survey questionnaires in a single case study design with a pre-, post- and delayed post-questionnaire and incorporated both qualitative and quantitative data analysis procedures (Tashakkori & Teddlie, 1998; Adadan et al., 2010). The open-ended questions focused on students' understanding of basic concepts of quantum mechanics in the study of quantum mechanics. The research questions were mainly addressed through coding and analyzing the primary data sources of open-ended questionnaires and also few student interviews. Brief descriptions of the quantum mechanics conceptual survey questionnaire used and methods employed for analysis were given in sections 6.5 and 6.6.

6.3 THE COURSE STRUCTURE, CONTENT AND STUDY CONTEXT

In most undergraduate physics curriculum, quantum physics courses are often preceded by a modern physics course (along with special relativity), but these are typically rather introductory; the highly abstract and fundamental concepts of quantum mechanics remain largely untouched. In Ethiopian universities, for example, an essential qualitative introduction with some quantitative formalism to fundamental quantum mechanical ideas is given starting from the first year (i.e., starting with a modern physics course) in the Bachelor of Science physics program (see Chapter 1; Section 1.5). In the second- and third-year physics program, basic quantum mechanics and its most important applications are studied in detail. This study focused on student learning of quantum mechanics (Quantum Mechanics I) at a second-year level in Wollo University, Ethiopia. The second-year quantum mechanics course (Quantum Mechanics I) comprise a 45 hours lecture course which builds on the basics of quantum mechanics covered in the first-year Modern Physics topics: blackbody radiation, Planck's hypothesis, the photoelectric effect and Compton scattering. This course is offered in the second semester of a three-semester undergraduate level sequence on the fundamental concepts, mathematical methods and applications of quantum mechanics. The goal of the course is to introduce the students to the fundamental quantum concepts (although some of the concepts should be known from the first-year modern physics course) and to prepare them to use the methods to solve problems. The emphasis of the courses is on conceptual understanding and problem solving. The course consists of two parts with different emphasis. The emphasis of the first part is on purely conceptual understanding and qualitative reasoning (see Figure 6.1). In the second part, the abstract mathematical part, an introduction to the quantum mechanical formalism is given. Below in Figure 6.1, the structure of the Quantum Mechanics I course was summarized. Although, the general philosophy of teaching quantum mechanics courses in the Physics Department at Wollo University is based on the desire to equip students with the basic conceptual understanding and problem solving skills, it has been taught in a predominantly traditional way relying only on passive-student lectures and algorithmic problem exams.

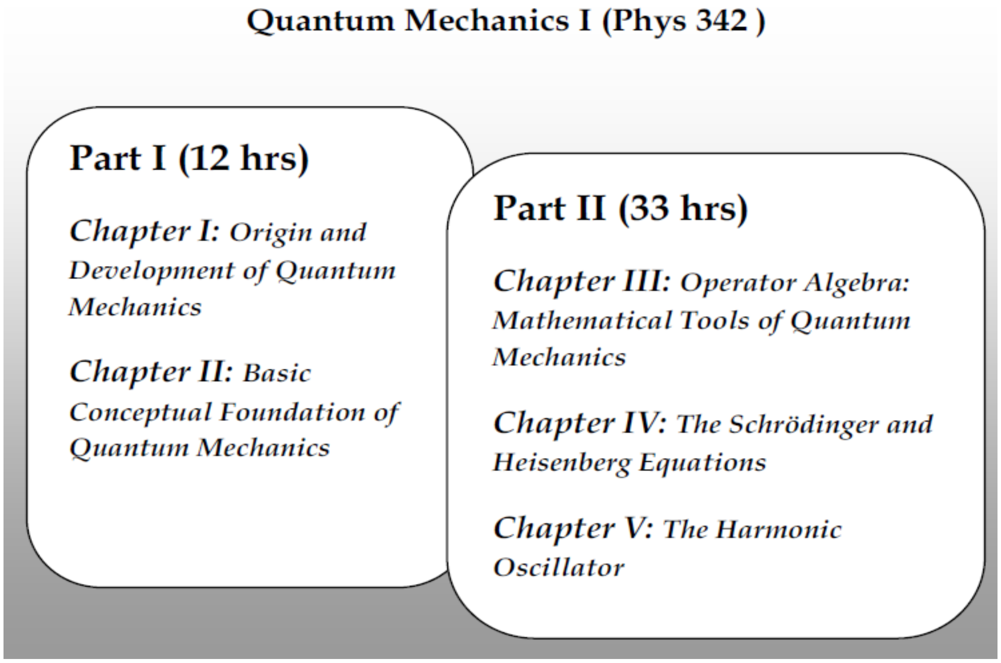


Figure 6.1: Structure of the Quantum Mechanics I course at Wollo University, Ethiopia

Previous findings indicate that quantum mechanics conceptions acquired during traditional instruction are embedded in a conceptual structure incompatible with the contemporary quantum models (Hadzidaki, 2008; Greca & Freire, 2003). These empirical findings overlap with ours in that the usual lecture presentations used in the undergraduate quantum mechanics classroom favor inconsistent learning and fail to provide conceptual understanding in Ethiopian contexts (Ayene et al., 2011; 2013; see also

Chapters 4 & 5). There might be different ways of research-based instructional strategies to teach this course (Quantum Mechanics I) to provide greater conceptual coherence. This part of the study, however, presents the key aspects of the sequence that has contributed to better conceptual coherence and has facilitated deeper learning of the basic quantum concepts by introducing multiple representations of quantum phenomena and in interactive quantum learning tutorials. The participants are all physics majors who enrolled in Quantum Mechanics I course in 2012 academic year at the Department of Physics, Wollo University, Ethiopia. They were all in their second year of study, and they comprised 41 male and 7 females. These students had already completed a Modern Physics course which comprise 45 traditional lecture hours in their first year. In this course, they had been introduced to the fundamental concepts and basic mathematical skills necessary to follow the Quantum Mechanics I course. The instructional design was based on physics education research (e.g., Muller & Wiesner, 2001; Singh, 2008; Pereira et al., 2009; Abdurrahman, 2010) using multiple representations and interactive quantum tutorials. It was designed to address common student difficulties with the basic concepts of quantum mechanics, which were known from previous findings (Ayene et al., 2011; see Chapters 4 and 5). The main content and emphasis of the multiple representations-based instructions complemented with the interactive tutorials were, thus, on the first part of the Quantum Mechanics I course, or basic topics. These topics are mainly emphasizing on conceptual and qualitative reasoning. The details of these basic topics were discussed below in section 6.4.

6.4 EMPHASIS AND SEQUENCE OF THE MULTIPLE REPRESENTSIONS-BASED INSTRUCTIONS AND THE INTERACTIVE QUANTUM TUTORIALS

The purpose of the modified sequence and emphasis in the instructional design were to increase conceptual coherence, give physics students time to develop and master the basic concepts of quantum mechanics, add concreteness, and help students to develop quantum models that facilitate reasoning about microscopic entities. The organization of topics was hierarchical, and the overarching theme of the entire sequence was the formation of standard quantum ontology. The sequence and emphasis was organized into three large segments:

I. **Planck's theory of quantization**
   1. Ultra violet catastrophe;
   2. The quantum rules of quantization of energy.

II. **The photon model of radiation**
   1. Photoelectric and effect and Compton scattering experiment;
   2. Wave-particle behavior of light radiation in the Mach-Zehnder Experiment;
   3. Light quanta interference pattern in the cases of low-intensity photons.
   4. Wave-particle duality of light

III. **Matter waves**
   1. De Broglie hypothesis and the wave particle aspects of matter;
   2. The gradual formation of an interference pattern in the cases of low-intensity electron beams;
   3. Wave-particle duality of microscopic entities;
   4. Uncertainty principle (as a limit to the use of canonically conjugated variables and as an intrinsic property of quantum world, not as a limit of the measurement apparatus or ignorance of the system variables);
   5. Using the concept of quantum probability concepts in explaining microscopic phenomena.

The instructional sequence consisted of three one-hour multimodal lecture demonstrations per week for four weeks, in a conventional physics classrooms, and one hour interactive tutorial per week for four weeks in a virtual laboratory setting. The multiple representations-based instructional sessions made extensive use of pictorial and symbolic representations, static versions of dynamic and interactive visualizations and videos. In all sessions, the majority of class time was occupied by students working together through conceptual questions and the instructor played more of the role of a facilitator who promotes thinking and questioning by leading and focusing the discussion. Thus, in all the instructional sessions the students experienced the basic concepts of quantum mechanics in two consecutive learning phases. In the first learning phase they were provided with symbolic representations and static versions of dynamic and interactive visualizations. In the second learning phase they explored dynamic and interactive visualizations using virtual environments in a guided way tutorial. The detail descriptions of the instructional sequences were outlined below in sections 6.4.1 and 6.4.2.

6.4.1 Instruction Based on Multiple Representations

In the traditional Quantum Mechanics I course sequence, the usual approach to the basic concepts of quantum mechanics and ways of reasoning is to gloss over it, going through the fundamentals at high speed, and spending most of the course on rote problem solving. The ideas of quantization, the photoelectric concept, light quanta interference, duality, matter wave and the uncertainty principle were often presented within the first week of the Quantum Mechanics I course. As an alternative to the traditional setup, a multiple representation- based instructional sequence was developed to provide multiple learning opportunities for students to undergo conceptual change toward constructing a deeper understanding of the basic concepts of quantum mechanics. In each instructional sequence, a quantum concept (e.g., duality) was given or interpreted from multiple perspectives based on different representations of quantum phenomena. The instructional process was further facilitated by the teacher-researcher, who guided the students to create and grapple with the multiple representations, obtain a refine set of representations and thus to gain a better understanding of the basic quantum mechanical concepts and use these concepts to interpret different quantum phenomena. Besides, interactive tutorials, a set of supplements to the multiple representations-based instructions, were developed with more emphasis on the development of conceptual understanding of the basic quantum mechanical concepts. The details of the interactive tutorials were discussed in section 6.4.2.

In general, the main design criterion was to have the instructional sequence as simple and pedagogical as possible while offering the flexibility to vary representations to illustrate several aspects of quantum ideas. Quantum phenomena can be considered as a multimodal construction of understanding because it is usually presented as a figure in which words, pictures, graphs, and mathematical equations are combined and a deep conceptual understanding arises from the contribution of the multiple communicative modes. Looking from this perspective, efforts were given toward the development of instructional sequences that would allow a comparative description of the role played by each mode of representation in the classroom. The design principles were specifically constructed to be consistent with a constructivist theory of learning which facilitated students' articulation and justification of their own representations, clarification of and reflection on their partners' views, and negotiation of new, shared meanings. Furthermore, the multiple representation-based instructional designs were structured to be in accordance with the student's conceptual models so as to engage their prior knowledge and to help the students modify their misconceptions and develop more scientifically accurate understanding. For this purpose, the key sets of sequence of learning design and learning processes developed by Abdurrhaman (2010, p.94) were also adapted and implemented:

1. Evaluating previous concepts
2. Determining the learning objectives in each level for knowing student's conceptual capture
3. Choice of multiple ways to help to the student (verbal, texts, graphs, images, simulation, analogy etc.)
4. Developing activities and interaction (clicker questions, collaborative work, peer works, home work)
5. Integral evaluation: diagnostic, formative and summative.

Besides, to create a constructivist-learning environment and to support deeper conceptual understanding, the instructional sequences progressed from concrete to abstract, built bridges among the various representations used for the same concept. However, the use of the various representations varied for each concept and lesson presented in the instructional sequences. Figure 6.2 and 6.3 present the multiple representations of quantum phenomenon for the photoelectric effect and matter waves (i.e., the gradual formation of an interference pattern in the cases of a low-intensity electron beam) respectively. Furthermore, with the multiple representation sequence, the constructivist instructional environment was established for each quantum concept covered in sessions. For instance, the following sequences were developed for the photoelectric effect:

1. Present different levels of the photoelectric effect concept (physical, textual, pictorial, graphics and equations);
2. Discuss the complexity of this quantum phenomenon (Introduction of the concept of the quantization of light, particle-like properties of light and investigation of interaction between electrons and photons using simulations and analogies)
3. Provide visual models of the experiment (experiment using virtual laboratory)
4. Support collaborative work and interaction with peers and lecturer (including constructing and implementing of clicker questions and homework activities).

This approach helps students to visualize abstract concepts through multiple representations. For example, the concepts of the photoelectric effect were represented in verbal, pictorial, the bar chart (as a physical representation), analogy and simulation and also complimented by mathematical representations (see Figure 6.2). In addition to helping students learn about the basic concept of the photoelectric effect, the multiple representations also teach students how to apply the concept of Einstein’s equation in the photoelectric effect problems. For example, the concept of Einstein’s equation was introduced from a numerically intuitive approach in which tables were used to collect the data and refine them on activities from demonstrated virtual experiments. An explanation was then used to complement what was the relationship among the numbers in the other modes of representation. Finally, to check and ensure that the students understood the issues related to the topic of photoelectric effect, the multimodal instructional sequence also gave students the opportunity to generate their own representation modes, discuss about, work through and solve problems that bear directly on key conceptual issues.

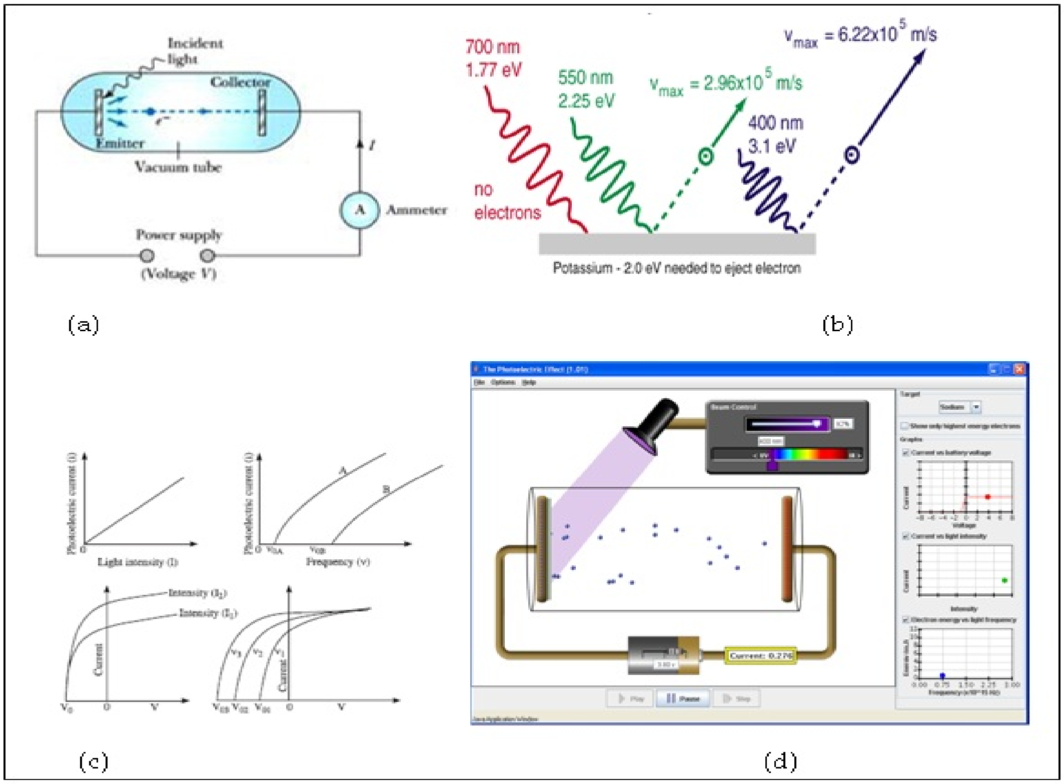


Figure 6.2: Multiple representations of the photoelectric effect (with (a) schematic representation (b) pictorial representation (c) plots depicting the variation of photoelectric current with intensity, frequency and accelerating potential (d) the photoelectric effect simulation)

As discussed above as an example, the usage of representation varied for different quantum concepts presented in the instructional design. It was also varied for the sequences of activities with the same concept. For example, for understanding the concept of matter waves the double-slit experiment was first presented by analogy and contrast with things familiar with the students: performed with bullets, with water waves and electrons. The objective was to organize a representation and depict what would be in that representation using particles, then what students would expect to happen if waves were involved, and finally what happens when there are actually electrons. The analysis of the double-slit experiment considered in this reformed instructional design was more or less taken from Volume III of the Feynman Lectures in Physics. For this reason, sketches or pictures, called a pictorial representation, were used to represent these processes (see Figure 6.3).

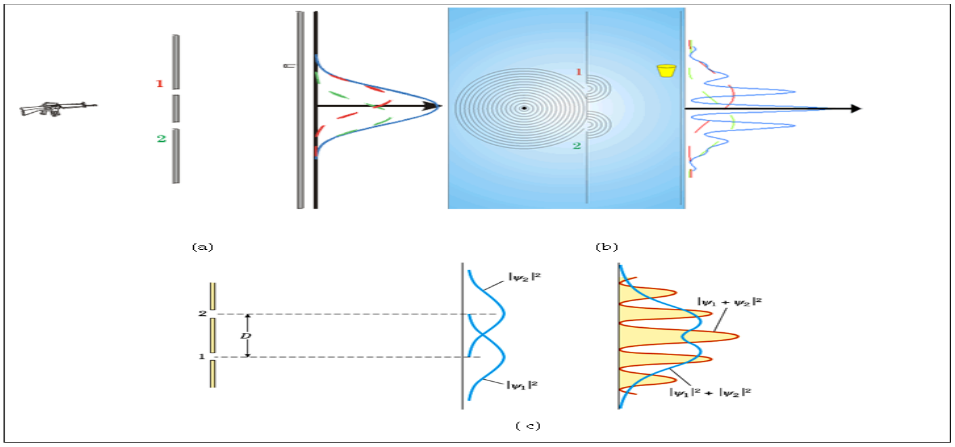


Figure 6.3: The double-slit experiment in pictorial presentations with ((a) bullets (b) water waves and (c) electrons)

In Figure 6.3 (c), students understand that when the double-slit experiment is performed using a mono-energetic electron beam instead of water waves, the electron beam forms an interference pattern on the screen. Next, the process was depicted mathematically by using basic quantum mechanics principles to describe the process. The gradual formation of an interference pattern in the cases of a low-intensity electron beam was then demonstrated in pictorial, images and simulations (see Figure 6.4). Experimental results such as Figure 6.4 show students that the same experiment done using a low-intensity electron beam in time-lapse photography shows that the interference pattern builds up from particle-like impacts on the screen. Figure 6.4 is evidence that electron is a wave in a field an extended real physical entity that comes through both slits and interferes with itself. In other words, Figure 6.4 shows that the matter wave is quantized with quanta that are called electrons. These electrons (i.e. particle-like properties) appear indeterminately on the screen, but with probabilities that are determined by the wave (the probability density is proportional to the squared modulus of the matter wave). These guided visualizations of experimental results help students understand the quantum aspect of these particles is that they are accompanied by a spatially extended wave that comes through both slits and somehow directs the particles to strike the screen in an interference pattern (Hobson, 2005).

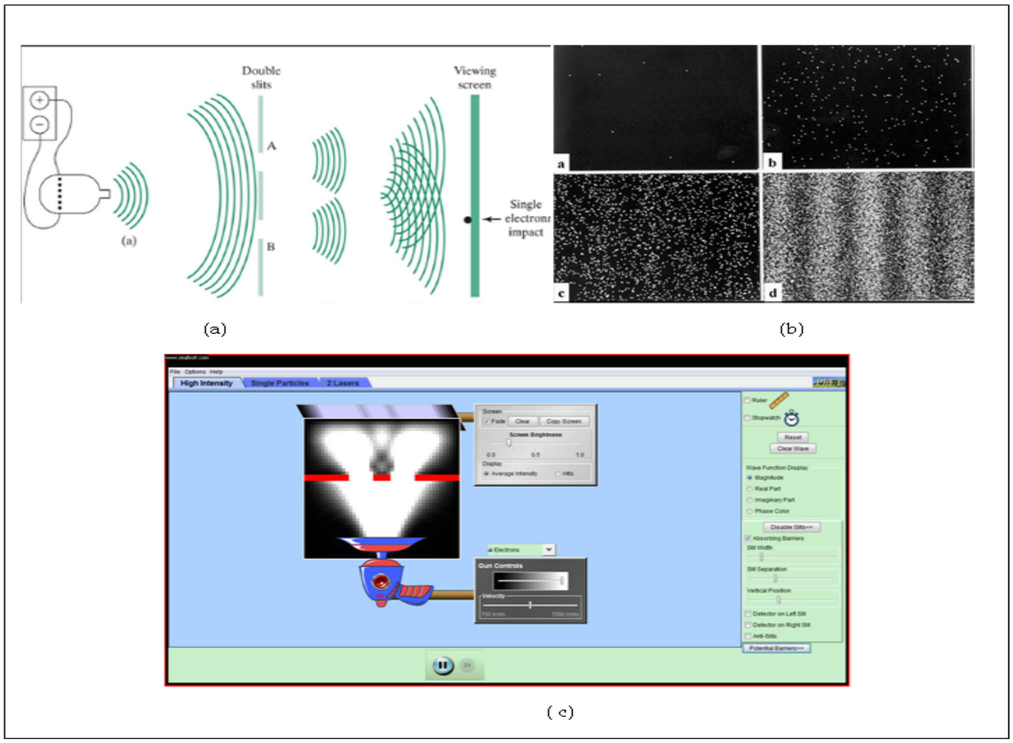


Figure 6.4: The double-slit experiment in the cases of low-intensity electron beam ((a) pictorial (b) images (c) simulation adapted from the Quantum Wave Interference PhET simulation)

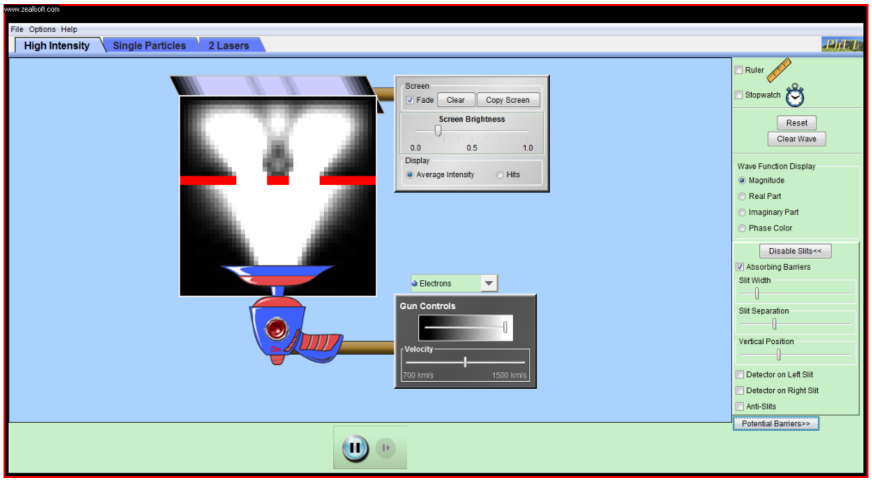
Only after a full discussion of the conceptual fundamentals was students engaged in the quantitative details quantum mechanics related with matter waves. At the end of the lesson, a summary of multiple representations was given to the students about the wave nature of electrons, the importance of the phase of the probability amplitude for the occurrence of the interference pattern, and the connection between having information about which slit an electron went through and the loss of an interference pattern.

As it has been stated in the course description, the instructional sequences for the selected topics consists of three one-hour multiple representations-based lessons per week for four weeks, in a conventional physics classrooms, and one hour interactive tutorial per week for four weeks in a virtual laboratory setting (see section 6.4.2). While the multimodal instructional lessons were implemented in the conventional physics classroom, it was restructured with respect to the condition of that particular lesson. Throughout all the classroom sessions and tutorials, when the students were on the given task, they were provided appropriate feedback on their difficulties and questions.

6.4.2 The Interactive Quantum Learning Tutorials

The interactive quantum learning tutorials are an interactive learning environment that exploits computer-based visualization tools in which students have an opportunity to confront their conceptions, draw qualitative inferences and build links between the formal and conceptual aspects of quantum mechanics (Singh, 2008). As part of the instructional design, in this study, four different computer-based visualization tools from PhET interactive simulation (McKagan et al, 2009; McKagan et al, 2008b) and other sources (e.g., Pereira et al., 2009) were adapted for interactive learning tutorials. These interactive tutorials were given as part of laboratory session to further reinforce students' understanding of the wave- and particle-like properties of quantum entities. They were used both as supplements to the multiple representations-based sessions and as self-study tools. The main concepts covered in the tutorials were among the previously discussed, that is, the photoelectric effect, the double-slit experiment in the cases of low-intensity light and an electron (wave-particle duality) and the photon interference with itself. The four tutorials were used with simulations to teach physics students about the wave– and particle-like properties of quantum entities. The photoelectric effect simulation, adapted in this study, was designed as part of the Physics Education Technology Project (PhET) and is available for free download from the PhET website (McKagan et al., 2009). These simulations allow students to interactively create the graphs commonly found in textbooks, such as current vs. voltage, current vs. intensity, and electron energy vs. frequency (McKagan et al., 2009). In the photoelectric simulation, students compare their theoretical predictions with practical observations, expand the meaning of specific ideas and develop their qualitative reasoning power.

Similarly, the double-slit experiment tutorials used the PhET (Quantum Wave Interference) simulation to teach physics students about the wave –and particle-like properties of quantum entities, the importance of the phase of the probability amplitude for the occurrence of the interference pattern and the connection between having information about which slit a quantum entity went through and the disappearance of the interference pattern (see Figure 6.5).



☑ Fade

● Average Intensity ○ Hits

● Magnitude

○ Real Part

○ Imaginary Part

○ Phase Color

☐ Ruler

☐ Stopwatch

☑ Absorbing Barriers

☐ Detector on Left Slit

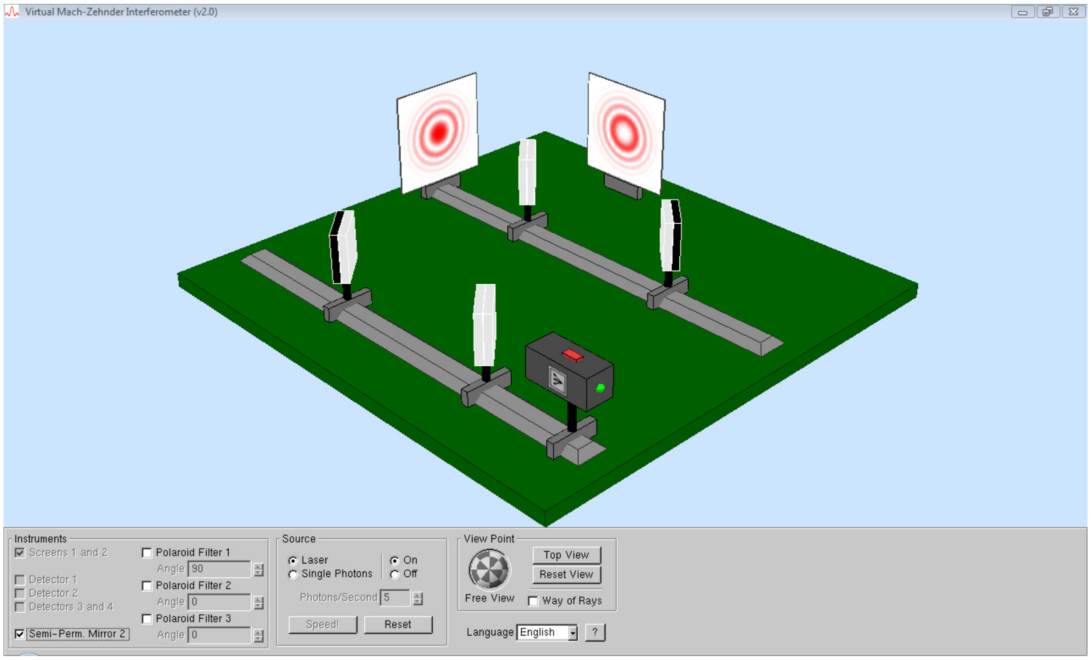
☐ Detector on Right Slit

☐ Anti-Slits

Figure 6.5: The Quantum Wave Interference PhET simulation used in the interactive tutorial sessions

In order to enhance students' understanding of the odd behavior of photons, a computational simulation of the Mach–Zehnder interferometer (developed by Pereira et al (2009)) were also adapted. In general, the interactive tutorials are flexible and are easily adapted to the desired situations. The Mach–Zehnder interferometer simulation-based tutorials are following a learning cycle method in which students involved in the series of activities. Students can explore the basic concepts through facilitated questions, observation and explain what they have learned with the teacher-researcher facilitating discussion to refine their understanding (Singh, 2008). Each tutorial requires students to involve in three basic tasks: to make predictions and justifications about what and why they expect a certain outcome in a particular situation before exploring the relevant concepts with the simulations; then to observe attentively the scientific phenomena using simulations; and finally to compare their observations with predictions and to explain the observations with their own knowledge. At this third stage, it was designed that the tutorials provide them proper guidance to help construct an expert-like understanding of the concepts and reconcile the mismatch between their predictions and observations. The interactive tutorial arrangement of the virtual Mach–Zehnder interferometer experiment can help students to glimpse the conceptual problem of the photon's path choice, which can highlight the notion that quantum objects and classical particles have quite different behaviors.

Below, an example of an interactive tutorial based on the use of the virtual Mach–Zehnder interferometer that followed a prediction, observation and explanation strategy is presented. For illustrating the sequence of activity, a screen shot from the virtual experiment was shown in Figure 6.6.



☑ Screens 1 and 2
☐ Detector 1
☐ Detector 2
☐ Detectors 3 and 4
☑ Semi-Perm. Mirror 2
☐ Polaroid Filter 1
Angle 90
☐ Polaroid Filter 2
Angle 0
☐ Polaroid Filter 3
Angle 0
● Laser
○ Single Photons
● On
○ Off
Photons/Second 5
☐ Way of Rays
Language English

Figure 6.6: A screen shot of the Mach–Zehnder interferometer simulation

Below, an interactive tutorial session based on the virtual Mach–Zehnder interferometer was presented. A short guide and clicker questions were written to direct the students throughout the tasks. Given this context, the students were organized in groups of three and were prompted to engage in a continuous collaborative interactional process throughout the tutorial, which required the negotiation of ideas and practices among them. In order to make the odd behavior of photons a little more intuitive to the students, an analogy between with single photons and with laser beam virtual experiments were adapted. First, by doing the experiment with the laser beams, students were provided which beam splitter is responsible for the interference pattern formed by the two laser components. Students were then asked to first make predictions about the experiment with single photons (quantum mode) and why they expect a certain outcome before exploring the idea with the simulations. After predicting what they expect in this situation, students were asked to check their predictions using simulations. That is, by selecting the single-photon option, the students changed the second beam splitter and replaced both screens by photon detectors and then interpreted the phenomenon shown in Figure 6.7 (a).

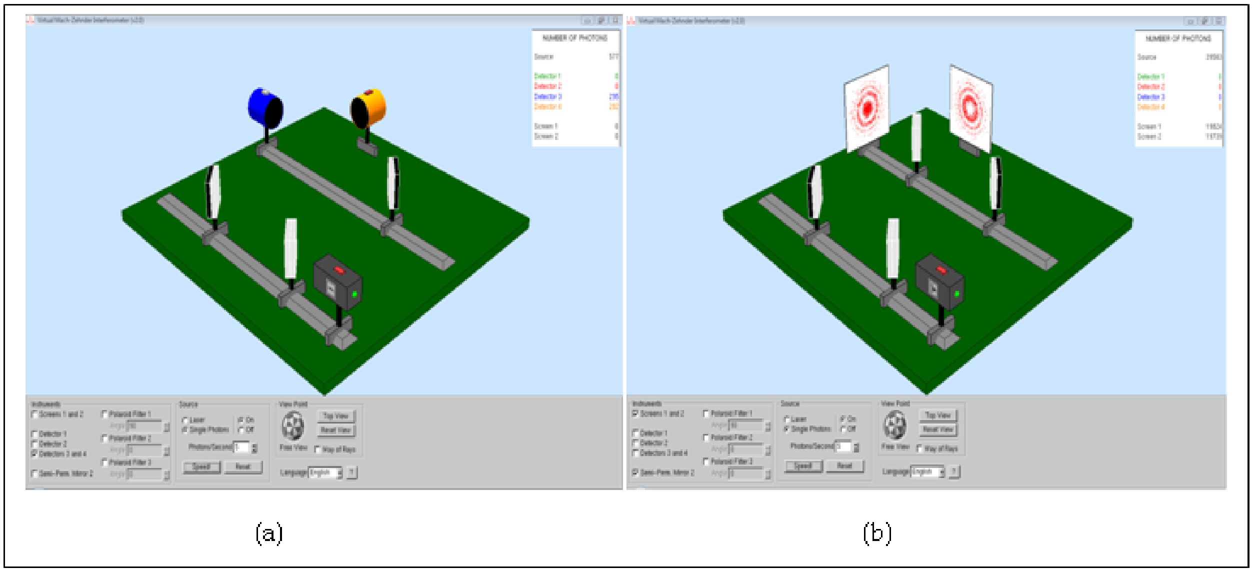

(a) (b)

Figure 6.7: The virtual Mach–Zehnder interferometer ((a) No photon is visible (b) Quantum interference with single photons)

Next, students replaced the second beam splitter and for the second time they replaced the photon detectors by screens, as in Figure 6.7 (b). They obtained, for single photons, the same interference pattern as was previously observed when using the laser beam. The phenomena observed in the sequences of activities have shown the photon's odd behavior, avoiding the misconception in which quantum objects are seen as classical particles. To observe these phenomena in the virtual simulation, in general, implies to observe one of the fundamental properties of quantum world. The sequence of phenomenon (e.g., Figure 6.7 (b)) observed in the interactive tutorial could then ascertain the students that a single photon can interfere with itself and produce an interference pattern after it passes through both paths of the Mach–Zehnder interferometer.

6.5 METHODS AND PROCEDURES FOR DATA COLLECTION

There is a growing consensus across PER that traditional quantitative probing instruments are insufficient for producing a sufficiently refined description of both what students understand and how they build and revise that knowledge. For example, advanced level quantum mechanics students who excel at quantitative assessment tools and at solving mathematical problems are often unable to answer qualitative versions of the same questions (Singh et al., 2006). As a result, in order to have refined descriptions of student conceptual frameworks, researchers have turned to more descriptive tools, such as semi-structured interviews, open-ended questionnaires and concept maps in which students are asked to describe, explain and depict their understanding in their own words, diagrams, pictures and/or apply that understanding in selected activities (Good, 2005; Driver & Easley, 1978). Researchers claim that such interpretive tools provide much more detailed snapshots not only of what students know, but also what they conceptually understand (Smith, Blakeslee, & Anderson, 1993). According to Good (2005), carefully structured questionnaires, mainly using prediction as a common strategy, can reveal the nature of the student's (mis)conception, and in the process help both student and researchers see the source(s) of the learning problem and/or the progress of conceptual understanding. With a focus on changes in students' conceptual understanding over a term, progress in student learning toward a target level of understanding of the basic quantum concepts was the objective of this study. A thoroughly refined conceptual survey questionnaire targeting students' quantum (mis)conceptions is a central feature of the data collection tool used in this part of the study (see section 6.5.1).

6.5.1 Open-ended Quantum Mechanics Conceptual Survey Questionnaire

The open-ended questionnaire, entitled the Quantum Mechanics Conceptual Survey Questionnaire (QMCSQ), was primarily derived from our previous probing tools, the semi-structured quantum mechanics interview questions (Ayene et al., 2011; Ayene et al., 2013); and also from the Quantum Mechanics Conceptual Survey (QMCS) by McKagan et al

(2010), the Quantum Mechanics Concept Inventory (QMCI) (Falk, 2004) and the Quantum Physics Conceptual Survey (QPCS) (Wuttiprom et al., 2009). In the QMCSQ all utilized activities were rewritten with respect to the purpose of the current study. However, unlike the above surveys, prediction questions were the central emphasis in the QMCSQ as a powerful pedagogical tool and in identifying it as one of the keys defining characteristics of the questions. Prediction questions require students to anticipate an outcome of a situation and explain or justify that prediction. The strength of this kind of questionnaire is that it focuses on the ways students apply their personal meanings of the concept. Unlike questions about instances, which require students to explain a concept, prediction questions emphasize the application of that particular conceptual understanding. And because they require application, prediction questions are the central emphasis in QMCSQ. The final full sets of questions of the open-ended QMCSQ were given in Appendix IV.

Design and validation of a standardized conceptual survey questionnaire needs an independent research and in-depth statistical analysis. However, the major aim of this study was not to design a general and standardized quantum mechanics survey instrument that could be used to measure different curricula in different contexts. The study carried out here focused on a few definite and limited activities. Thus, the open-ended QMCSQ was intended to be used to investigate these purposes. However, during the design phase of the QMCSQ, in order to establish the content validity, credibility and applicability, the researcher went through several iterations of the questionnaire with the science faculty members and quantum physics instructors. For example, the draft QMCSQ was administered to 25 physics students at various levels (i.e., ranging from beginning undergraduates taking only a modern physics course to senior undergraduates taking three consecutive quantum physics courses) at Wollo and Bahir Dar Universities. The groups of students were five beginning undergraduates (from Wollo University), fifteen second year students (ten from Wollo and another five from Bahir Dar Universities) and the final five senior undergraduates from Wollo University. The students were asked to complete the first draft of the questionnaire and to give feedback on the appropriateness of the questions, wordings, relevance to mainly introductory quantum physics, ambiguity in question wording and other structural difficulties. After administering the questionnaire, there was an in-depth discussion in the physics laboratory, followed by individual discussions with interested students. The results from students' responses were used for further refinement. The content validity of the questionnaire was also established by a panel of experts, including two physics education researchers and three quantum physics lectures. Based on the comments from the instructors and discussions with the students, the questionnaire was further modified before being administered to the students in the actual study.

In the main study, the QMCSQ questionnaire was administered to the participants at three different occasions: First, it was administered two days before starting the implementation of the instructional interventions. The purpose of administering the prêt-instruction questionnaire was to identify students' preexisting understanding about aspects of the basic quantum concepts. Secondly, the QMCSQ was administered twice and served as post-instruction: first, five days after completion of the reformed instructional interventions to assess the change in students' understanding of the quantum concepts; and second, seven weeks after administering the post-instruction to examine to what extent students retained what they learned about the basic quantum mechanical concepts.

Interviews

After analyzing the post-questionnaire responses, fifteen students were chosen for further in-depth interviews to better understand their way of thinking and to confirm their responses on the posttest. Students were chosen to elicit their understanding of the given phenomena based on the following: those whose responses displayed largely formal descriptions of the quantum phenomena and entities; whose responses displayed synthetic and hybrid descriptions of the quantum phenomena. The choice was also dependent on getting participants who are willing to engage in discussion around the envisaged content of the interview. Researchers claim that the purpose of an in-depth interview is to reveal a person's understanding or conception of a particular phenomenon and to explore what is in and on someone else's thinking, point of view and/or mentality (Patton, 2002; Åkerlind, 2005). Students were asked the same prediction questions as on the post-questionnaire during the interviews, and when needed, students' ideas were probed using follow-up questions.

6.6 DATA ANALYSIS

6.6.1 Data Analysis Phase I: Collective Categorization of Students' Conceptual Understanding

This questionnaire data was collected three times during the entire period. Once at the beginning of the reformed instructional design, a second time at the end of the intervention and a third time after seven weeks since the end of the reformed instructional design. In all cases, students' written responses to the QMCSQ were copied, and the figures that they drew as part of their responses were also scanned to be able to easily read, code and organize. The interviews were also transcribed. All students' responses were explored in detail to identify, categorize, and characterize the types of depictions of quantum concepts. This was done by reading, rereading, and coding the dimension of description in order to identify the participants' types of conceptual understanding of the concepts under investigation. Thus, in the interpretative analysis, ideas of students' conceptual patterns were constituted with two focuses for analysis carried out iteratively. Initially, the focuses were at the collective level, considering the whole of all the QMCSQ responses: mainly qualitative analysis was used to constitute categories of conceptual understanding of quantum mechanical concepts, with an interest on the key aspects which varied between ways of understandings. The focus of analysis at individual level was to consider individual responses and sets of all responses from each student in relation to the categories of conceptual understanding constituted at a collective level (the details were given in section 6.6.3).

The actual analysis was done by looking for all the extracts from the written explanations and drawings and also the interview transcripts that was relevant to the research perspective. This was done by assigning descriptive figures, subsets of descriptions, words or phrases to each unit of explanation notes. In qualitative analysis this process is referred to as coding the dimension of description. Essentially, coding begins the process of selecting what is meaningful from the rest of the extracted data. This helps to look for what is significant and how to make relationships and create description patterns. Therefore, coding gives a set of dimensions through which qualitative data can be treated in a given situation. In the preliminary analysis process, words and phrases were grouped into relevant themes which represented the meaning and the general understanding (i.e., students' types of conceptual understanding) from the data. After coding the dimensions of description and clustering of the data from the students' pre-instruction responses, the data collected from the posttest were analyzed. The same process was repeated for the data analysis of the post-instruction. Participants' responses to the QMCSQ on the post-instruction were explored and new codes of description and relevant themes were identified and recorded on the coding sheet and integrated into the coding scheme constructed in the pre-instruction. Similarly, the same procedure was repeated for the interview data and the participants' written responses to the delayed post-instruction.

The next step in the analysis process was a more in-depth and refined analysis of the emerging subsets of description, coded line of descriptions and themes. Therefore, the most distinctive characteristics of each subset of depictions, codes and themes, illustrating qualitatively different ways of conceptualizing the phenomena under investigation were identified. That is, the tentative subsets of description, codes and themes were carefully described in terms of their variations and then in terms of their defining qualities. Thus, at this stage, meaningful variation began to emerge between different subsets of description, codes and themes. This process helped to form the initial set of categories of conceptual understanding which represented the variations in physics students' initial depictions of the basic quantum concepts. Once this initial categorization was complete, an outcome space was constructed that incorporated the least number of categories of conceptual understanding which explained all the variations in the data. With these categories of conceptual understanding in mind all the written explanations and drawings to the QMCSQ on the pre-instruction, post-instruction and delayed post-instruction and on the interview combined were reexamined, to determine if the categories were sufficiently descriptive and indicative of the collective sets of data. This iterative data analysis procedure was also consistent with the phenomenographic approach, as Marton (1981) states that "definition for categories are tested against the whole data, adjusted, retested, and adjusted again."(p. 43) Iteration between the processes described above continued until the final categories had been established. In this study, the process of analyzing and constituting the categories of description of students' depictions and variations in quantum mechanics conceptual awareness took place over six months often with rather substantial breaks in between. Although a few of these breaks were forced due to extra work load, most of the breaks were an intentional respite from the analysis. The intention was that this strengthened the analysis because it effectively served as 'a fresh perspectives' with which to view the data. Five types of categories of students' conceptual understanding about the basic quantum mechanical concepts were constructed (see Table 6.1).

6.6.2 Categories of Students' Conceptual Understanding

The analysis generated five main categories of description (i.e., conceptual understanding), which can be interpreted in terms of students' depictions of quantum phenomena, range from Non-scientific to Quantum Thinking/Descriptive Models:

I. Non-scientific
II. Classical intuitive descriptive model
III. Synthetic/blurred descriptive model
IV. Mixed thinking Descriptive model
V. Quantum thinking/descriptive model

The categories of conceptual understanding were the collective reflection of answers from the students' responses to the QMCSQ at the three data collection points. A representation of the five categories of students' conceptual understanding along with their key dimensions of interpretation was presented below in Table 6.1. The main focus of the table was to portray which of the key dimensions of description were used in constructing each category of conceptual understanding.

Table 6.1: Categories of students' conceptual understanding of the basics of quantum mechanical concepts

Categories of Description	**Key Dimensions of Interpretation and/or Facets of Understanding**
Non-scientific	Irrelevant answers with no clear scientific evidence Descriptions impossible to characterize in any scientific way Undifferentiated description of quantum phenomena driven by everyday language Duality as light can be changed into matter and vise verse Devoid of substance or meaning about the wave- and particle-like properties of quantum entities Uncertainty principle is discerned as the quality or state of being undecided
Classical Intuitive	All objects are depicted either as a particle or as a wave as if they are mutually exclusive Visualizing particle as a billiard ball which carries energy and momentum Wave characteristics are described as a simple disturbance Measurement can be serve as basis for predictions the precise state of an atomic object Electron moves along a well- defined trajectory Uncertainty is the error caused by technological limitations and also associated to deficiencies of measuring instruments
Synthetic/Blurred Descriptive Model	Electrons are moving in a wave-shaped trajectory Light consists of two properties; a wave and particles A photon is a particle of light described by its localized position and its momentum Electrons are either waves or particles depending on experiment and observation The interference pattern builds up from particle-like impacts on the screen and it is an outcome of a juxtaposition of two separate interference patterns There are hidden variables that could specify a particle's position between localizations Motion by quantum entities is just like that of the classical picture of the path of a massive particle—like a marble—moving in space-time Position and momentum cannot simultaneously be measured with precision, because each one is separately not measured
Mixed Thinking	Light is a wave in a field-an extended entity and behaves like a classical particle when it is detected

Categories of Description	Key Dimensions of Interpretation and/or Facets of Understanding
	The interpretation of light as speeding bullets of energy (photons) Photon is described by a delocalized probability wave that instantly collapsed down to a classical particle when interacting with a detector The momentum of a photon and other massive microscopic objects with the wave nature is expressed as $h/\lambda \ and \ h\nu/c$ equivalently Uncertainty principle is associated to irregular properties of the particle's trajectory Interference is depicted to be a result of the repeated occurrence of hits on the screen and interaction between them The conception of trajectory is intermixed with probability and randomness
Quantum Thinking	Electrons are quanta of a continuous matter field The interference pattern builds up from particle-like impacts on the screen, indicating that light is made of particles The probability is proportional to the squared modulus of the matter field The paths an electron follows from one point to the other cannot be sketched Uncertainty is a concept about the standard deviations of momentum and position, not about individual measurements Identical conditions lead to different, and thus unpredictable, outcomes The measurement cannot serve as basis for predictions the precise state of an atomic object A photon is perceived as a field-extended entity that comes through both slits and obeying the superposition principle Particle-like behavior of electrons are associated with localized detections on the screen

Non-scientific descriptive model: This category is broadly defined to mean that students' explanations and reasoning were not based on any type of scientific understanding. Students often used isolated, undifferentiated, non-scientific and wrong terminology and metaphors in making explanations related to the concepts of quantum mechanics. In this category, the acquired understanding of quantum phenomena, in general, reflected insufficient explanatory power, undifferentiated description driven by everyday language and were inconsistent with the principles taught in any previous physics courses.

Classical intuitive descriptive model: It is characterized by, for example, [Matter is to be made of discrete particles while light (or electromagnetic radiation in general) is to be purely a classical wave phenomenon] and [The uncertainty principle is the state of being unsure about things (i.e., classical ignorance) or an error resulting from inaccuracies of the measurement process]. In this category, the behavior of light is depicted purely with reference to simple wave phenomena (such as, a disturbance, an extended object, a diffusing of object in space and time which has wavelengths and frequencies interference, diffraction and emission). On the other hand, students were depicting the particle-like properties that quantum entities (i.e., electrons) could show, mentioning the fact that electrons have some defining classical properties (e.g. as localized, compact, hard, and massive objects that carry charge, energy and momentum). In this category, since the idea of a particle as being localized, compact and hard was at the core of students' conceptual understanding, the concept of trajectory is heavily depicted just like that of classical picture of the path of a massive particle moving in space-time.

Synthetic/blurred descriptive model: This category is appeared to use distorted quantum worldview to visualize quantum phenomena. As with classical intuitive description, a significant part of a synthetic model category is dominated by a classical and intuitive interpretation of quantum phenomena. However, the nature of this category was not necessarily of the character we had anticipated from the classical intuitive model category. It subtly maintained the dominance of the particle aspect of matter, in spite of the fact that the wave nature of matter was recognized and loosely presented for depicting the properties of quantum entities. Students' responses in this category did not capture the true picture of the wave- and particle-like properties of quantum entities beyond stating that the duality for matter and radiation can be thought of in the same way as classical waves and particles. It is thus appeared to be slightly different from the pure classical intuitive description one. Or it can also be seen as a special case of a mixed model state despite the fact that it is characterized by lower levels of complexity and sophistication.

Mixed Thinking/Descriptive Model: Unlike the three previous description categories, in this category, the general level of students' depictions of the basic concepts- wave-particle duality, uncertainty principle and probabilities were somewhat following the quantum views of reasoning. The wave-like properties of quantum entities were understood by the students in this category. Students took things even further by suggesting that this wave-particle duality is not restricted to microscopic entities, but must be universal: all matter should also display dual wave-particle properties. However, students in this category were still struggling with the notion of abandoning 'the mechanistic-deterministic framework of classical physics.' For example, the mixing of quantum uncertainty with disturbance of measurement (statistical interpretation) is found in this category of responses. Although conceptual conflicts are remained in this category, the quantum worldview with classical ingredients were continued to dominate students' thinking about the nature of quantum phenomena.

Quantum thinking/descriptive model: Students' responses in this category have illustrated a deep understanding of the wave- and particle-like properties of quantum entities. For example, photons and electrons are seen as non-localized or extended entities obeying the linear superposition principle. Particle-like properties of quantum entities is assigned to observed interaction events that lead to changes in the state of the quantum system. It appeared that students have obtained a deep understanding that quantum objects have no fixed properties. Students' responses illustrated that the attempt to observe the electron's trajectory in the double-slit experiment violently disrupts it. Quantum mechanically the concept of a particle trajectory includes two basic ideas: that of position and that of the rate of change of position or the velocity. Indeed, students in this category identified how the uncertainty principle connects these two. They explained that the precise specification of an electron trajectory depends upon the simultaneous specification of both position and momentum of an electron, and this is forbidden. Their argument was that quantum mechanics radically alters the way we must think about the microscopic world, for in classical physics we are, of course, accustomed to thinking of the trajectories of macroscopic objects through space. In general, in this category of description, students' explanations illustrated that they have developed a meaningful conceptual understanding of quantum mechanics.

6.6.3 Data Analysis Phase II: Exploring Change in Students' Conceptual Pathways

The principal focus of analysis at this second stage was at individual level, considering individual responses and sets of all responses from each student, in relation to the categories of conceptual understanding constituted at a collective level. Individual student ways of understanding the basic quantum mechanical concepts in each of their responses were compared to the categories constituted at a collective level, with the purpose of identifying whether their understanding of quantum concepts had changed over time as a result of the intervention. The emphasis was on whether there was evidences of conceptual change, for example from an intuitive, deterministic classical ontology- to quantum model-based ways of understanding across the set of three data collection points from each physics student.

A process of constant comparison analysis, focusing from different perspective underpinned by qualitative approach was adopted. The constant comparative analysis is a method of analyzing qualitative data where the information gathered is coded into emergent features of themes or codes of description. The data was constantly revisited after initial coding, until it was clear that no new features of understanding were emerging (Adadan et al., 2010). Individual questionnaire responses across three data collection points from each physics student were explored separately to identify, characterize and code the types of depictions each physics student has about the quantum phenomena under investigation before, after, and seven weeks after the reformed instruction. Using the written responses to the QMCSQ a 'student depiction map' was constructed of each pre-, post- and delay post-instruction responses. Thus, each physics student was assigned a type of depiction map or codes of depictions before, after, and seven weeks after the reformed instructional intervention. Individual student ways of conceptual understanding on the pre-, post- and delayed post-instruction were compared to the five categories of description, with the purpose of identifying whether their conceptual understanding had changed over time as a result of the instructional intervention. Then, the categories of description for each physics student were compared across the three data collection points to identify the conceptual pathways that individual physics student pursued from the beginning to the end of the study.

Furthermore, in order to address the first problem (i.e., exploring whether physics students' conceptual understanding or ways of depicting quantum concepts had changed over time as a result of the instructional intervention), the frequency of students' types of conceptual understanding at three data collection points was identified. To determine if there was any statistically significant difference across these data collection points in terms of students' conceptual understanding over time, the Sign test statistics was chosen to analyze the numeric data that could be obtained in the study. For example, to generate a numeric data and run the Sign test statistics, students' types of depictions that were identified in the qualitative analysis were quantified as zero (0) for Non-scientific Descriptive Model, one (1) for Classical Intuitive Model, two (2) for Synthetic/Blurred Descriptive Model, three (3) for Mixed Thinking/Descriptive Model and finally four (4) for Quantum Thinking/Descriptive Model. These numerical values were assigned for the types of quantum mechanics conceptual understanding displayed by the students on the pre-, post-, and the delayed post-instruction. Adadan et al. (2010) claimed that the traditions for the Sign test statistics were gratified with having one variable, one sample, and independent observations. According to Adadan et al (2010), nonparametric statistics of the Sign test was employed for the paired categories of conceptual understanding (pre–post and post–delayed post). For depicting the patterns of students' conceptual pathways, student nature of conceptual understanding was compared across the three data collection points to identify the patterns of their conceptual pathways. The nature of categories of conceptual understanding were considered to be on a continuum from the lower category (Non-scientific) to the highest category (Quantum Thinking), and the degree of progression/regression/no change each student has shown on this continuum from pre- to post-instruction and from post to seven weeks after the instruction portrayed the pattern of student conceptual pathway.

6.7 RESULTS AND FINDINGS

This section consists of mainly two parts and follows the research questions. To answer the first question of whether physics students' understanding of the basic concepts of quantum mechanics differ, the first part presents a short statistical results regarding physics students' conceptual understanding before, after and seven weeks after completion of the reformed instructional sessions. The second part then describes the main findings of the qualitative data analysis, which indicate possible explanations of students' conceptual learning patterns from pre- to post-instruction and from post to seven weeks after completion of the reformed instructional sessions.

6.8 STUDENTS' TYPES OF CONCEPTUAL UNDERSTANDING

6.8.1 Students' Prior Understanding of Quantum Mechanics

The most common conceptual understanding of quantum concepts found in the undergraduate physics students before the instructional units on conceptual topics of quantum mechanics were grouped into the first four set of categories. That is, the majority of students' conceptual understanding of the basic concepts quantum mechanics was characterized as non-scientific, classical and a synthetic mixture of classical ideas with quantum fragments before they entered the instruction. Thus, 16.67% of the students' conceptual understanding demonstrated the features of the types of conceptual understanding that mostly included nonscientific descriptive model. The majority of students (56.25%) exhibited classically inappropriate depictions of aspects of the quantum mechanical concepts so that their conceptual understanding was categorized as classical intuitive model description. These students often used this classical model of description to construct mental models of the quantum phenomena. Table 6.2 summarized students' types of conceptual understanding before the instructional interventions with specific notes that indicate the key aspects of understand held to discern the basic quantum concepts.

Table 6.2: Students' types of conceptual understanding prior to the instructional intervention

Category of Conceptual Understanding	**Frequency and Name of Students Expressing this Understanding**	**Key Facets of Understanding**
Non-scientific	**8 (16.67%)** **S_4 ; S_8 ; S_{10} ; S_{11} ; S_{14}; S_{20} ; S_{35} ; S_{39};**	Irrelevant answers with no clear scientific evidence Descriptions impossible to characterize in any scientific ways Undifferentiated description of quantum phenomena driven by everyday language
Classical Intuitive	**27 (56.25%)** **S_1 ; S_3 ; S_5; S_6; S_9 ; S_{13} ; S_{17}; S_{19}; S_{21}; S_{23} ; S_{24} ; S_{25} ; S_{26} ; S_{27} ; S_{28} ; S_{30}; S_{31}; S_{32}; S_{33}; S_{34}; S_{38} ; S_{41}; S_{42} ; S_{44} ; S_{45} ; S_{46} ;S_{48}**	All objects either as a particle or as a wave as if they are mutually exclusive Visualizing particle as a billiard ball which carries energy and momentum Wave characteristics are described as a simple disturbance Electron's energy is a continuous function of its velocity
Synthetic	**12 (25%)** **S_2; S_7; S_{12} ; S_{15}; S_{16} ; S_{18} S_{22} ; S_{29} ; S_{36}; S_{37}; S_{43} ; S_{47}**	Electrons are moving in a wave-shaped trajectory Light consists of two properties; a wave part and particles Photons are waves moving vaguely like solid objects Photons and/or electrons are particles that travel in classical waves
Mixed Thinking	**S_{40}**	Light is a wave in a field-an extended entity and behaves like a classical particle when it is detected The interpretation of light as speeding bullets of energy (photons) The momentum of a photon and other massive microscopic objects with the wave nature is expressed as h/λ *and* $h\nu/c$ equivalently Uncertainty principle is associated to irregular properties of the particle's trajectory

The remaining 25% of the students held a synthetic model of description about the aspects of the quantum phenomena. These students' dominantly held elements of classical mechanistic ideas about the aspects of the quantum phenomena, but with fragments of quantum ideas of the basic concepts of quantum mechanics within their conceptual understanding. For only one physics student quantum phenomena were dominantly understood from quantum formalism but still included fragments of classical mechanistic ideas of the basic concepts of quantum mechanics within their conceptual understanding.

6.8.2 Students' Understanding of Quantum Mechanics after the Multiple Representations-based Instructions and Interactive Tutorials

In general, after the multiple representations-based instructions and interactive learning tutorials, almost all physics students (97.9%) progressed to the type of understanding that was at least one category advanced from their previous types of conceptual understanding. That is, students made clear progress toward a scientific understanding after their involvement in the multiple representations-based instructions and interactive tutorials. Immediately after the instructions, 72.92% of the students progressed toward the targeted conceptual understanding of quantum model of description. Additionally, 25% of the students' conceptual understanding was identified to be a mixture of quantum model understanding with classical fragments. These students actually had both the quantum and classical models of description. This mixed model, however incomplete, can provide the students some rational conceptual understanding for the quantum mechanical system they were dealing with. Table 4 summarizes the frequency of students' type of conceptual understanding immediately after the instruction.

Table 6.3: Students' types of conceptual understanding immediately after the instructional intervention

Categories of Conceptual Understanding	**Frequency and Name of Students Expressing this Understanding**	**Key Facets of Understanding**
Synthetic	**S_{16}**	Electrons are moving in a wave-shaped trajectory Light consists of two properties; a wave part

Categories of Conceptual Understanding	Frequency and Name of Students Expressing this Understanding	Key Facets of Understanding
		and particles Photons are waves moving vaguely like solid objects Photons and/or electrons are particles that travel in classical waves Electrons are either waves or particles depending on experiment and observation
Mixed Thinking	**12(25%)** **S_{14} , S_{39} , S_3 ; S_5; S_{24} ; S_{28} ; S_{30}; S_{38} ; S_{46} ; S_{48}; S_{15}; S_{29} ;**	Light is a wave in a field-an extended entity and behaves like a classical particle when it is detected The interpretation of light as speeding bullets of energy (photons) Uncertainty principle is associated to irregular properties of the particle's trajectory
Quantum Thinking	**35(79.92%)** **S_4 ; S_8 ; S_{10} ; S_{11} ; S_{20}; S_{35};S_1 ; S_6; S_9 ; S_{13} ; S_{17}; S_{19}; S_{21}; S_{23} ; S_{25} ; S_{26} ; S_{27} ; S_{31}; S_{32}; S_{33}; S_{34}; S_{41}; S_{42} ; S_{44} ; S_{45} ; S_2; S_7; S_{12} ; S_{18} S_{22} ; S_{36} ; S_{37}; S_{43} ; S_{47} ; S_{40}**	Electrons are quanta of a continuous matter field The probability is proportional to the squared modulus of the matter field The paths an electron follows from one point to the other cannot be sketched Uncertainty is a concept about the standard deviations of momentum and position, not about individual measurements Identical conditions lead to different, and thus unpredictable, outcomes The measurement cannot serve as basis for predictions the precise state of an atomic object

Only one student conceptual understanding persistently showed dominantly the components of the classical description with quantum fragments in many aspects of the quantum phenomena and met the criteria set for the category of synthetic descriptive model. No student's conceptual understanding was classified as either classical intuitive model description or non-scientific and naive understanding of quantum mechanics following the multimodal instruction and the interactive quantum learning tutorials.

6.8.3 Students' Understanding of Quantum Mechanics Seven Weeks after Instruction

As can be seen in Table 6.3, shortly after the reformed instructional intervention, there was a noticeable rise in the number of students with a reasonable conceptual understanding of the basic concepts of quantum mechanics. Eventually, seven-weeks after the instructional intervention, individual student's questionnaire responses were related to the categories of conceptual understanding constructed at a collective level. Seven-weeks after the instruction, 58.33% of the students still held an appropriate conceptual understanding of the basic concepts of quantum mechanics (see Table 6.4). In other words, many of the students were still retaining much of what they have learned about the aspects of quantum mechanics seven weeks after instruction. In a more specific sense, 28 (58.33%) students were identified as quantum model, 16 (33.33%) students as mixed model and 4 (8.33%) students as synthetic/blurred model description.

Table 6.4: Students' types of conceptual understanding seven-weeks after the instructional intervention

Categories of Conceptual Understanding	**Frequency and Name of Students Expressing this Understanding**
Synthetic/Blurred Descriptive Model	**4 (8.33%)** **S_{16} ;S_{39}; S_{30}; S_{38}**
Mixed Thinking	**16 (33.33%)** **S_{14}; S_{8} ; S_{11} ;S_{3} ; S_{5}; S_{24} ; S_{28} ; S_{46} ; S_{48}; S_{13}; S_{25} ; S_{32}; S_{42} S_{15}; S_{29} ; S_{2};**
Quantum Thinking	**(58.33%)** **S_{4} ; S_{10} ; S_{20}; S_{35} ; S_{1} ; S_{6}; S_{9}; ; S_{17}; S_{19}; S_{21}; S_{23} ; S_{26} ; S_{27}; S_{31}; S_{33}; S_{34}; S_{41}; ; S_{44} ; S_{45};**

Categories of Conceptual Understanding	**Frequency and Name of Students Expressing this Understanding**
	S_7; S_{12} ; S_{18} S_{22} ; S_{36} ; S_{37}; S_{43} ; S_{47} ,S_{40}

Still no student conceptual understanding was classified as either purely classical intuitive model description or non-scientific and naive understanding of the basics of quantum mechanics. Seven students' ways of depicting the basics of quantum mechanics were interpreted as changing from quantum model into mixed model description in relation to one or more of their explanation contexts. For example, students (number S_8 , S_{11} , S_{13} , S_{25} , S_{32} , S_{42} , S_2) all appeared to change their most complex ways of depicting the basics of quantum mechanics in their delayed posttest questionnaire responses from predominantly quantum model (the highest and an appropriate category) to predominately mixed model description.

6.8.4 Relationship of Pre-, Post- and Delayed Post-Conceptual Understanding

From the questionnaire data obtained for all 48 physics students, a comparison of the students' pre-, post and delayed post-instructional conceptual understanding was made in section 6.8. The results were shown how students' types of conceptual understanding of the basic concepts of quantum mechanics differ from pre- to post-instruction and from post to seven weeks after completion of the instructional intervention on those basic concepts of quantum mechanics. Table 6.5 summarized the frequency of students' type of conceptual understanding before, immediately after and seven weeks after completion of the instructional intervention.

Table 6.5: Summary of students' types of conceptual understanding of the basics of quantum mechanics

Categories of Conceptual Understanding	**Before Instruction**		**After Instruction**		**Seven weeks After Instruction**	
	#	**%**	**#**	**%**	**#**	**%**
Non-scientific Descriptive Model	8	16.67	0	0	0	0
Classical Intuitive Model	27	56.25	0	0	0	0
Synthetic/Blurred Descriptive Model	12	25	1	2.08	4	8.33
Mixed Thinking/Descriptive Model	1	2.08	12	25	16	33.33
Quantum Thinking/Descriptive Model	0	0	35	72.92	28	58.33
Total	48	100	48	100	48	100

#- Number of students, %-Percent of students

In general, following the instruction, 35 of the 48 physics students' conceptual understanding displayed a progression to a full quantum model understanding of the basic concepts of quantum mechanics (see Tables 6.5). Three months after the instruction, 28 of the 48 students maintained their full quantum mechanical understanding of the basic quantum phenomena. To determine if there was any statistically significant difference across these data collection points in terms of students' conceptual understanding over time, the Sign test statistics was chosen and used. Table 6.6 presented the results of the Sign Test statistics.

Table 6.6: The Sign test statistics for changes in students' types of conceptual understanding

Types of Understanding	Pre to Post instruction	Post to Seven weeks After the Instruction
Conceptual decay	0	10
Conceptual progression	47	0

No change (stable)	1	38
p	0.000	0.13

The Sign test statistics on students' pre- and post-instructional conceptual understanding scores revealed that 47 of the 48 students progressed to the type of conceptual understanding that was at least one category advanced from their previous types of conceptual understanding ($p<0.01$). Furthermore, 10 of the 48 students' post instructional conceptual understanding of the basic concepts of quantum mechanics decayed over the seven weeks period, whereas 38 of the 48 students held onto their post-instructional types of conceptual understanding ($p > 0.05$). The results of the Sign Test statistics were in accordance with the qualitative analyses, which showed substantial change in students' conceptual understanding (See section 6.9). Furthermore, the analysis were in line with prior works that has documented the use of the Sign Test Statistics in examining the role of multimodal representational instruction on student learning from the standpoint of the students self-reported perceptions (Adadan et al., 2010). Adadan et al. (2010) confirmed that using the numerical data for the paired categories of conceptual understanding and utilizing a nonparametric statistics of the Sign Test could provide more sensitive information for assessing the impact of multiple representations-based instructions on student conceptual learning progression.

6.9 The Nature of Physics Students' Conceptual Pathways of Quantum Mechanics

Prior studies documented that unique pattern in students' understanding of the basic scientific concepts (such as, particle nature of matter) from the beginning of the instructional interventions to the posttest were defined as '*conceptual pathways*' (Scott, 1992; Adadan et al., 2010). According to Scott (1992), these unique patterns of conceptual pathways characterized students' "learning routes along which students passed in developing understanding" of the scientific concepts from the beginning of the instructional interventions to the posttest to the time of the delayed post-test (Scott, 1992, p.221). Adadan et al (2010), for example, reported that nine different conceptual pathways hierarchically arranged from radical progress to no progress were identified in the students' conceptual understanding of the particle nature of matter. Consistent with previous studies, in this study, physics students' understanding of the basic concepts followed diverse patterns of pathways from the pre to the post to the delayed post-instruction. However, interpretive analysis of the data obtained revealed only four different patterns of pathways, which were hierarchically arranged from radical progress (I) to no progress (IV). Table 6.7 presented summary of the patterns of conceptual pathways.

Table 6.7: Summary of the identified patterns of conceptual pathways

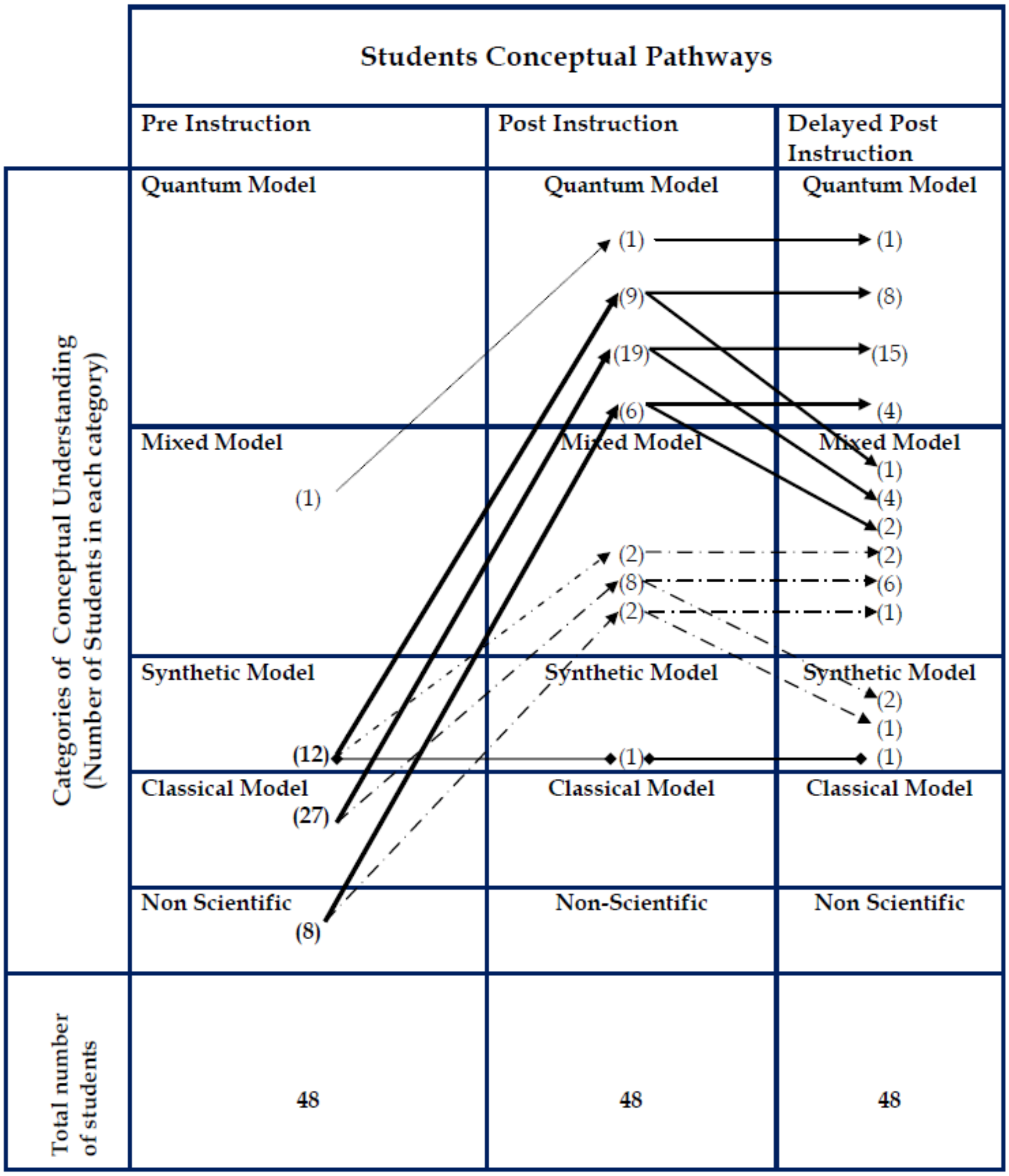
No.	Major Conceptual Pathways
Conceptual Pathway I	**Radical Progress** (Either stable or moderate decay)
Conceptual Pathway II	**Moderate Progress and Stable**
Conceptual Pathway III	**Slight Progress** (Either stable or slight decay)
Conceptual Pathway IV	**No Progress**

If students developed a quantum mechanical ontology by advancing their initial no-scientific, classical or synthetic description of quantum phenomena, the nature of the conceptual progression was characterized as radical progress. A progression into a quantum mechanical model by initially beginning with a conceptual mix-up of quantum model with classical description of quantum phenomena was defined as moderate progress. As the conceptual progression from the three lower categories of conceptual understanding toward a quantum model category decreased, the degree of conceptual progression was recognized to be slight. If students' type of conceptual understanding of the basics of quantum mechanics indicated persistence with no change over time, this case was considered to be no progress (stable). Furthermore, the extent of conceptual decay was changed with respect to students' initial types of conceptual understanding. Below, the typical patterns of conceptual pathways were presented and illustrated by exemplary cases of students' pre-, post- and delayed post-instruction conceptual understanding.

6.9.1 Conceptual Pathway I: Radical Progress and Either Stable or a Moderate Decay

As can be seen in Table 6.8, the majority of participant students (47 students) entered the instruction with non-scientific, classical and synthetic models of description. After the instruction, thirty four students raised their types of conceptual understanding of quantum phenomena into a quantum model, which can be described as radical progress (see weighted arrows in Table 6.8). Twenty seven of the thirty four students' delayed post-instructional conceptual understanding remained stable (see weighted arrows in Table 6.8). However, the remaining seven students' conceptual understanding of quantum mechanics moderately decayed (i.e., one conceptual understanding category regressed) into a mixed model description over a seven-week period.

Table 6.8: A radical progress conceptual pathway (i.e., represented by weighted arrows) following the instruction and either stable or a moderate decay over a seven week period



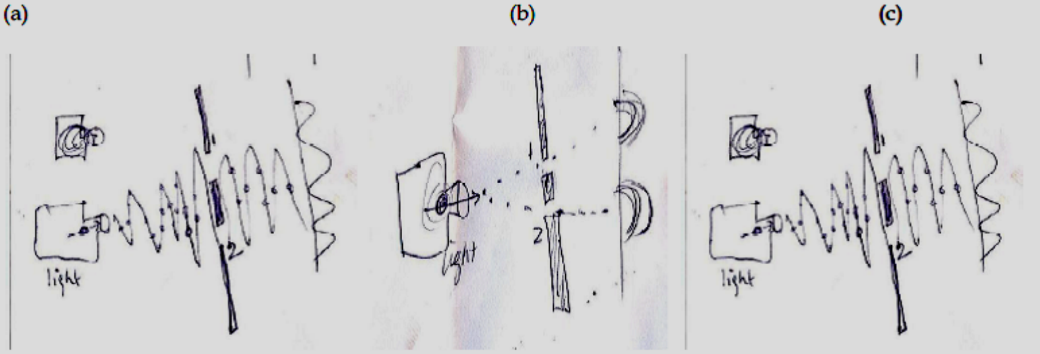
Among these twenty seven physics students, student **S₉**'s pre-, post-, and delayed post-instruction written explanations and drawings were chosen as an exemplary case for illustrating the conceptual pathway, radical progress and stable (which implies that it did not change even after seven weeks). Similarly, among the seven students (numbers, S_2, S_8, S_{11}, S_{13}, S_{25}, S_{32}, and S_{42}), Student **S₁₃**'s written explanations and drawings were chosen as an exemplary case analysis for illustrating the conceptual pathway, radical progress and a moderate decay.

S_9's Patterns of Conceptual Pathway, Radical Progress and Stable

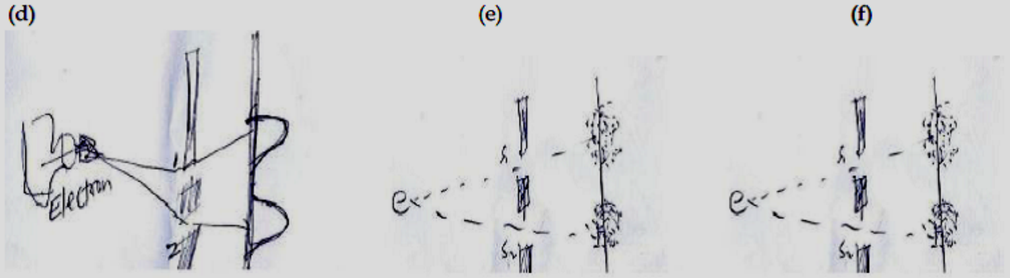
Prior to instruction, **S_9**'s answers are found to be that microscopic entities (i.e., photons and electrons) have the same characteristics as the macroscopic objects. An understanding of a particle as being massive was at the core of **S_9**'s explanations. This was seen in his interpretation, characterized by, [a photon is a particle of light that has a classical particle property such as mass]:

> […] light photon is a particle; a photon has a particle property […] e.g., it has velocity v mass m and momentum mv, energy $E = \frac{mv^2}{2}$ position $r(t)$, and the like. […] photons are particles which transport both mass and energy as they move.

Likewise, quantum entities were considered to have certain physical quantities (i.e., position, momentum) that can be accurately determined at any instant. A typical element of S_9's perspective was that he appeared to believe intuitively that photons move along sinusoidal paths. For example, he drew a figure (see Figure 6.8(a)) to account for wave phenomena of light by considering photons as point particles that travel along sinusoidal curves in the double-slit experiment. In his written explanations and drawings, depictions of photons following certain trajectories form the dominant pattern of understanding. Typical examples of S_9's depictions are shown in his Figure 6.8 (b), (c), (d): illustrating that quantum entities were classical particles with a defined trajectory. Furthermore, as shown in his Figure 6.8 (d), (e) and (f), quantum entities were assumed to be indestructible and hence arrive on the screen in identical lumps. It seems that S_9 also maintained the classical particle idea of the electron and photon that placing a detector even in just one of the slits will not result in the disappearance of their distribution on the screen.



Pre-questionnaire response: a sinusoidal curve representing "the path that a photon of light would take" in different contexts (*Classical intuitive descriptive model*)



Pre-questionnaire response: a trajectory-based curve representing "the path that an electron would take" in different contexts (*Classical intuitive descriptive model*)

Figure 6.8: S_9's pre-instruction representations of a double-slit experiment ((a) the path that a photon of light would take in double-slit (b) when only one photon is travelling at a time (c) when a detector is added to the first slit (d) the path that an electron would take when both slits are uncovered (e) when only one electron is travelling at a time (f) when a detector is placed in just one of the slits)

Another crucial point found in **S_9**'s pre-instruction responses is that he had been assuming that the classical concept of trajectory applies to all quantum phenomena. Figure 6.8 (d) and (f) indicated that he seemed to be confined to the classical description where electrons have definite locations and moves along definite paths. S_9 has also problems depicting aspects of the photoelectric effect. For example, he believed that the energy of ejected electrons is related to the intensity of light, claiming, [a change in the intensity of light affects the energy of individual photons]. While interpreting the experimental results and implications of the photoelectric effect about the nature of light, he wrote:

> […]I understanding, varying the color of light over a broad range from IR to far UV do not affect the energy of the ejected electrons. Because we do not know the light intensity. But if I

> increase the intensity then energetic electrons become ejected after some times. Since a very high intensity light hitting the metal surface gives more energy to many electrons. (***Classical Intuitive Model***)

S_9 did not recognize the effect of varying the frequency of light on the kinetic energy of the ejected electrons. His explanations were based on the classical idea that any frequency with sufficient intensity can supply the necessary energy to free the electron from the metal surface; which is characterized as classical intuitive understanding. Similar conceptual difficulties in understanding the role of the de Broglie wavelength to describe the wave-like properties of matter were also common in S_9's pre-instruction explanations. While explaining the contrast between the simplest "wave-like" and "particle-like" properties that electron and other microscopic objects could show, S_9 wrote:

> I defined a wave as a disturbance. For example water waves are a disturbance of the water surface in the upward and downward ways. It has crest and trough. So it has wavelength, frequency and amplitude. Therefore if electrons are waves, I think it has the same nature. It may be also like string waves (***Classical Intuitive Model***).

Apparently the wave-like properties of electrons are characterized by classical wave properties as a simple disturbance, like water waves moving in an extended medium and as diffusing of objects in space and time which has wavelengths and frequencies. In a similar vein, further naïve and classical thinking is also seen in S_9's explanations on questions related to the concept de Broglie wavelength and the wave properties of matter in the double-slit experiment. He failed to recognize that changing the momentum of a particle affects its de Broglie wavelength. Mainly, S_9 did not identify that particles with different mass can have different de Broglie wavelength. In general, the central ideas of S_9's written explanations and drawings are seemed to be that quantum entities have the same characteristics as the macroscopic everyday objects.

Following the multiple representations-based instructions and interactive tutorials, it was detected that S_9 formed quantum ontology and showed a reasonable understanding of the basic concepts of quantum mechanics for the undergraduate level. He incorporated the principal ideas discussed to describe quantum phenomena in his answers, such as: the wave-particle duality, the de Broglie wavelength, uncertainty principle, probability distribution, and superposition of states. He succeeded in answering the questions and gave appropriate reasoning for the concepts included in the post-questionnaire. This student also depicted quantum phenomena and the wave- and particle-like properties of quantum entities from general principles and established distinctions between classical and quantum frameworks. In the double-slit experiment with low intensity light beam and an electron, S_9 understood the spots emerged on the screen as localization of interaction events which leads to changes in the state of the system. S_9's depictions of electrons in the double-slit experiment are visualized in Figure 6.9. He considered that the quantized field for an electron comes simultaneously through both slits, spreads over the entire pattern, and collapses upon interacting with the screen, into a small region of the detecting screen.

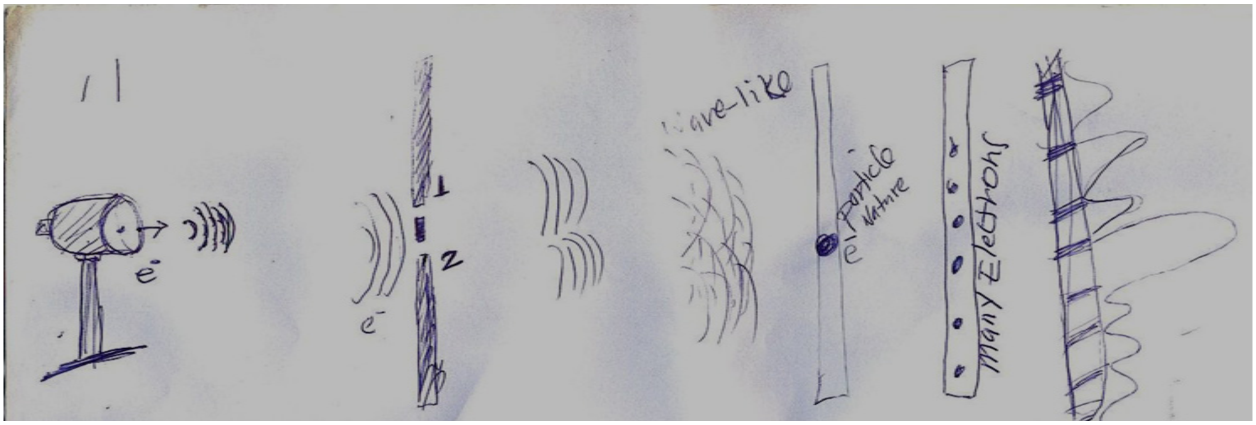


Figure 6.9: S_9's prediction of the double-slit experiment with a very low-intensity electron beam

He further explained the concept of matter waves in the double-slit experiment for a very low-intensity electron beam by providing a basis for his explanation as:

> When a single electron is emitted from the source, this electron then passes through the two slits. By forming an interference pattern, it approaches the screen. Each electron is not localized before interacting with the screen. But immediately after, it collapses into a point particle by interacting with the screen. The dot on the screen represents the probability for an electron at a point on the screen. Particle-like impacts or dots on the detection screen then form interference. Electrons are detected as particles at localized spots. But the distribution is determined by superposition of waves. **(*Quantum Model*)**

S_9 showed both the field aspects (the extended patterns) and particle aspects (the localized impacts). It seemed that he maintained the quantum particle-and wave-like properties of the electron. It is possible that the way S_9 used to depict electrons would be a progress to understand electrons as quantum systems. The concept of a matter wave which defies simple classical visualization would possibly be understood by S_9 as a new property of electron that do not correspond to vibrations in a medium nor are they the result of particle vibrations. S_9, in turn, was referring appropriately the 'thing' that spreads (or oscillates) in matter waves is usually referred to as the wave function or the probability amplitude. He also obtained appropriate predictions. The following excerpts presented three questions from the QMCS questionnaire and the explanations by S_9. These three questions deals with the behavior of electrons when passing through a double-slit:

> **Question (a): An electron gun is set to fire thousands electrons per second. Predict and reason the pattern that will form, if the slit S1 is opened and the slit S2 is blocked.**
>
> **S_9**: If either S1 or S2 is covered, a scatter pattern of electron will appear in the screen behind the slit S1. There would be no interference pattern.
>
> **Question (b): If a detector is added to either slit. This will be able to detect whether the electrons went through the S1 or S2. It will not block the electrons**.
>
> **S_9**: Placing a detector will result in the disappearance of the interference pattern. When we detect the path of electron going through either slit then the pattern on the screen is not interference. Wave-like natures of electron disappear. When we look at its path, we do not see the wave pattern. When we do not look at it, the electron is act like a wave.
>
> (**c) What would you say are the defining properties of matter wave that an electron could show?**
>
> **S_9**: The matter wave is not about vibrations of electrons. The wave is the electron spreading out in the matter field. It is a wave of probability describing the possibility for the electron. It is a non-local wave of probability, with no definite or objective existence. But matter waves show all wave properties; such as interference, diffraction and superposition principle. **(*Quantum Model*)**

S_9 understood that the path of the electron from the source to the screen is not knowable when we see the interference pattern. He identified that the observation of the electrons by the detector will define the phenomenon as either wave-like or particle-like. It seemed that he applied the uncertainty principle, indicated random positions, the basis of his argument that the paths an electron follows from one point to the other cannot be sketched, as it is impossible for its position and momentum to be simultaneously and precisely determined. S_9 depicted the uncertainty in quantum mechanics as a fundamental principle and not as an accidental error due to an imperfection in our methods of measurement and which could be avoided by improved methods and/or technologies. In the questionnaire, students were asked: "Uncertainty principle is significant in the domain of quantum mechanical world (say, for electrons) but we don't use this principle for macroscopic world (say, for a basketball), why?" The answer from S_9 was fundamental. He claimed that the uncertainty principle, as it is called, is present in the macroscopic world but the uncertainties implied by the principle are too small to be observed:

> All objects are subjected to uncertainty. By uncertainty principle is: $\Delta p_x \, \Delta x \geq h/2\pi$ where h is the Planck's constant $h = 6.6x10^{-34}$ J.s. Then its momentum is uncertain by $\Delta p_x = h/2\pi \, \Delta x$ and its velocity is uncertain by $\Delta v= h/2\pi\Delta xm$. So for the baseball the velocity uncertainty Δv is too small to be considered because Planck's constant (h) is too small and the mass is larger. i.e., quantum uncertainty is unobservable.Thus, the path of the base ball is deterministic and predictable. When $\hbar \to 0$ all quantum effects disappear. The de Broglie wavelength $\lambda = h/p$, which is very small to be considered then the wave nature of the baseball is not also observable and thus neglected. **(*Quantum Model*)**

Apparently, his explanations of the uncertainty principle revealed an understanding of the concepts. S_9 grounded his argument on the Planck's constant and the mathematical expression of the uncertainty principle. He conceived that a baseball, a million trillion times more massive than an electron, is so predictable that quantum uncertainties are insignificant. Following the instruction, most of S_9's answers were classified under the quantum category "accepted," as he revealed no signs of confusion nor of different (quantum and classical) frameworks' overlapping. The pre-post data analysis with respect to the implemented instructional design showed that the results of the questionnaire analysis offered clear evidence establishing a radical conceptual change in S_9's worldview.

Seven weeks after the instruction, S_9's accounts of quantum phenomena and were consistent with his post-instructional explanations and drawings. On the delayed post-test, he was able to interpret, for example, the photoelectric experiment in terms of the photon model for light:

> Light comes in packets of energy (photons) that the energy of a photon is proportional to the frequency, and that higher energy photons can eject more energetic electrons.

Thus, on the delayed post-instruction, he retained a quantum mechanical picture of the photoelectric effect problem by claiming that light interacted with matter like a particle, coming in discrete quanta of energy called photons. S_9 maintained his post-instructional quantum mechanical perspective about the wave-and particle-like features of quantum entities exhibited in the double-slit experiment:

> A quantum mechanical wave of probability passes through both slits, […] but that the path of the electron from the source to the screen is not knowable without disrupting the interference pattern (Quantum Model)

A further interesting point prolonged in S_9 's delayed post-instruction response was that he, accordingly, depicted the uncertainty principle as a built-in consequence of the quantum theory concerning the limit to the sharpness with which one could simultaneously measure two complementary variables.. He wrote:

> No matter how precise our instruments position and momentum it cannot be measured simultaneously beyond the limits of accuracy defined by Planck's constant h

In the QMCS questionnaire, there is another vital question which was designed to elicit students' use of the de Broglie wavelength to quantum phenomena in which it is relevant. In this question, students were asked to predict how an interference pattern would be affected by varying the speed of the electrons in the double experiment and also to predict the effect of replacing the electrons with heaver particles of the same kinetic energy. They were expected to realize how the concept of de Broglie wavelength was relevant in predicting the outcome for each possible change mentioned above. Analysis of the delayed post-instruction responses confirmed that student S_9 had recognized that those changes would cause a decrease in de Broglie wavelength and thus would cause the positions of the interference pattern to get closer together. S_9 established his justification by relating the de Broglie wavelength to the velocity of electrons and the momentum of the heavier particles:

> Increasing the speed v forces the interference pattern to move close together. When v increased, then momentum of electrons $p_e = mv_e$ increased. Based on de Broglie, an electron with momentum p_e has a quantum mechanical wave of probability associated with it having

> a wavelength or de Broglie wavelength of: $\lambda = h/p_e$. from this higher momentum means smaller λ (wavelength) and then the interference pattern become narrower.
>
> When electron is replaced by heavier particle, the interference gets close together. From $KE = p^2/2m$, $p = \sqrt{2mKE}$ then heavier particle will have larger momentum. Again the de Broglie wavelength λ became smaller with heaver mass. Therefore the pattern will close together. **(*Quantum Model*)**

As it can be seen, student S_9 applied appropriate mathematical equations (i.e., $\lambda = h/p$ and $p = \sqrt{2mKE}$) to predict that either increasing the speed of electrons or replacing the electrons with the heavier particles would decrease the de Broglie wavelength. This indicates that student S_9 maintained the quantum descriptive model in the delayed post-instruction. The comparative analysis revealed that S_9 who already had the classical intuitive model of understanding in the pre-instruction responses achieved the target model (quantum model) of understanding following the instruction.

S_{13}'s Patterns of Conceptual Pathway, Radical Progress and a Moderate Decay

As mentioned earlier, twenty seven of the thirty four students delayed post-instruction responses indicated persistence in their quantum thinking over a seven-week period. Although the remaining seven students' status moderately decayed, their understanding still advanced from the non-scientific, classical and synthetic models toward a quantum model immediately after instruction. Certainly, their post-instructional responses revealed a conceptual development of these students' quantum mechanical thinking. For illustrating this conceptual pathway, radical progress and a moderate decay S_{13}'s written explanations were chosen as a case analysis. S_{13}'s post-instruction written explanations are presented below:

> When only one photon is fired at a time, dots on the screen represented the particle-like nature of photons. Light is quantized and appeared as localized quanta having energy $h\nu$. When many photons are sent through the slits one by one, then interference pattern emerges. That is, a particle-like photon is detected as dots hitting the screen passes simultaneously through both slits with an extended wave nature. The wavelike nature is not a classical wave. But if light don't behave as wave-like there would be no interference pattern. If light were totally a wave then light energy would not arrive in discrete quantities. Performing a measurement to determine which way the photon followed destroys this interference. Intrinsically a photon cannot be assigned a specific trajectory. A single photo's

> impact point is indeterminate. But the probability distribution of impacts on the screens is predicted. **(*Quantum Model*)**

Indeed, his post-instructional responses revealed a conceptual shift of S_{13}' quantum mechanical perceptions of the microscopic world. S_{13} identified the fact that each photon spreads as a delocalized wave and passes through both slits, interferes with itself, then becomes instantly localized in its interaction with the screen. An important development was his capability to discern the fact that the nature of light observed in the double-slit experiment was depicted as an extended entity and as localized bundles or quanta having energy $h\nu$. Thus, the instruction helped S_{13} to understand that the interference pattern and the particle-like interpretation of a photon cannot be explained by the classical theory neither by the intuitive idea that the photons are like microscopic balls.

For the same questionnaire, in the delayed post-instructional survey, S_{13}'s level of understanding of the basic concepts showed moderate decay in basic knowledge, especially in using the accurate quantum mechanical terminology. In the delayed post-instructional survey, S_{13} argued about matter waves justifying that each electron went through both slits, a typical wave behavior, even though they are imagined to be tiny particles. However, when there were multiples of electrons in the space around the slits at time, his interference depictions gave the impression that he viewed the interference observed as a result of an interaction between the electrons. For instance, S_{13} wrote the following for depicting the properties of matter wave in double-slit experiment with electron beam:

> When multiples of electrons fired at a time, then the interference pattern will be created. Electrons followed multiple paths but at the two slits some of them may use slit 1 and some other use slit 2 or the vise-verse. Multiples of electrons are coming from the two slits simultaneously and the interference between these electrons created interference on the screen. (C***lassical-like descriptive model***)
> When the double-slit experiment is performed with one electron, interference pattern is also created. Electrons pass through both slit and hit the screen and create the spot of one electron when many electrons do the same, interference pattern, then developed. (***Quantum model***)

The interference pattern –the probability distribution - was created, as S_{13} intermixed, both by the simultaneously incoming electrons and also through the interference of the single electron wave function when the electrons pass through the double-slit one by one. Similarly, when describing the uncertainty principle as an intrinsic consequence of the quantum formalism, S_{13} revealed no signs of confusion, but when it comes to interpreting the meaning of Δx and Δp_x, he argued in contradiction with the quantum uncertainty. S_{13}'s interpretations of the meaning of Δx and Δp_x, seven weeks after the instruction:

> Δx indicates that the possible position between x and Δx where the electron can place. Δp_x, indicate the possible extended space between p_x and Δp_x covered of electron in its wave form.

It appeared that his conceptual understanding of the uncertainty principle remained stable for almost all aspects of the quantum phenomena, but often included some classical intuitive and unnamed expressions when he tried to interpret the meaning of the mathematical tools within the principle.

Above all, although S_{13} has started the instruction with a rather classical intuitive perception of quantum mechanics, he then exhibited considerable progress in his conceptual framework by incorporating new ideas and changed the ones competing with the quantum perspective. Over a seven-week period, his conceptual framework has not changed extensively. However, a few classical intuitive and fragmentary ideas were mixed up with his quantum picture. Thus, seven weeks after instruction, as articulated above, he regressed into the mixed descriptive model with a moderate decay in his conceptual understanding of the basic concepts of quantum mechanics. In view of this conceptual decay (regression), it was more likely that S_{13} achieved the desired conceptual knowledge but then forgot some of it after a period of time. Indeed, some of the students (e.g., S_2, S_8, S_{11}, S_{13}, S_{25}, S_{32}, and S_{42}) regressed back towards mixed thinking, sometimes due to the fact that classical intuitive ingredients that might have existed in their conceptual framework before the instruction would not have been diagnosed, and at other times because the experience of other parallel physics concepts threatened their quantum thinking.

6.9.2 Conceptual Pathway II: Moderate Progress and Stable

Only one student (S_{40}) pre-instruction conceptual understanding was ranked as mixed model, but then this student's understanding progressed to a quantum mechanical thinking following the instructions, and he unrelentingly maintained his quantum mechanical picture of the intricate elements of quantum phenomena.

S_{40}'s Patterns of Conceptual Pathway, Radical Progress and Stable

Prior to the instruction, S_{40}'s responses were characterized by, in many instances, an intermixture of quantum model and classical intuitive model. For example, his descriptions of quantum phenomena manifested in the context of a single-photon double-slit experiment, a random-looking scatter of dots where photons were absorbed by the film (particle-like behavior of light) was connected to a trajectory; the photon in the apparatus was described by a delocalized probability wave that instantly collapsed down to a point particle (a particle in the familiar tiny baseball way) when interacting with a detector; the photon-screen interactions occurred randomly on the screen but depicting that the resulting interference pattern was created by the sum of the individual waves. Listed below were typical excerpts of S_{40}'s predictions and implications in response to the key features of the observed quantum phenomena in the cases of low-intensity light beam:

> Light is a wave when it propagates but from quantum physics' point of view, light is quantized. In the double slit experiment with one photon light beam produces white dots randomly scattered on the screen. i.e., the dot is representing particle of light. This means light is like small particles hitting the screen surface. In quantum physics a photon is a probability wave. When we have only one photon at a time, it should follow either slit 1 or slit 2.

S_{40} tried to confirm simply that light is a wave in a field-an extended entity and behaves like a particle when it is detected. When logical reasoning is needed, he went back to search for a classical interpretation of the photons thinking that the photon represents an object that can be pinned down like a tiny material object. S_{40} kept the same mixed description in predicting the properties of quantum phenomena formed in the cases of low-intensity electron beams. As presented in his drawing shown in Figure 6.10, the electron in the apparatus was described by a delocalized probability wave that takes however a well-defined path (trajectory).

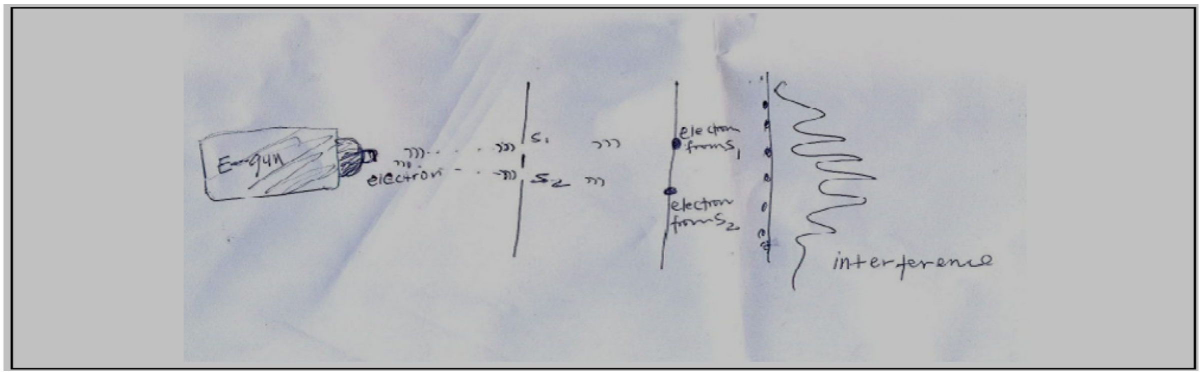


Figure 6.10: S_{40}'s representation of the quantum phenomena exhibited in the double-slit experiment with one electron at a time

A closer look of Figure 6.10 illustrated that S_{40} actually thought that in the case of low intensity electron beam, it is possible to predict the individual impact point of each electron on the screen at an earlier time, and then the overall pattern of hits on the screen randomly distributed, as formed by multiple of electrons at once. Clearly, he was found to have mixed and/or conflicting views (about the wave- and particle-like properties of quantum entities) that coexisted at the same time. Further a conflict of thinking was also seen in S_{40}'s responses on questions and statements related to the concept uncertainty, de Broglie wavelength and the wave properties of matter.

Following the instruction S_{40} has developed better perceptions for key features of quantum concepts, such as wave–particle duality, uncertainty principle, the relevance of the de Broglie wavelength, superposition and delocalization of quantum states and which-way measurements. The preliminary progress that stands out from S_{40}'s responses was the 'accepted' understanding of quantum phenomena exhibited in the double-slit experiment in the case of high and low intensity light beam. S_{40} perceived a photon as a field-extended entity that comes through both slits and obeying the superposition principle. He explained briefly what is discovered on screen in the cases of low-intensity light beams. For instance, the white 'dots' appearing on a viewing screen were often cited by S_{40} as evidence that quanta are acting like particles. Thus, to this student, localization was understood as the random interactions of this small particle-like bundles or quanta with the screen. Listed below were typical excerpts of S_{40}'s responses to open-ended questions related with quantum phenomena exhibited in the double-slit experiment with light beams.

> Light is a wave and it forms interference phenomena on the screen. Light wave is quantized. In the double-slit experiment with one photon, the white 'dots' are representing particle-like nature of light. It is quantized and interacts with screen only in discrete particle-like quantities. The interaction of photons is random. Interaction of a single photon with screen is unpredictable but it is possible to predict the overall pattern of dots on the screen.
>
> Quanta have energy E=hν. It is particle-like because it localized at a point and carries energy and momentum.
>
> A photon is an extended entity that passes through both slits and interferes with itself as it passes through the apparatus. If many photons are passing through the apparatus at the same time, photon only interferes with itself. If a detector is place on either slit 1 or slit 2 and if a single photon goes through the slits the interference pattern disappears. (*Quantum Thinking/Descriptive model*)

An interesting phenomena, clearly depicted in S_{40}'s explanations, was the non-localized or extended nature of photons appearing randomly on the screen, but with probabilities that are determined by a predictable interference pattern. He was also appropriate in asserting that, despite the intensity of light, the interference pattern produced by light beam was interpreted as a consequence of 'self-interference' of photons. S_{40}'s emphasis relating probabilities to the principle of indeterminacy, applied to individual events, was suggesting his meaningful understanding of the essentially probabilistic predictions of quantum mechanics. Once again, S_{40} offered a quantum mechanical sketch to those questions dealing with the behavior electrons in the double-slit experiments. As can be seen in his sketch shown in Figure 6.11(a), he depicted matter (electron) as a wave in a field-an extended entity that takes both slits. He claimed that the wave-like electron takes both paths in this double-slit experiment and connecting this wave-like behavior to self-interference or indefinite trajectories. S_{40} predicted the gradual formation of the interference pattern in the case of low intensity electron beams as an inherent property of each electron;

it is as though each electron 'interferes' with itself as it passes through the apparatus from the source to the screen.

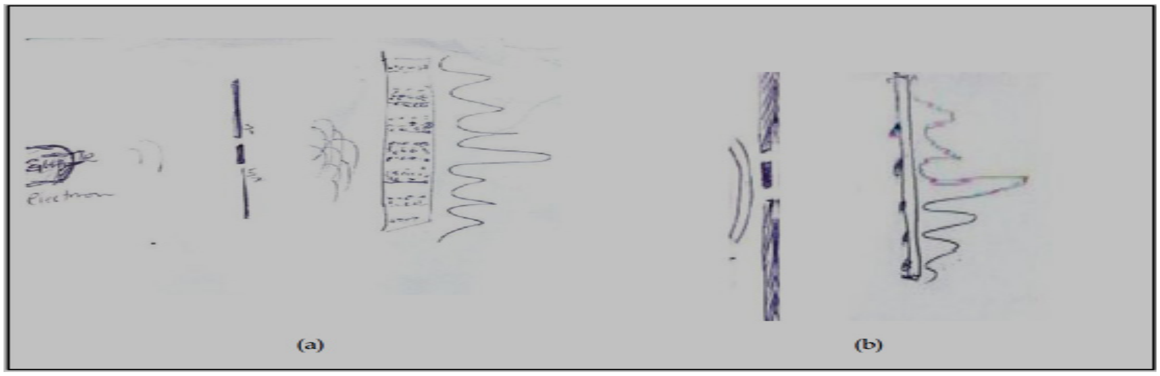


Figure 6.11: S_{40}'s sketches of the double-slit experiment in the case of low-intensity electron beam ((a) indicates his post-instruction (b) indicates his delayed post-instruction)

Conceptual progression into the quantum model is also evident from the analysis of S_{40}'s answers to typical questions concerning the uncertainty principle and on the questions that test the relationship between the de Broglie wavelength and momentum. For instance, S_{40} has written the following in response to questions related with the uncertainty principle:

> **Question:** What is the meaning of the uncertainty principle? Can you describe mathematically the Heisenberg uncertainty relations? What is the meaning of Δx and Δp?
>
> **S_{40}**: uncertainty is a fundamental limit on what can be known about quantum entities. It is expressed as $\Delta x\Delta p \geq \hbar/2$. $\Delta x\Delta p \geq \hbar/2$ means, if we correctly locate electron at point, we don't say anything about the momentum. Only probabilistic prediction is possible about momentum. It is not possible to have quantum state so that $\Delta x\Delta p \geq \hbar/2 < \hbar/2$. Δx and Δp represents the spread (standard deviation) in a series of measurements.
>
> **Question:** Uncertainty principle is significant in the domain of quantum mechanical world (say, for electrons) but we don't use this principle for macroscopic world (say, for a basketball), why?
>
> **S_{40}**: uncertainty is a fundamental principle. It is general for all objects. But because the Planck's constant h is very small and the uncertainty for baseball and larger objects are insignificant or cannot be considered. According to de Broglie the wave-like behavior of the baseball is depended on the de Broglie wavelength which inversely proportional to its momentum: $\lambda = h/mv$ so large mass means very small (≈0) λ and thus quantum phenomena is not significant.

S_{40} appropriately differentiate the conceptual bases of quantum uncertainty from classical ignorance. He clearly associated the irrelevance of the uncertainty principle in the classical world to the smallness of Planck's constant and the de Broglie wavelength of a macroscopic object. The uncertainty principle largely responsible for the non-observability of trajectories in the atomic domains was also linked to his perception that a well-defined trajectory depends upon the simultaneous specification of both position and momentum, and this is impossible in quantum world. The same appropriate reasoning was elicited in S_{40}'s post-instruction answers on questions that test the relationship between the de Broglie wavelength and momentum. In these questions, students were asked to predict how an interference pattern in the double experiment would be affected by varying the speed of the electrons. S_{40}'s answers to these questions (see the full list of questions in Appendix IV) also shed light in his post-instructional understanding of quantum mechanics:

> From de Broglie hypothesis, $de\ Broglie\ wavelength\ (\lambda) = h/p,$ $p = \sqrt{2mKE}$ then $\lambda = h/\sqrt{2mKE}$. When speed of electrons is increased in the double-slit experiment, it means $p_e = mv$ is greater. By de Broglie matter wave formula, higher speed lowers the de Broglie wavelength (λ). Then the probability distributions, i.e. the electrons interference pattern become narrower or closer together.
>
> If I changed the electrons with heavier particles having same kinetic energy in the double-slit experiment, I expect the interference pattern created on the screen still close together. Even if it has the same kinetic energy, the new microscopic object still have larger momentum as a result of larger mass and this lowers the de Broglie wavelength (λ).

S_{40} understood the relevance of the de Broglie wavelength to situations that involve the wave-like behavior of matter. He assigned energy and momentum to matter wave in (reversed) analogy to photons. Incorporating de Broglie relationship into the wave-like interference of matter demands a proper understanding of quantum mechanics. Thus, as long as a student express the wavelength λ through the momentum p and use the form of the kinetic energy $E = p^2/2m$ to write $p = \sqrt{2mE}$, one can say that S_{40} has got a quantum thinking of the de Broglie wavelength $\lambda_{deBroglie}$ for matter wave.

Thirdly, S_{40}'s delay post-instruction responses confirmed the conceptual progression he has attained through the instructions and maintained over a seven-week period. S_{40} clearly outlined basic features of the quantum theory of radiation including photon detection and interaction with the screen (as particle-like property) and light quanta interference (as wave-like property) as he related to a double-slit experiment. Below, it was noted that he properly maintained his post-instruction conceptual pictures over a seven-week period:

> Light radiation can behave as a wave-like or a particle-like based on the situation. The random scatters of white dots represent a particle-like interaction of light with the screen. Wave-like interference appear from the randomly scatter of dots. The wave-like interference pattern created by interferes of each photon with itself as it passes through the apparatus; because a photon is an extended entity that passes through both slits. Placing a detector in determining through which of the slits each photon passes destroy the interference pattern. If we turned off then the interference again appear. It is an inherent property of a photon.

S_{40} seemed to have maintained the quantum model to the wave- and particle-like properties of quantum entities. It was also liable to judge that S_{40} did retain his depictions about matter wave which quantized with quanta that appear indeterminately on the screen, but with probabilities that are determined by the wave-like property. S_{40}'s sketches of the double-slit experiment using a low-intensity electron beam illustrated that, like the light beam, an electron beam was represented as a wave that comes through both slits and interferes with itself (see Figure 6.11(b)).

Furthermore, Student S_{40} delayed post-instruction explanations to questions concerning the uncertainty principle and the de Broglie wavelength revealed that he maintained his quantum mechanical picture over a seven-week period. Note the following selected questions that pertain to quantum uncertainty and S_{40}'s delayed post-instruction responses to these:

> **Question:** What is the meaning of the uncertainty principle? Can you describe mathematically the Heisenberg uncertainty relations? What is the meaning of Δx and Δp?
>
> **S_{40}**: Quantum uncertainty reefers that simultaneous quantum description of position and momentum is impossible. It represents in nature itself a fundamental indeterminacy. Uncertainty is expressed as $\Delta x \Delta p \geq \hbar/2$. Δx and Δp represents the spread (standard deviation) in a series of measurements, not about individual measurements.
>
> **Question:** Uncertainty principle is significant in the domain of quantum mechanical world (say, for electrons) but we don't use this principle for macroscopic world (say, for a basketball), why?
>
> **S_{40}**: Uncertainty applies to all objects but not significant for large bodies. The reason behind is related to the Planck's constant h which is very small. For the basketball Planck's action is

> insignificant. The de Broglie wavelength λ that indicate the nature matter wave almost zero and the uncertainty and other quantum phenomena are not observable.

On this basis, his perspectives on quantum mechanics were more or less in complete agreement with the perceptions of expert conceptions over a seven-week period.

6.9.3 Conceptual Pathway III: Slight Progress and either Stable or Slight Decay

From the initial 47 students of the non-scientific, classical intuitive and synthetic descriptions of categories of understanding, twelve (S_{15}, S_{29}, S_3, S_5, S_{24}, S_{28} , S_{46} , S_{48}, S_{30}, S_{38}, $S_{14,}$ S_{39}) students' depictions of quantum phenomena were identified and categorized in the mixed thinking model after instruction. These students showed slight conceptual progression toward the 'accepted' understanding of quantum phenomena. Some of these students maintained their newly developed post-instructional depictions of quantum phenomena over a seven-week period. Three (S_{30}, S_{38}, S_{39}) students' conceptual understanding slightly decayed into a synthetic model over this seven-week period (see Table 6.8 & 6.9). S_3's written explanations and pictorial illustrations at three data collection points were presented here as an exemplary case for the conceptual pathway, slight progress and either stable or slightly decay.

Table 6.9: A slight progress conceptual pathway and either stable or a slight decay following the modified instruction

	Students conceptual pathways throughout the study		
Categories of conceptual understanding from higher to lower	Pre	Post	Delayed Post
Quantum Thinking/Descriptive Model			
Mixed Thinking/Descriptive Model		**2** (S_{15}; S_{29}) **6** (S_3; S_5; S_{24}; S_{28}; S_{46}; S_{48}) **2**(S_{30}; S_{38}) **2**(S_{14};S_{39})	**2** (S_{15}; S_{29}) **6** (S_3; S_5; S_{24}; S_{28}; S_{46}; S_{48}) **1**(S_{14})
Synthetic/Blurred Description Model	**2** (S_{15}; S_{29})		**2**(S_{30}; S_{38}) **1**(S_{39})
Classical Intuitive Model	**6**(S_3; S_5; S_{24}; S_{28}; S_{46}; S_{48}) **2** (S_{30}; S_{38})		
Non-Scientific Descriptive Model	**2**(S_{14}; S_{39})		

S_3's Patterns of Conceptual Pathway, Slight Progress and Either Stable or Slightly Decay

Prior to the instruction, S_3 never took the important elements of the basic quantum concepts to explain all the different microscopic phenomena. He employed classical and naïve ideas in interpreting the wave-and particle-like properties of quantum entities. Classical model of descriptions were prevalent in his explanations: particles were characterized by measurable properties such as the position, velocity, momentum, and kinetic energy; and light was only endowed with a classical wave which was specified by measurable properties as well, namely, the wavelength and frequency. The following responses manifested S_3's depicting of the simplest particle- and wave-like properties that light could show:

> **S_3**: There is a wave-particle paradox in light. But it possible to find anywhere in physics light is an electromagnetic wave. Light has frequency and wavelength and but it is impossible to see practically particle of light. Particle-like nature is only ideally to light. It is not practical of this particle property for light.

> **S$_3$**: I don't understand one photon at a time in the double-slit experiment. How could light is one photon? Light waves of electromagnetic energy moves continuously. But light is a wave or a disturbance and like waves it shows diffraction and interference. If the ideal particle of light is true, I expect no wave property in the double slit experiment. Since the solid particle which is massive don't have frequency, wavelength, disturbance and the like.
>
> **S$_3$**: I don't expect placing a detector on slit 1 or slit 2 changes the nature of light wave or in the case of particle of light.

The foregoing responses suggest that S$_3$ has the notion that light can be seen in terms of a classical electro-magnetic wave. It is also clear that the conceptual picture of particles of light as outlined by S$_3$ is consistent with the idea that light consists of a stream of photons which are localized classical particles. He thought of a stream of photons in the same way as electrons, with a well-defined position and size (presumably small) and moving along definite trajectories. S$_3$'s representations of matter waves are also in line with the above explanations that (i.e., in the double-slit experiment with low intensity electron beam) electrons were depicted as classical particles with well-defined trajectories (see Figure 6.12). To this student, it seemed reasonable to describe that when low intensity electron beams are presented with two possible trajectories, one for each slit, electrons seemed to pass along either trajectories in a classical particle-like way, arrive on the screen in identical lumps behind each slit and built up no interference pattern (see Figure 6.12).

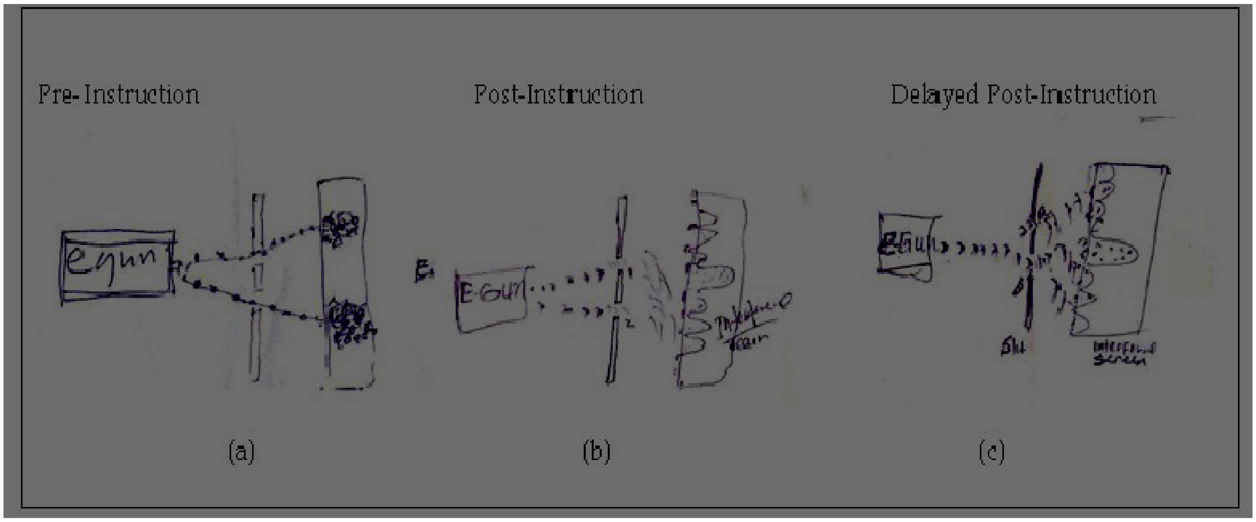


Figure 6.12: S_3's sketches of the double-slit experiment using a low-intensity electron beam ((a) indicates his pre-instruction (b) indicates his post-instruction and (c) indicates his delayed post-instruction)

Indeed, S_3's predictions of the behavior of electrons were typical for that of classical macroscopic objects: single electrons passed through either slit and did not form any interference fringe on the screen. Furthermore, thinking about probability of an electron's position was unreal for S_3 too. On questions concerning the uncertainty principle and on other related questions that test the relationship between the de Broglie wavelength and momentum, S_3 still used incorrect and classical intuitive worldviews. His classical thinking was typified by, for example, [The uncertainty relation is a consequence of the measurement process], [Uncertainty is a reflection of classical ignorance] and [Quantum uncertainty is that uncertainty caused by technological limitations, or it is the error in the measurement of the position of the particle as a result of single measurement; that is, an error or deviation from an actual value].

Following the instructions and interactive tutorials, S_3 has started depicting that light is a wave in a field-an extended entity and behaves like a particle when it is detected. His post-instruction explanations showed that he somehow gained an efficient knowledge for many of the concepts covered during the lessons and interactive tutorials in relation with light: a) the wave and particle-like aspects of light, b) the fact that the light wave is quantized, and appears as localized quanta having energy *h*ν and c) the fact that the "trajectory" of a quantum entity (i.e., photon), cannot be defined/ predicted. However, the interference pattern that emerged later was still understood by considering light as classical electromagnetic waves with the consequence that the interference pattern is the result of an interaction between the photons or an outcome of the constructive or destructive combination of photons. The following response manifested this conceptualization:

> **S$_3$**: A photon is a wave or an extended quantity. In the case of low intensity light beam, a photon goes through both slit and hit the screen at random point. The white dot on the screen represents particle-like nature. After longer time many photons are randomly hit the screen and finally a white and dark fringes (interference pattern) created by an interaction between those photons.
> If we place a detector, we can see the photon going through slit 1 or slit 2. Quantum mechanically it is forbidden tracing a path.

As it is observed, S$_3$ held a quantum mechanical answer with a classical reasoning. Example of such a mixed thinking is also found in his prediction of a double-slit experiment with low intensity electron beams. The student's sketches are illustrated in Figure 6.12(b), which appeared the same as the accepted representations. However, his interpretation still included classical reasoning. This mixed notion came through when he discussed his predictions:

> **S$_3$**: When electrons are striking the screen one by one after passing in slit 1 and in slit 2, the electrons are like particles. Electrons are propagating like waves from the source to the slit and randomly distributed all over the screen. When more electrons are striking the screen the white and dark fringe formed by constructive and destructive interaction of those electrons on the screen. Interference pattern is the wave part of electron formed in the case of both high and low intensity electron beam. Electrons and other microscopic particles show the quantum wave interference phenomena and this is not occur in large objects. As quantum theory said wave nature disappear as the objects become larger and larger. Electrons are passing in both slit when they are many. Electrons are taking slit 1 or slit 2 if the intensity is low like one at a time. The interference is disappearing if detector is placed.

The foregoing explanations could depict that the wave-like property of the electrons could possibly be understood by S$_3$ but the resulting wave phenomena on the screen was seen as the constructive and destructive interactions of electrons. He predicted that two or more electrons are required to produce interference pattern on the screen. S$_3$ held some kind of mixed view on the wave- and particle-like aspects of electrons in that the conception of trajectory was intermixed with probability and randomness, or showed little distinction between the idea of trajectory and indeterminacy. That means he still did not abandon the classical particle viewpoint, though he described the wave-like behavior of the electrons. About the uncertainty principle, S_3 remarked that quantum uncertainty represents the most essential aspect distinguishing quantum properties from the classical ones. According to his view, the uncertainty principle manifests an inner indeterminism inherent to quantum states. Examine what S_3 stated about the uncertainty principle:

> **S_3:** Heisenberg uncertainty principle is due to the fact that the very process of measurement introduces the uncertainty because measurement interferes with the state of microscopic objects.
> Uncertainty is not lack of knowledge or because of measurement error and lack of technology. Uncertainty is simply inherent impossibility. Uncertainty states that: it is impossible to simultaneously measure the position and the momentum of a micro object with an arbitrary high precision in nature. Uncertainty principle is stated: $(\Delta x)\ (\Delta px) \geq \hbar/2$.
> Uncertainty principle works in all objects such as micro macro objects. In quantum physics because of the Planck's constant h, the uncertainty in basketball is not seen.

What S_3 did not clearly realize, however, was that the meaning of Δx and Δpx denote the standard deviation of the x-component of the position and the x-component of the momentum and not about individual measurements. These type of reasoning are evidenced in his answers of the uncertainty related questions:

> **S_3:** […] the meaning of Δx and Δpx in the uncertainty principle is indicate its principle. i.e., position disturbs momentum or vice verse. Δx tells us we are not sure about it and also Δpx represent not sure about momentum.

Here, S_3's reasoning was not guided by quantum uncertainty. It seemed that he was trying to remember and apply what he had learned in classical courses of experimental uncertainty. He maintained a conceptual picture that includes the classical and naïve ideas. However, S_3 gave a quantum-like conceptual picture that recognizes the inverse relationship between the de Broglie wavelength and the electrons momentum when predicting how an interference pattern would change if the speed of electrons was changed and/or replacing electrons with heavier particles of the same kinetic energy.

Seven weeks after the instructions and tutorials, S_3's ways of explanations as to the aspects of quantum phenomena were consistent with his post-instructional perspectives. S_3's pictorial representations (see Figure 6.12(c)) reflected that he maintained his post-instruction conceptual picture (mixed thinking) about the double-slit experiment with matter waves. Aspects of quantum thinking with classical reasoning were also drawn from S_3's delayed post-questionnaire responses and were typified by, for example, [the fact that the "trajectory" of a photon cannot be defined or predicted], [The detection point of a single electron is completely unpredictable in all experiments and tracing the electron's path] and [The matter wave pattern is caused by interactions between different electrons and the same interference pattern also builds up from particle-like impacts on the screen using a low-intensity electron beam]. Aspects of mixed thinking about the uncertainty principle were also found in S_3's delayed post-instruction responses, [Stating quantum uncertainly is an inherent uncertainty in microscopic events; describing quantum uncertainty mathematically as $\Delta x \Delta px \geq \hbar/2$ and interpreting as a measurement of position ''disturbs'' the value of momentum] and [Treating quantum uncertainty with the concept of trajectory though both include the two fundamental concepts: that of position and that of the rate of change of position—the velocity, or p / m]. Simultaneously, aspects of quantum thinking can be drawn from this student delayed post-instruction responses, typified by, for example [The Planck's constant and then the de Broglie wavelength of a macroscopic object (e.g., a basketball) are responsible for the non-observability of quantum uncertainty in the classical world]. Thus, over a seven-week period, his depictions of the quantum phenomena exhibited stability with continuation of the same mixed perspectives. However, the remaining three (S_{30}, S_{38}, S_{39}) students' newly constructed perspectives (i.e., mixed thinking model) as a result of the instructions and interactive tutorials slightly deteriorated into a synthetic model over a 7-week period (see Table 6.9).

6.9.4 Conceptual Pathway IV: No Progress

No progress was identified in student S_{16}'s conceptual understanding of the basic concepts of quantum mechanics from the pre- to the post- to the delayed post-instruction. This student's (S_{16}) written explanations and drawings at three data collection points were, therefore, presented here as an exemplary case analysis for the conceptual pathway, no progress with synthetic description.

S_{16}'s Conceptual Pathway, No Progress with Synthetic Description

Note the following selected context that pertain the wave- and particle-like properties of photons in the double-slit experimental setup with low-intensity light beam and S_{16}'s pre-, post, and delayed post explanations to these:

> **[Pre-instruction explanations]:**
>
> Light shows interference and diffraction. When only one photon is travelling at a time, the light has low frequency so first diffraction occurs on the screen that is represented by light points on the screen. Again interference occurs as result of constructive and destructive interference of photon. Photon is a particle of light and thus, some photon passes in slit 1, some photon reflected back and the remaining others follow slit 2.If either slit closed, no interference. Placing a detector for example on slit 2 changes the interference pattern behind slit 2 and only slit 1 interference remains.
>
> **[Post-instruction explanations]:**
> Light is a particle passes through slit 1 or slit 2 and collide with screen.
> Light is a wave so photons pass through slit 1, through slit 2 and form diffraction and interference. Quantum mechanics is a probabilistic science. So photons after passing slit 1 hit the screen behind slit 1 randomly. Photons passing across slit 2 hit the screen randomly behind slit 1.
> Interference disappear behind each slit when a detector is placed because interaction between photons on the screen.
> **[Delayed Post-instruction explanations]:**
>
> Photons passing one by one through slit 1, through slit 2 and hit the screen. Photons create diffraction but after some interaction between photons, they form large interference behind slit 1 and behind slit 2.
> Here photons show wave and particle properties.
> Photons hit the screen randomly behind slit 1 and slit 2 and it shows probabilistic phenomena.
> If the detector is placed it affects the interaction between photons from slit 1 with photons from slit 2 so parts of the pattern show only diffraction. So interference pattern is hidden.

The foregoing explanations reveal that the quantum model of light particularly the wave- and particle-like properties of quantum entities (photons) were only synthetically understood. Often S_{16} cling to his classical intuitive and naive ideas. There are few quantum-like ideas that S_{16} has loosely applied into his explanations of the wave- and particle-like properties of quantum entities. However, most of his explanations relied on assigning the classical ontology directly as a property of quantum entities as shown consistently in his responses that photons are taken as point-like particles, much like material objects. Note that most of the responses evidenced on the delayed post-instruction already existed in his pre- and post-instructional conceptual frameworks. S_{16} seemed to have maintained what he had grasped prior to instruction to the delayed post-instruction.

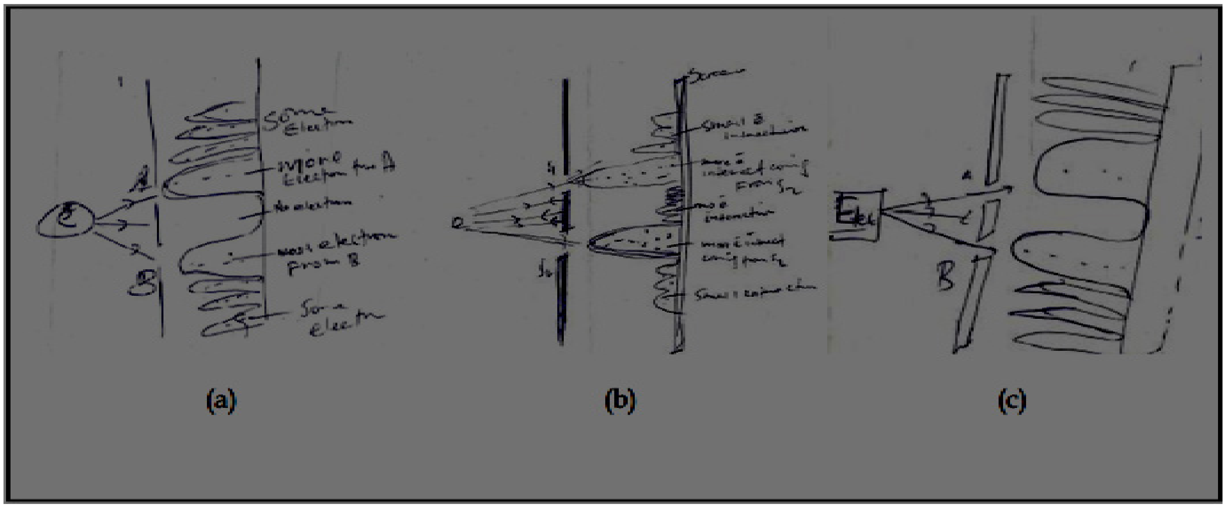


Figure 6.13: S_{16}'s predictions of the interference pattern in the case of low intensity electron beam ((a) indicates his pre-instruction sketch, (b) indicates his post-instruction sketch and (c) indicates his delayed post-instruction sketch)

Furthermore, on contexts that pertain the quantum model of matter wave in the double-slit experiment with low-intensity electron beam, the post- and delay post-instructional responses characterized most of S_{16}'s pre-instructional depictions. For example, S_{16} had a continuous picture of matter wave as a classical electro-magnetic wave described in all pre-, post and delayed post-instruction responses. The pictorial descriptions shown in Figure 6.13 (a), (b) and (c) illustrated that S_{16} extended his synthetic descriptions about the quantum model of matter wave from pre-to delayed post-instruction. As shown in his drawings (see Figure 6.13 and 6.14), the post-instructional explanatory framework characterized most of S_{16}'s pre- and delayed post-instructional understanding of phenomena and concepts related to the microscopic world. For S_{16}, the wave- and particle-like properties of quantum entity meant that electron should be considered both as a wave and particle simultaneously. Most strikingly, from what he drew at the three data collection points it was obvious that the double-slit was perceived as an experiment which brings forth, simultaneously, both wave- and particle-like properties of matter. The synthetic model developed from S_{16}'s pre-, post- and delayed post-instruction responses could have been used to explain wave-particle duality (which is not a quantum duality since both coexist), the de Broglie wavelength, wave function (as trajectories followed by electrons) and photoelectric and Compton effects. However, he was not able to predict and explain in any way which aspects of wave-like behavior are related in a quantum-mechanical treatment of matter, or where to distinguish between the wave- and particle-like aspects of matter and how to justify the duality.

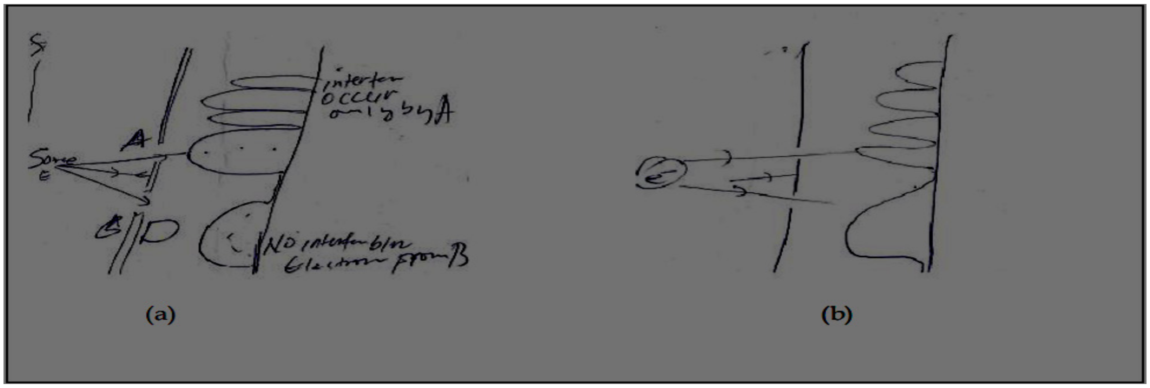


Figure 6.14: S_{16} predictions of the interference patterns in the cases of low intensity electron beam and a detector in either of the two slits ((a) indicates his post-instruction sketch and (b) indicates his delayed post-instruction sketch)

This line of thinking was also seen in S_{16}'s post- and delayed post-instruction drawings for representing the pattern shift on the screen when a detector is placed at one of the slits (see Figure 6.14 (a) and (b)). More intuitively, S_{16} predicted that the interference pattern developes from particle-like impacts on the screen for electrons but he treated it as an outcome of a juxtaposition of two separate interference patterns, each created by one of the two slits. He argued that each slit was responsible for half of the interference pattern and the interference maxima behind each slit was due to electrons passing through each of the slits. S_{16} has erroneously associated the possibility of observing electrons both in the source and in the detector as being well-localized with some of the textbook misrepresentations of paths. Such an interpretation may have led to the generation of a picture in S_{16}'s mental image that only half of the interference pattern would disappear when a detector was placed at one of the slits (see Figure 6.14 (a) and (b)).

Furthermore, a thorough analysis of his pre, post and delayed post-instruction conceptual understanding about the concept of de Broglie wavelength and uncertainty principle depicted no progress in S_{16}'s descriptive model in the form of either addition of a new quantum idea or elimination of or change in his classically blended conceptions. Although he was able, from pre-to delayed post-instruction, to repeat the textbook definitions, used the mathematical languages of quantum uncertainty and the de Broglie wavelength such as $\Delta x\Delta px \geq \hbar/2$ and $\lambda = h/p$, he often did not understand what was meant by these terms in a quantum mechanical context. Note S_{16} answers in the pre- and post-instruction when he was interpreting the meaning of uncertainty:

> **Question:** Uncertainty principle is significant in the domain of quantum mechanical world (say, for electrons) but we don't use this principle for macroscopic world (say, for a basketball), why?
>
> **[Pre-Instruction]**
>
> **S_{16}**: The uncertainty principle $\Delta x\Delta p \geq \hbar/2$ works for small objects and de Broglie theory of wave-particle is also applicable in small objects. The reason may be our technology or measuring apparatus don't correctly measure these objects.
>
> **[Post-Instruction]**
>
> **S_{16}**: Quantum mechanical principles work in atomic size object. The current technology handle for large object and hence measurement is not a problem in the case of basketball. But in small object the uncertainty equation $\Delta x\Delta p \geq \hbar/2$, always holds true. Because of the apparatus and others problems no one can performs measurement without position and momentum uncertainty.

It is clear that the above conceptual picture as outlined by S_{16} is consistent with the idea that the principle of uncertainty is caused by the technological deficiencies. He persistently carried some thoughts from classical physics. Except for repeating the mathematical descriptions, he explicitly did not mention any inconsistencies between quantum uncertainty and simple experimental error or classical ignorance. His descriptions in the delayed post-instructional questionnaire had also similar statements about the quantum uncertainty as being error in classical measurements. Overall, no progression was noticed in S_{16}'s conceptual understanding of the basic concepts of quantum mechanics from the pre- to post- to delayed post-instructions. Despite the instructions, which often rationally analyses some of the alternative conceptions, S_{16} persisted in synthetic description. The result was also supported by the findings of previous studies in the same domain that alternative conceptions often endure instruction that was assumed to supplant it (Driver & Easley, 1987; Hess, 1987; Ebenezer, 1991; Talanquer, 2009; Adadan et al., 2010). Considering how difficult it is to understand quantum mechanics, it is not surprising, therefore, that simple extension of classical pictures or overlapping of classical and quantum ideas persisted in S_{16}'s responses in spite of the multiple representations-based instructions and interactive tutorials.

6.10 DISCUSSIONS AND CONCLUSIONS

Part II of this thesis mainly explored the patterns of undergraduate physics students' conceptual pathways of the basic concepts of quantum mechanics from pre- to post-instruction to seven weeks after the multiple representations-based instructions and interactive tutorials. Prior to the instructional and tutorial intervention, none of the physics student participants in this investigation held complete quantum model of understanding of the basic concepts of quantum mechanics. Their conceptual understanding of quantum mechanics were incomplete and typically include nonscientific and a rather classical perception of quantum phenomena. The positive post-instruction results have reflected impressive conceptual growth in the quantum models of understanding for the majority of participants. Further, the desirable conceptual pathways were durable for the majority of participants at 7 weeks later. However, some student participants showed evidence of experiencing partial decay in their conceptual understanding of the basic concepts of quantum mechanics. As a whole, the findings has implied encouraging conceptual progression in 47 of the 48 physics students' conceptual understanding of quantum mechanics, varying from radical to slight change. For example, following the instruction, 35 of the 48 physics students' conceptual understanding displayed a progression to a quantum model of understanding of the basic concepts of quantum mechanics (see Tables 6.5). The majority of these physics students also maintained their post-instructional conceptual understanding over a seven-week period (see Tables 6.5 & Figure 6.15).

In general, the findings of the implementation of the instructional strategy showed that more than half of the physics student participants attained a reasonable understanding of the basic concepts of quantum mechanics for the undergraduate level. These findings were well-aligned with the findings of a number of previous investigations as to the patterns of progression from radical to no change as an immediate learning outcome and then either stability or regression in students' conceptual understanding (Adadan et al., 2010; Malandrakis, 2006; Trundle et al., 2007; Malandrakis, 2006). Conceptual pathways in physics student understanding as identified in this study through the students' pre-, post- and delayed post-instruction questionnaire responses were represented by the typology described in Figure 6.15. It is noticeable in this figure that 34 of the 48 physics student participants experienced radical conceptual progress in their understanding of the basic concepts of quantum mechanics from before to after the instructions, and only 7 of these 34 students regressed to mixed model description, exhibiting a moderate decay over a 7-week period. However, the lack of a full decay into a non-scientific, classical and synthetic description models among these physics students' understanding of quantum mechanics was an encouraging result in terms of the effectiveness of the multiple representations-based instructions and interactive tutorials.

Indeed, some classical perception of quantum phenomena were weakly intermixed into the mental models of seven students who experienced moderate decay and, thus, the pure quantum ideas had not stayed longer in these seven students' thinking of quantum phenomena. With the lack of time to reflect on the inexperienced ideas that serve as cues for more sophisticated descriptions, Tytler (1998) claimed that the occurrence of decay in the newly constructed scientific ideas months after instruction is not surprising.

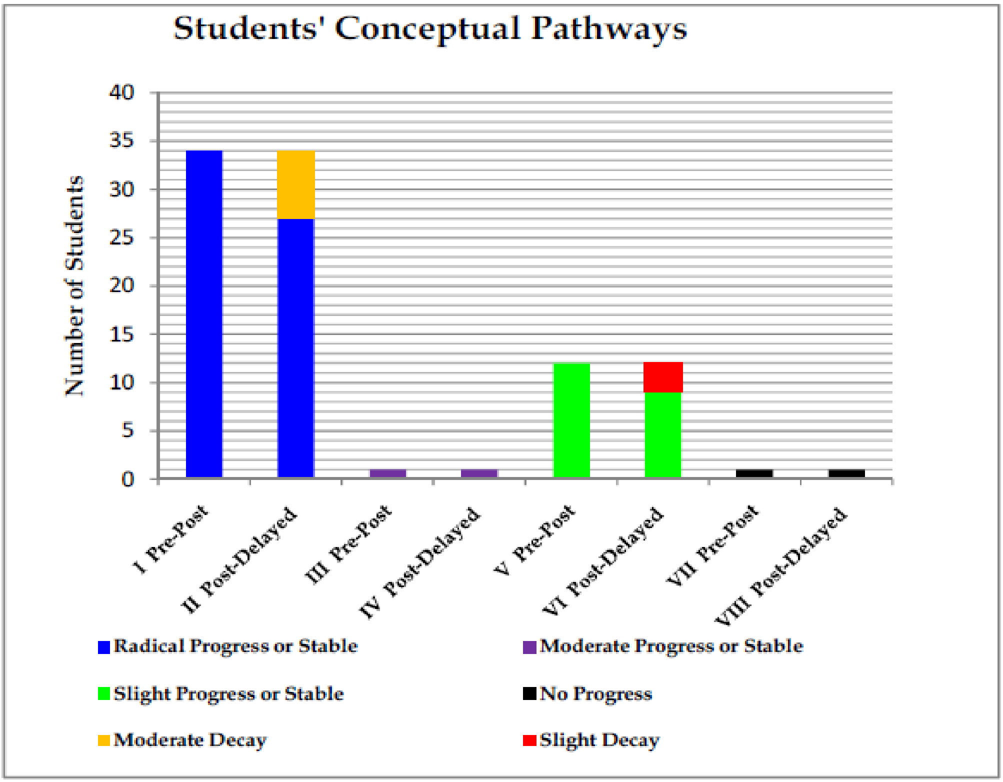


Figure 6.15: Conceptual pathways over time

Thus, quantum thinking of the seven students who experienced radical progress and then moderate conceptual decay may have been sustained with ongoing support and reflection. Aspects of quantum ideas such as the quantization principle, the wave-particle duality and the probabilistic nature of basic events in quantum mechanics have central role to account for a range of microscopic phenomena (Mannila et al., 2002). Thus, if the seven students had been confronted with the newly developed quantum pictures of these quantum ideas while learning other advanced topics in quantum mechanics, they might have been able to maintain the quantum perspective over longer periods of time.

In terms of the conceptual pathways dynamics only one student was found who started with a mixed perception of quantum phenomena and showed moderate progression toward a pure quantum model following the instruction and then maintained his newly developed quantum ontology over a seven-week period (see Figure 6.15). Apparently, in the pre-instruction, this student's responses were characterized by the quantum model descriptions diffused with the classical ideas. His explanations offered no evidence of an expert-like understanding of the conceptually demanding concepts of the wave- and particle-like properties of quantum entities. Adadan et al. (2010) claimed that the less alternative prior conceptions students held, the greater the possibility of changing these alternative conceptions to a scientific conception during the reformed instruction. This factor seems to play a crucially propulsive role in this study for student's conceptual change from the mixed model description into a stable expert-like understanding of quantum mechanics. This result is also in agreement with the functions of multiple representations on students' conceptual learning; where previous studies documented that students with fewer alternative ideas receive the maximum benefit from the conceptual change instructional strategy that features multiple representations and interactive visualizations (Gunel et al., 2006; Adadan et al., 2010; Abdurrahman, 2010; Singh, 2008; Bodemer et al., 2004).

Twelve physics students who showed slight progress by achieving a mixed model of quantum phenomena from pre- to post-instruction were likely to maintain their mixed model description over a seven-week period (see Figure 6.15). However, three of the twelve physics students' delayed post-instructional conceptual understanding regressed to synthetic model of understanding with a slight decay. Prior to instruction, all these twelve physics students held either a non-scientific, classical or synthetic description about various aspects of the basic concepts of quantum mechanics. While these physics students were able to change some of their prior understanding to a quantum model of understanding, the classical ideas that were resistant to change continued to exist in their conceptual framework along with the quantum model after the instruction. These physics students' failure to develop the quantum model about quantum entities despite instruction may have been due to a presupposition (e.g., photons are thought of in the same way as classical particles and electrons, with a well-defined position and size) that intermixed with the quantum view of photons and electrons. Furthermore, while multiple representations of the wave- and particle-like properties of quantum entities were used as a reference model during the instruction, these twelve physics students might have relied on the various quantum physics textbooks that simply speak of photons in terms of classical particles, classical waves, or both. According to Adadan et al (2010), besides to these possible difficulties, students may not have had strong spontaneous metacognitive skills to manipulate their inconsistent ideas concerning microscopic phenomena. However, previous studies still reported that mixed and/or split conceptions reflected how students had learned a scientific response from the modified instruction, without having reconciled that conceptual understanding with their prior scientific or non-scientific intuition (Bao & Redish, 2006; Baily & Finkelstein, 2010). In spite of the instruction that features multiple representations and interactive tutorials one of the 48 students continued to hold the same type of conceptual understanding category, synthetic model from the pre- to the post- to the delayed post-instruction without showing any conceptual progression in his type of conceptual understanding. The student did maintain all of his original conceptual understanding about quantum mechanics despite the instruction. The finding extends those of Hess (1987) and Ebenezer (1991) confirming that alternative conceptions persist in spite of instruction. For example, Hess (1987) claimed that "alternative conceptions often outlive the instruction that was meant to supplant them".

It has been argued in this study, at length, that the multiple perspectives or visualizations are the means to the best possible understanding of a microscopic phenomenon in the context of quantum mechanics. The findings of the study also provided evidences that many students were able to undergo conceptual progress toward the 'accepted' understanding of quantum mechanics when provided with opportunities for learning microscopic phenomena with multiple representations and interactive learning tutorials. The success about the pedagogical use of multiple representations and interactive learning tutorials can be interpreted as confirming the rationale implied in its design regarding the instructional materials. Instructional strategy involving multiple representations and interactive learning tutorials then can be considered for other advanced quantum topics to promote conceptual progression among undergraduate students. However, multiple visualizations may also overburden the students' capabilities due to extensive amounts of continuously changing information, particularly if it is represented as non-interactive animations that do not provide learners with the opportunity to watch single frames (Lowe, 1999). Thus, active integration of the visualized information should be considered during instruction with static, symbolic, pictorial and dynamic representations, and not only in combination with interactive visualizations. Empirical studies recently indicate that the active integration of static representations can lead to better learning outcomes (Ploetzner et al., 2001; Adadan et al., 2010). Additionally, instruction that actively integrate multiple representations should improve students' understanding comparatively more during interactive-based discovery learning (Bodemer et al., 2004). Van Meter et al. (2006) further hypothesized that engaging students in the integration processes across verbal, symbolic and pictorial representations, ultimately leading to the realization of consistent expert-like conceptions. Adadan et al. (2010), in agreement with the findings of this study, explored that students' pre-instructional conceptions of scientific ideas differ from one another in terms of its sophistication, the nature and structure of alternative ideas so that individual student made different level of progress with respect to their prior conceptual understanding. As a result, it seems important to suggest that physics students with numerous naïve and inappropriate scientific ideas based on perceptual experience and/or prior instruction may require particular attention in the conceptual instruction involving multiple representations. In order to ensure that students have precisely assimilated the scientific conceptions through instructional intervention along these lines, previous studies claimed that physics teachers should be clear about in what way the scientific conception is linked to the previous ideas and often strengthen these links as fitting (Taber, 2008; Adadan et al., 2010). In case of quantum mechanics, for instance, students may assimilate the newly considered quantum mechanical concepts intuitively into the modes of the classical worldview and thus physics instructors should be aware of the possible presuppositions students may hold about aspects of the quantum model of microscopic phenomena.

In summary, the findings in this study were in accord with the previously quoted research regarding the pedagogical use of multiple representations and interactive tutorials, suggesting that: (a) using multiple representation tools and interactive tutorials that illustrate microscopic phenomena encouraged physics students to engage in a discussion of the underlying quantum concepts; (b) multiple representation tools and interactive tutorials appeared to provide different learning opportunities for physics students to undergo conceptual change toward constructing a deep understanding of the basic concepts of quantum mechanics; and (c) their complementary purposes, particularly, appeared to contribute to developing the extent of physics students' conceptual understanding of quantum mechanics in one or another ways. Thus, from many perspectives, these instructional strategies used here in this study, in contrast to the traditional ones (Ayene et al., 2011), found to be capable of achieving a demanding instructional objective: to provide a deep understanding of the basic concepts of quantum mechanics. This study provided mainly qualitative and also quantitative data to examine the learning effects of using multiple representation tools and interactive tutorials. A positive learning outcome, shown by the radical conceptual progression from pre- to post-instruction, may be attributed in most instances to using multiple representations tools and interactive tutorials in quantum mechanics contexts. It is cautious, however, to generalize that physics students achieved the radical conceptual progression by sheer exposure to the multiple representations tools and interactive tutorials in quantum mechanics. In general, the results of this study demonstrated that a well-designed multiple representations coupled with interactive tutorials used within a conceptual change model of instruction can be very effective in promoting the quantum mechanical account of subatomic systems. Students' conceptual learning can benefit from multiple representations-based instructions and guided exploration of interactive tutorials. This has relevance not only to the basic concepts of quantum mechanics, but also to advanced topics of quantum mechanics and other science disciplines. Nevertheless, wider use and controlled trials are needed to completely investigate the conceptual learning benefits of these innovative instructional strategies.

CHAPTER 7

CONCLUSIONS, IMPLICATIONS AND FUTURE CONSIDERATIONS

7.1 INTRODUCTION

Chapter 7 consists of the conclusions of the study, an overview of some of the issues that originated from the interpretations of the research data presented in earlier chapters, implications of this research for instructional practice and recommendations for further inquiry. There are two sets of conclusions arising from Part I and Part II of the study. The first sets of conclusions are specific in that they stem directly from the general research question: What depictions of the basic concepts of quantum mechanics do undergraduate physics students have, if any? These conclusions are presented in an overview without much in-depth discussion as they formed an intricate portion of the detail analysis and findings discussed in Chapters 4 and 5. With regard to the issue of generalizability in this first part of the study, these sets of conclusions should be viewed as potential hypotheses generated for future inquiry rather than as generalizations in the traditional scientific perspective. That is, the conclusions arrived at in Part I of the study are those of a phenomenographic type characterized by their applicability to similar contexts and experiences (Ebenezer, 1991).Thus the conclusions drawn from this part of the study can be generalized to other studies which might be conducted in similar subject matter and educational situations and circumstances.

The investigation in Part I of the study revealed that undergraduate physics students had serious conceptual and reasoning difficulties in developing an understanding of the basic concepts of quantum mechanics. This finding is similar to many of the findings from quantum physics education over the past two decades. As discussed in Chapters 4, 5 and 6, the findings of the study into physics students' depictions of quantum mechanics were extrapolated to scaffold possible changes to instructional practices at the university that provided the context for this study. Thus, using this background investigation, two research-based instructional treatments were developed to teach the conceptual topics of quantum mechanics. The first one consisted of a multimodal visualization-style explanation with different abstraction levels of certain quantum mechanics concept presented. This instructional approach presented quantum concepts based multiple representations such as: through verbal (oral and texting), symbolic and equation, graphical, pictorial, tabular/bar, analogy and simulation. The second took the form of interactive quantum learning tutorials. The interactive tutorials used a guided inquiry-based approach to learning and help physics students in building a conceptual knowledge structure by guiding them to discern the structure of quantum phenomena. The learning that results from these instructions was evaluated using a conceptual survey questionnaire on the basic concepts of quantum mechanics. Therefore, the second set of conclusions was derived mainly from general observations made from this part of the study as a whole. The in-depth analysis and discussions of this study were also presented in Chapter 6.

7.2 CONCLUSIONS TO PART I OF THE STUDY

This qualitative study investigated physics students' depictions of the basic concepts of quantum mechanics. The data of the study were collected by semi-structured interviews with 35 undergraduate physics students and analyzed by using developmental phenomenographic analysis method. Mainly, interview responses were analyzed using the phenomenographic analysis where a picture of physics students' conceptual understanding was built by interpreting the given responses and their implications. As a result of the phenomenographic analysis, the description categories which form the basis for physics students' depictions of quantum concepts, such as (i) quantization, (ii) the photon concept, (iii) light quanta, (iv) matter wave and (v) the uncertainty principle were characterized. After they had been exposed to the traditional teaching to quantum mechanics, the description ways of the physics students who participated in this study when depicting the basic concepts of quantum mechanics can be summarized as follows: (a) physics students did not have enough knowledge to depict the basic concepts of quantum mechanics properly; (b) they were influenced by the perspective of classical physics and their naïve perceptions in making explanations related to quantum mechanics; (c) they were also applied mixed ideas, one based on their classical model and the other from newly introduced quantum mechanics; (d) students made inappropriate links to previous classical and QM learning; and (e) only very few number of students made a quasi-quantum explanations by using examples frequently used in quantum mechanics lectures and textbooks.

In conclusion, the findings of physics students' depictions of quantum mechanics do indeed confirm previous studies that quantum mechanics traditional teaching methods favor unsuccessful learning: none of the quantum concepts considered basic to explain quantum phenomena seem to have been adequately understood by the majority of participating undergraduate physics students. When giving explanations related to the properties of quantum entities, they often used non-scientific, classical (often wrong) and mixed terminologies and metaphors. It is therefore viable to conclude, in Ethiopia, that physics students' common difficulties in the quantum mechanics can be traced, in most instances, to superficial generalizations of interpretations (i.e., accessible only in a restricted set of situations) learned earlier from everyday experience, classical physics and/or quantum mechanics. Physics students often failed to understand that some concepts essential to classical physics are discarded or take on new meanings in quantum mechanics, e.g., light is no longer the classical wave of Maxwell's electromagnetic theory, the idea of the trajectory itself is no longer meaningful in quantum mechanics. These conceptual difficulties could be addressed by a change in instructional pedagogy which is informed by research such as implemented here in Part II of the study. On the other hand, the conclusions of this study regarding physics students' depictions might not be generalized to all levels and contexts, but they may give useful insights about conceptual understanding of undergraduate physics students in similar settings.

Specific conclusions arising from Part I of the study were discussed in Chapters 4 and 5, which have been summarized in sections 7.2.1 and 7.2.2 as follows:

7.2.1 Conclusions from Chapter 4

Chapter 4 presented physics students' depictions of (i) energy quantization, (iii) the photon concept and (iii) light quanta interference in the double-slit experiment as it pertained to the first three research questions of the study (see section 1.3 for full set of research questions). Students' depictions on these quantum concepts were addressed using an approach based on qualitative problem solving interviews. The specific problems selected apply: to figures presenting the blackbody spectrums, to the photoelectric experimental results that lead to the photon model of light and finally to the gradual formation of an interference pattern in the cases of low-intensity light beam. In responding to the specific objectives, physics students' interviews responses about the basic features of the quantum model of light were sorted and grouped together into the three basic quantum concepts such as, quantization, the photon concept and light quanta creating three different pools of understanding. Interview responses under each of the three pools of data were analyzed using developmental phenomenographic analysis where a picture of physics students' depictions of (i) quantization, (ii) the photon concept and (iii) light quanta was built by interpreting the given responses and their meaning. Consistent with previous studies (e.g., Mannila et al., 2002; Domert et al., 2005) that have used developmental phenomenographic approach, the analysis has generated three set of descriptive categories which form the basis for students' depictions of each quantum concept. These descriptive categories, for instance, for the concept of quantization are energy in BBR as a factor of "square of frequency", hybrid description of energy in BBR and energy in BBR as "Quanta" of energy size $E = h\nu$. Secondly, the descriptive categories for the photon concept are classical intuitive, mixed and quasi-quantum model description. Finally, the descriptive categories for the light quanta are classical wavy and intuitive, mixed and incipient quantum model description. With regard to learning the quantum model of light, the first category (in each quantum concept) made clear that students' depictions were bounded by their naïve perceptions; and most students' depictions were associated to naïve and inadequate descriptions based on classical ontology. An interpretation of these results could be that the majority of students' depictions of the quantum model of light were strongly mediated by classical ontology and primitive intuitions. The second category, hybrid and mixed model description, correspond to overlapped descriptions based on both classical mechanistic ontology and quantum ideas. Students used concepts non-discriminately that are completely different in classical and quantum contexts. Their depictions appeared to be a collection of rather blended ideas which combine aspects of the student's naive views (one based on classical ontology and/or everyday experience) and the other one based on 'accepted' understanding of quantum phenomena.

Furthermore, when considering the research question – "Do students use a consistent depiction of one key quantum concept when presented with different physical situations? – the answer seems to be a clear Yes. In this study, it is shown that physics students with inappropriate depictions of one concept also give inappropriate depictions of other concept in quantum mechanics (see sections 4.6.1 and 4.6.2). There is a close relationship among the concepts of quantization, the photon concept and light quanta, and the categories of description in Tables 4.2, 4.3 and 4.4 showed similar patterns for understanding of these concepts. In the data, most students expressed understanding of the concepts in corresponding categories. For example, as can be seen in Tables, 4.6, 4.7 and Figure 4.8, most students expressed an understanding of quantization corresponding to the first category, these students also expressed an understanding of the photon concept and light quanta corresponding to first category (i.e., identified as inadequate and naïve descriptions based on classical ontology). There are no examples where physics students showed an advanced understanding of one concept (e.g., quantization), and a poor understanding of the other concepts (e.g., the photon concept and light quanta). Finally, since clear relations between depictions of quantization of energy and light quanta were found, depictions of quantization and the photon concept may be a key to understanding inappropriate and/or appropriate depictions in the quantum model of radiation.

7.2.2 Conclusions from Chapter 5

The physics students' depictions of matter wave and the uncertainty principle were discussed in depth in Chapter 5. In this section, an overview of the conclusions which address research question "How do physics students depict the quantum model of particles (matter waves) and the uncertainty principle?" are presented. The depictions of matter waves held by undergraduate physics students after they had been exposed to the traditional approach to quantum mechanics for one quarter of a semester are grouped into three set of description categories. These descriptive categories are classical and trajectory-based model description, an intricate blend of classical and quantum model description and incipient quantum model description. In the classical and trajectory-based model description category, the depictions of classical particles following certain trajectories form the dominant pattern of explanations of quantum entities. Depictions of matter waves in the second category were usually mixed. The students' depictions of matter waves were characterized by an intricate blend of both the classical mechanistic ideas and quantum mechanical perspectives. For example, depiction of interference phenomenon as an outcome of collective behavior of several electrons was prevalent in this category. It is found that trajectory-based and classical ontology and elements of both classical and quantum ideas are dominant in the majority of students' responses. These description categories are variants of classical-like types of depictions, and only the third description category, identified in only three physics students' responses, could permit an incipient quantum model of understanding of matter wave (see Figure 5.6). In general, the majority of students' explanations reflected a lack of quantum mechanical knowledge.

Similarly, the developmental phenomenographic analysis has generated three set of descriptive categories which form the basis for these physics students' depictions of the uncertainty principle. These descriptive categories are quantum uncertainty as classical ignorance, quantum uncertainty as measurement disturbance and quantum uncertainty as a quasi-quantum principle. In the classical ignorance category, students depicted quantum uncertainty as a representation of our ambiguity created by missing of information that could be known. They also described uncertainty as a measurement error due to an external effect such as thermal agitation, noise, vibration, the surrounding contacts, etc. In general, the majority students in this category used the idea of classical ignorance in their responses when making explanations about the uncertainty principle. As with the first category, the second category (i.e., uncertainty as measurement disturbance) contained expressions of uncertainty where it was compared or contrasted with measurement uncertainty. In this category, students linked the idea of uncertainty principle to the term measurement disturbance. These ideas pointed to the contrasting meaning of the term. The distribution of all physics student answers was presented in Figure 5.9. It is revealed that many physics students did not understand the quantum mechanical description of microscopic particles and the interpretation of the uncertainty principle as an inherent indeterminacy in microscopic events. In particular, they did not show an understanding of the incompatibility between the concept of trajectory and quantum uncertainty. Students also had difficulty in distinguishing between the probabilities in the quantum world, the measurement disturbance and our classical ignorance. They seemed to be conceptually unaware of distinctions between classical and quantum perspectives of uncertainty. These findings are consistent with previous studies in different countries and contexts, confirming that after the traditional quantum mechanics instruction students' difficulties are real, stable over time and cross-cultural (e.g., Mashhadi, 1993; Mashhadi & Woolnough, 1999); Olsen, 2002; Ireson, 2002; Kalkanis et al., 2002; Greca & Freire 2003; Singh et al.,2006; Ayene et al., 2011).

7.3 CONCLUSIONS TO PART II OF THE STUDY

Part I of this study has presented the results from a developmental phenomenographic investigation of physics students' depictions of the basic concepts of quantum mechanics. During this investigation, several serious conceptual and reasoning difficulties were identified that physics students have in developing an understanding of the basic concepts of quantum mechanics. Identification of these conceptual difficulties can help the design of new instruction strategies and tutorials to improve physics students' understanding of quantum mechanics (Singh et al., 2006; Zhu & Singh, 2012;2013). Mainly, results from this study were applied to develop multiple representations-based instructions and interactive learning tutorials to improve physics students' understanding of quantum mechanics. The multiple representations-based instructions and interactive learning tutorials have provided a guided approach to bridge the gap between the qualitative and quantitative issues related to the basic concepts of quantum mechanics and helps student participants connect different quantum concepts and built an appropriate knowledge structure. The multimodal representations and interactive tutorials have kept students actively engaged in the whole learning process. In general, the preliminary assessment indicated that the multiple representations-based instructions and interactive learning tutorials are helpful in improving most physics students' understanding of the basic concepts of quantum mechanics.

Physics students' pre-instruction ideas in quantum mechanics was strongly influenced by classical ontology and students' difficulties in the basic concepts of quantum mechanics have been repaired through multiple representation-based instructions and interactive learning tutorials. In this study, immediately after the multiple representations-based instructions and interactive tutorials, 73 percent of the students demonstrated an understanding of a quantum mechanical ontology and using the quantum explanatory preferences in explaining microscopic phenomena that would be acceptable to a quantum physicist. Nevertheless, seven students who displayed radical progress toward a quantum model of understanding in explaining quantum phenomena on the post-instruction regressed to the types of conceptual understanding of the quantum model with classical fragments with indication of a moderate decay over a seven-week period. Significant to this study is that the case of a full decay into a non-scientific or classical perception of quantum ideas was not evidenced in any of these students' conceptual understanding. Indeed, this is a positive result because these physics students' conceptual understanding of quantum mechanics may have been sustained with ongoing assistance. However, some students did retain some of their naïve and classical perceptions of quantum ideas despite the multiple representations-based instructions and interactive tutorials. This is not astonishing since previous studies point out that alternative conceptions persist in spite of the reformed instruction (Driver & Easley, 1978; Hess, 1987). Hess (1987) pointed out that some "alternative conceptions often outlive the instruction that was meant to supplant them".

In conclusion, quantum phenomena are dynamical and multiple representations and interactive visualization learning tools brought a breakthrough by visualizing real time-dependent quantum mechanical processes. Empirical evidence has shown that the systematic strategy of representing quantum phenomena in the multiple representations and interactive learning tools can help physics students abandon these classical perceptions of quantum ideas and develop expertise in using quantum ontology in explaining microscopic phenomena. Thus, when multiple representations and interactive tutorials used to a lesser or greater extent, as in these quantum mechanics classrooms, they appeared to provide different learning opportunities for students to undergo radical conceptual change toward constructing a deep understanding of the basic concepts of quantum mechanics. Finally, this study has presented a way to use multiple representations and interactive learning tools in helping physics students gain a meaningful understanding of abstract concepts and in developing appropriate mental pictures. A well-designed multiple representations-based instructions and interactive learning tutorials used within a conceptual change model of instruction can be very effective in encouraging understanding (Abdurrhaman, 2010; Singh, 2008).

7.4 IMPLICATIONS OF THE STUDY

As a result of these two sets of conclusions and observations, pedagogical implications and considerations for further research, are presented in the subsequent paragraphs.

The findings discussed in Chapters 4 and 5 have revealed the presence of conceptual difficulties that persisted after traditional instruction in the undergraduate quantum mechanics course. Although students developed some skills in solving quantitative problems, they had serious difficulties depicting quantum phenomena that require a solid qualitative understanding of the basic concepts of quantum concepts. It is very important to understand the mathematical nature of quantum mechanics, but it is inadequate. For most undergraduate students, far more difficult than the mathematics of quantum mechanics are its counterintuitive and abstract concepts. The concepts in quantum mechanics are such that it took quantum physicists more than twenty-five years to appropriately understand them. Therefore, it is not surprising that an undergraduate student should find them difficult. For this reason, in teaching quantum mechanics courses, it is important that the teachers take a better way that logically connects the various concepts into a quantum system, instead of presenting each one separately. Besides, it is also necessary that the learners see how these concepts came into being, and this requires some representations and visualizations of quantum phenomena. Wherever possible, demonstrations or visual aids on fundamental ideas like the wave- and particle-like properties quantum entities, the uncertainty principle, and measurement of observables should be integrated into the teaching methods to involve students actively in the learning process, and help them established links between the abstract formalism and the conceptual aspects of quantum mechanics (Özcan, 2011). In particular, the uncertainty principle and wave-particle duality should be presented not just as theoretical ideas but in light of experiments and/or interactive tutorials for illustrations. These experiments and/or interactive simulations could be demonstrated during a lecture with students partaking in a discussion, or they could be executed as a tutorial with conceptual questions relating to wave-particle duality and the uncertainty principle. Mainly, presenting direct consequences of such concepts on interactive learning environments will help the students to visualize the quantum phenomena and, as a result, to construct adequate mental models to describe it.

Instructions in the undergraduate quantum mechanics classrooms should also aim to give physics students some understanding of how quantum mechanics fundamentally differs from classical physics. The understanding of a quantum mechanical explanation requires a more fundamental restructuring of the classical knowledge base, the revision of classical presuppositions and conceptions, before the intervention mechanisms can work. To this end, to demonstrate the logical, conceptual and ontological incompatibility of classical physics and quantum mechanics, a comparative instruction of the classical and quantum concepts seems to play a crucially role in processes of conceptual change.

Part I of this study has yielded a limited set of descriptive categories in accounting for physics students depictions of quantum phenomena. Within the categories of description for quantum mechanics, there were some variations in the pattern of reasoning. Consideration of the findings of this study suggests ways in which the description categories which form the basis of physics students' ideas of quantum mechanics might be refined for future research. An analysis of the physics students' depictions helped the researcher (instructor) to examine the teaching and learning of quantum mechanics and to reconsider issues: what makes conceptual understanding difficult and whether it is possible to identify the basic concepts students need to learn quantum mechanics. As well, a conscious effort was put forth to match instructional strategies and learning tools (i.e., multiple representations and interactive learning tutorials) with physics students' conceptual difficulties. Although the investigation into student depictions of quantum mechanics (Part I) and the instructional design, implementation and assessment of the study (Part II) took place in different student populations, evidence suggests that the multimodal activities and interactive tutorials that engage students and force them to challenge their understanding can benefit students of quantum mechanics. Thus, findings of the study suggest potentially important implications for the teaching and learning of physics, in particular, the basic concepts of quantum mechanics. It is hoped that the investigation into student depictions of quantum mechanics provides useful insight for instructors at any level of quantum mechanics instruction. Additionally, the teaching approaches used for the multiple representations-based instructions and interactive tutorials can be considered for other similar classrooms to promote conceptual change and/or learning progression among physics students. Overall, it had been observed that multimodal representations and interactive tutorials used within a conceptual change model of instruction enable physics students to build conceptual changes which explain their observations. Therefore, undergraduate physics teachers should emphasize applications of multiple representations and interactive tutorials. As well, the multimodal representations of concepts should be emphasized in most undergraduate physics courses.

7.5 FUTURE CONSIDERATIONS OF THE STUDY

From a practical point of view, it is believed that the results presented so far suggest a number of areas for future study. The findings shed light on how the instructional pedagogy of the multiple representations-based instructions and interactive tutorials contributes to the development of students' conceptual understanding of quantum mechanics. From several perspectives, the instructional pedagogy explored in this case study, in contrast to the traditional ones, seems to be capable of providing a deep conceptual understanding of the basic concepts of quantum mechanics. Nevertheless, further research would also be useful to explore whether adapted versions of this instructional pedagogy was successful in more experimental settings. We may, for instance, investigate more thoroughly how the instructional pedagogy of the multiple representations-based instructions and interactive tutorials contributes to the development of physics students' ideas of quantum mechanics both by studying individual students' conceptual change and using control groups. Further research could also be conducted beyond the quantum mechanics courses. Multimodal representations and interactive learning tutorials can be implemented to most topics in quantum mechanics. Few basic concepts of quantum mechanics were chosen for this case study, however it is recommended to use this instructional pedagogy in further related advanced topics of quantum mechanics and other physics courses such as statistical physics, solid state physics and nuclear physics.

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APPENDICES

APPENDIXI INTERVIEW QUESTIONS ABOUT QUANTUM MECHANICS

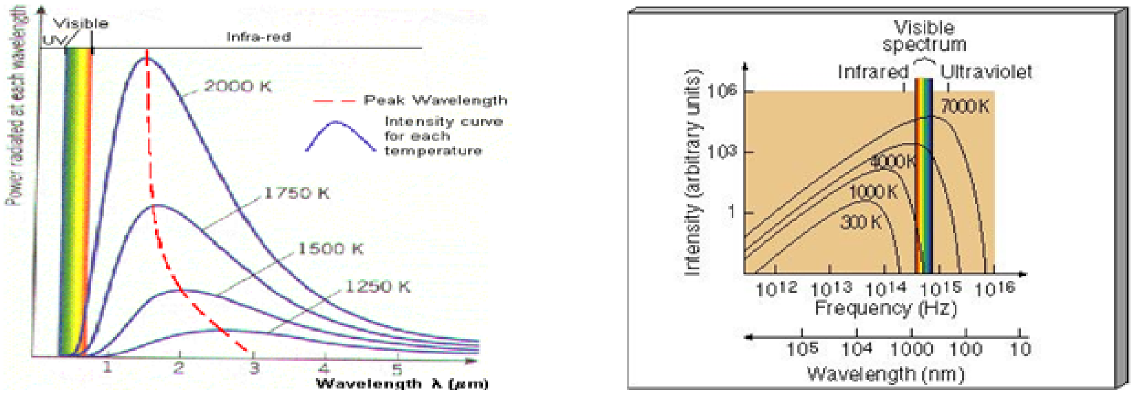
I.1 Questions about the Quantum Model of Light

I.1.1 Questions about the Quantum Rule of Energy Quantization in the BBR Spectrum

1. When heated, a solid object glows and emits heat radiation. As the temperature increases, the object becomes red, then yellow, then white. What underlying reason do you think is behind the change in color of a heated object as its temperature increases?

The curves in the figures below show the blackbody radiation spectrum ((a) as a function of the wavelength of the radiation and (b) a function of the frequency of the radiation) for different temperatures: In each case, explain your reason why blackbody radiation should be distributed in the manner observed as below in (a) and (b)? In particular answer the questions below.

1. In a BBR versus wavelength curve, how do you describe the blackbody curve in each region of the spectrum with temperature?
2. In a BBR versus frequency curve, how do you describe the blackbody curve in each region of the spectrum with temperature?



(a) (b)

Figure I.A: Blackbody radiation spectrum curve at different temperatures ((a) only as a function of wavelength, λ (b) mainly as a function of the frequency, ν)

3. What major effects do you expect that governs the distribution of BBR?
4. In a BBR versus Wavelength curve, as temperature is increased, intensity of emission increases, and peak wavelength λ shifts to smaller λs. But why does emission go to zero at very short wavelengths?
5. In a BBR versus frequency curve, you found that at a given temperature the energy radiated at given frequencies increased as the frequency was raised, reached a peak, and then why began to decrease as the frequency was raised still further? Why blackbody radiation is distributed in the manner observed over the entire range of frequencies?

6. Why does new peak radiation move into higher and higher frequencies as the temperature goes up? Or why is the new peak is at higher frequency than the previous one in the in a BBR vs frequency curve?
7. How do you account for the fact that the probability of radiation decreased as frequency increased in the blackbody spectrum?

I.1.2 Questions about the Photon Concept

Think of as many reasons as possible to support your answers for the following questions:

I. You perform the photoelectric effect experiment using sodium as the target metal. You find that a light intensity with 300nm light, you have about 1000 electrons being ejected per second. Suppose you are making observations of both the number of electrons being ejected per second and the kinetic energy of these ejected electrons. Describe your observations.

a. Describe what you observe when you turn the intensity down and down until it is 1/1000th of its current value. (Include qualitative graphs of the number of electrons ejected per second versus intensity, and max KE versus intensity, to support your words. Label any important points on your graphs.)
b. Describe what you would observe as you vary the color of light over a broad range (from far IR to far UV). (Include qualitative graphs of number of electrons ejected per second versus frequency, and initial KE versus frequency, to support your words. Label any important points on your graphs.)
c. From the observations in parts a and b, what inferences or conclusions can you make about the nature of light? List at least 2 inferences for part a and 2 for part b. Include the reasoning that leads you to these inferences.

II. In the Compton scattering experiment a photon of yellow light is Compton scattered through π *rad* by free electrons and you have observed the presence of only unmodified radiation (not color change is noticed to the scattered light radiation). For any possible change mentioned below, what changes do you notice if it exists about the scattered radiation? Explain your reasoning in detail in each case.
a. When the yellow light is replaced with an Infrared light radiation
b. When the yellow light is replaced with X-ray photons; or gamma ray photons

I.1.3 Questions about Light Quanta Interference in the Double-slit Experiment

- We accept that light radiation show particle-like properties. What would you say are the simplest "particle-like" properties that light radiation could show? Would you say that light radiation could also exhibit "wave-like" properties?

The patterns that appear in photographs of a-d are the typical interference pattern that appear after different periods of time, from a few minutes (the top pattern) to a few hours (the bottom one) obtained in double slit experiment when monochromatic light is projected through two adjacent narrow slits. Based on this figure answer the questions below. Explain your reasoning in each case. You may use a drawing or sketch to explain you answer.

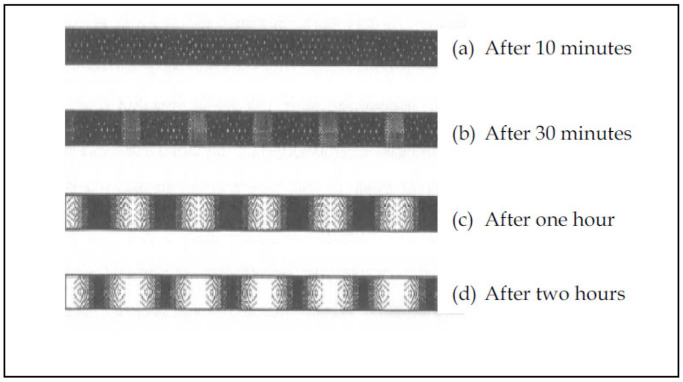


Figure I.B: The interference patterns of the double slit experiment that appears in the photographic images after different periods

1. Explain briefly what is discovered in figure (*a*), and how the occurrence of white 'dots' in it can be explained. What can you say about the behavior of light in this situation?
2. Explain briefly what is discovered in figure (*d)*, and how the occurrence of white 'stripes' in it can be explained. What is the process or course of events that causes the phenomenon?
3. What can you say about the property of light in this situation?
4. Why the shape and form of a typical interference pattern began to emerge in the distribution of the dots after longer periods of time?

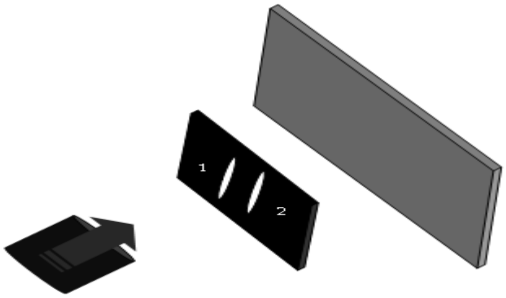
5. Do you think that the interference patterns that appear will be changed if the first slit is closed and the second is then opened for the same period of time as the first case? What will happen then when each slit is opened for half the time but never both at the same time?
6. Why both slits must kept open for an interference pattern to appear?
7. How the occurrence of the bright bands and the dark bands in the photographic image of the interference pattern corresponds to (or can be explained)?
8. Explain briefly the intensity of light at a particular point in the photographic image of the interference pattern where bright bands-intensity maxima- dark bands- intensity maxima occur.

I.2 Questions about the Quantum Model of Matter Waves

I.2.1 Questions about double-slit experiments with electrons

- In quantum mechanics courses we say electrons, protons and photons behave like waves, as well as like particles. What would you say are the simplest 'particle-like' and 'wave-like' properties that one of these things could show?

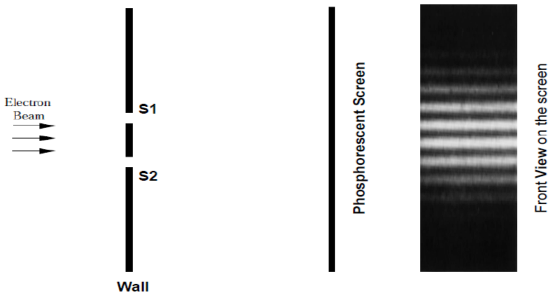
As shown in Figure I.3, an electron gun is set to fire thousands electrons per second. The screen at the back detects the electrons that make it through the slit(s). Predict what will happen on the screen for any possible change on the experimental setup and explain your reasoning and/or sketch the result in each case.



2. If only the first slit (S1) is blocked off and if the electron gun is fired for hours, what will the pattern look like? Sketch and explain the reason.
3. If only the second slit (S2) is blocked off and if the electron gun is fired for hours; what will the pattern look like? How does this pattern compare to the previous one?
4. When both slits are uncovered and if the electron gun is fired for hours; how does this pattern compare to the two single slit patterns? How does this pattern compare to the single slit patterns?
5. When the intensity is reduced so that there will only be one electron going through the slits at a time, predict where the next electron will hit the screen?
6. When the intensity of the gun is altered so that only one electron is travelling at a time, what will the pattern look like?
7. A detector is added to the left slit. This will be able to detect whether the electrons went through the left side or the right slit. It will not block the electrons. What will the pattern look like? How does this pattern compare to the two single slit patterns?

I.2.2 Questions about matter waves (electrons) interference

A beam of electrons is incident on a wall that contains two narrow slits. The simulated photograph shows the pattern seen on a phosphorescent screen placed at a distance from the slits. The brighter regions indicate the concentrations of electrons hitting the screen.



Assume this experiment was repeated with one change made at a time with the original setup. For any possible change mentioned below predict what will happen on the screen. Explain your reasoning in each case

- The speed of electrons is increased
- If the electrons are replaced with elementary particles, with each particle having the same kinetic energy as each of the original electrons but a higher mass.

I.3 Questions about the Uncertainty Principle

1. Is it possible for quantum physics teachers to carefully perform the same experiment (i.e., a quantum experiment) and get two very different results that are both correct? Explain your agreement or disagreement with reasoning.
2. If you know exactly the initial condition (say, for example, you do measure the position of an electron and you find it to be at a certain point P) can you determine where was the electron just before you made the measurement? Can you predict with 'certainty' the future states resulting from it?
3. In quantum mechanics, you cannot predict with certainty the outcome of a simple experiment to measure its position. Is it a peculiarity of microscopic world, a fault in the measuring apparatus, lack sophisticated technology, or what?
4. Recall the simple double-slit electron interference experiment; can you determine the impact point of an electron on the screen before the instant of

impact? Can you track the particle position without destroying its interference pattern?

5. In quantum mechanics, the degree to which a physical variable can be precisely measured is subject to some uncertainty. What does this meant to you? Do you think that repeated errorless measurements of the variable will always give precisely the same value? Why? Can you describe mathematically the Heisenberg uncertainty relations? What is the meaning of Δx and Δp?
6. Do you think that the Heisenberg Uncertainty Principle is generally applied to macroscopic objects such as electrons, photons, cars and tennis balls? If not, why don’t we see the uncertainty principle on larger objects such as cars and tennis balls?

APPENDIXII STUDENT CONSENT FORM

I, ______________________________, agree to participate in the research project, "Conceptual Understanding of Quantum Mechanics: An Investigation into Physics Students' Depictions of the Basic Concepts of Quantum Mechanics" (the Title is modified). Mengesha Ayene, who is a PhD student at ISTE, UNISA, is conducting this study.

I understand that the principal purpose of the study is to investigate physics students' depictions of the basic concepts of quantum mechanics and categorizing their depictions according to a set of categories constructed by the researcher using phenomenographic perspectives (Marton & Booth, 1997). I understand that the findings will form the basis for the development of research-based instructional strategies and learning tools to contribute towards efforts aimed at improving physics students' understanding of quantum mechanics in Wollo University, Ethiopia.

I understand that my participation in this research will involve being interviewed by Mengesha Ayene. This interview will involve reflection on my conceptual understanding of the basic concepts of quantum mechanics. I understand that the interview will be taped. I may be asked to comment subsequently on the analysis of the content of my interview and written explanations.

I agree that the research data gathered from this study will be used in the writing of a PhD thesis and may be published or presented in a form that does not identify me. Thus, I understand that my involvement is strictly confidential and no information about me will be used in any way that reveals my identity. I understand that my agreement or rejection will not in any way affect my status in classroom interaction or in academic assessment. I understand that I am free to withdraw from this project at any time without giving a reason. I will have access to the information that I have provided.

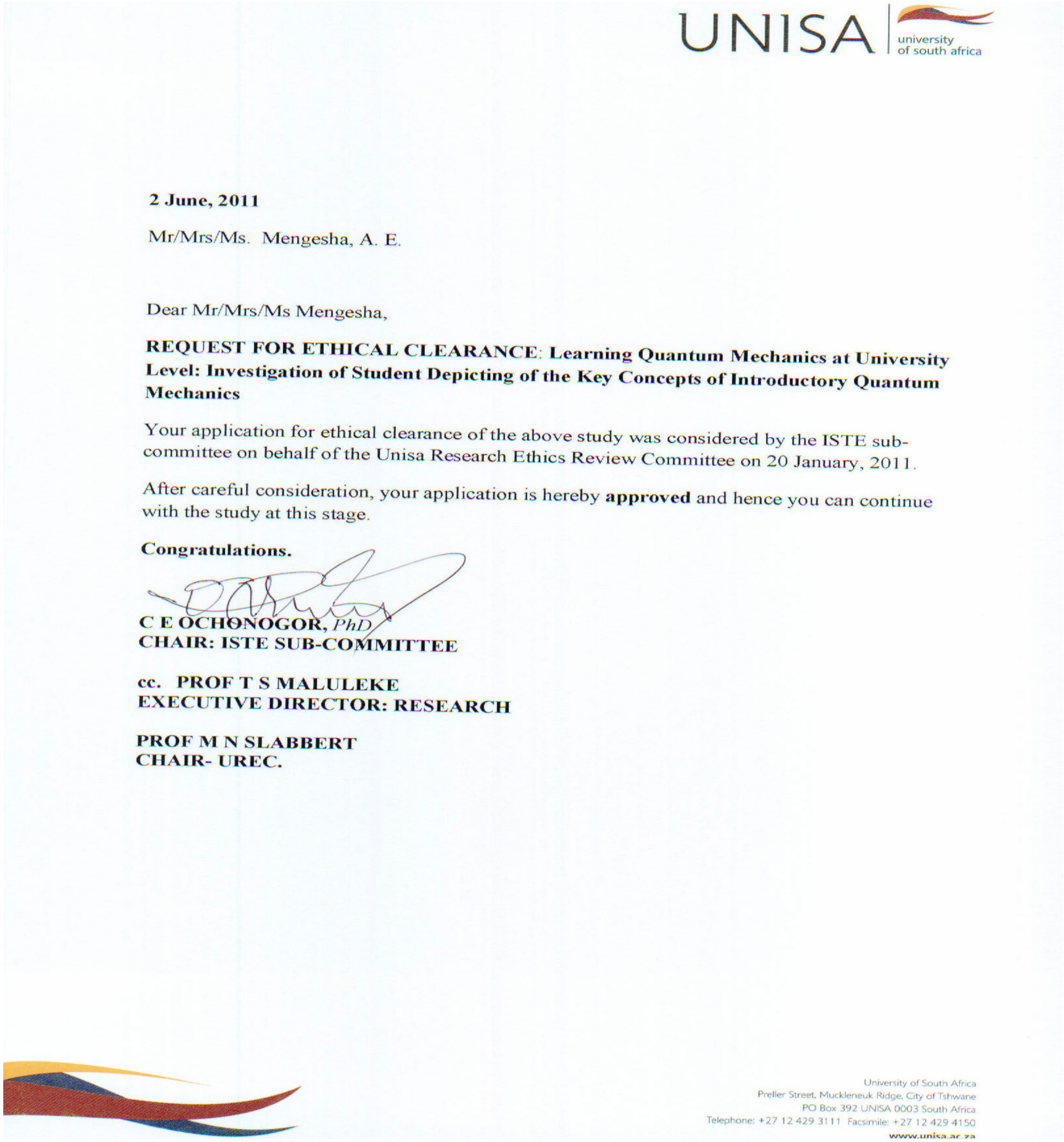
I agree that Mengesha Ayene has answered my questions fully and clearly. I understand that I am at liberty to contact Mengesha Ayene's Co-supervisor, Dr Baylie Damitie, here in Ethiopia if I have any concerns about the research project.

Signature: ____

Name: ____

Date: ____

APPENDIXIII ETHICAL CLEARANCE



UNISA
university
of south africa

2 June, 2011

Mr/Mrs/Ms. Mengesha, A. E.

Dear Mr/Mrs/Ms Mengesha,

REQUEST FOR ETHICAL CLEARANCE: **Learning Quantum Mechanics at University Level: Investigation of Student Depicting of the Key Concepts of Introductory Quantum Mechanics**

Your application for ethical clearance of the above study was considered by the ISTE sub-committee on behalf of the Unisa Research Ethics Review Committee on 20 January, 2011.

After careful consideration, your application is hereby **approved** and hence you can continue with the study at this stage.

Congratulations.

C E OCHONOGOR, *PhD*
CHAIR: ISTE SUB-COMMITTEE

cc. PROF T S MALULEKE
EXECUTIVE DIRECTOR: RESEARCH

PROF M N SLABBERT
CHAIR- UREC.

University of South Africa
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APPENDIXIV QUANTUM MECHANICS CONCEPTUAL SURVEY QUESTIONNAIRE (QMCSQ)

The Quantum Mechanics Conceptual Survey Questionnaire (QMCSQ) is primarily derived from our previous probing tools, the semi-structured quantum mechanics interview questions (Ayene et al., 2011; Ayene et al., 2013; see Appendix I). Thus, the majority of the questions are directly copped from interview questions (see Appendix I) and they were only rewritten with respect to the purpose of Part II of the study. According to its relevance to interpretive themes, the QMCSQ is grouped into three categories denoted as: Questionnaire I (Relevant to the dual wave/particle nature of light, or emphasizing its particle-like characteristics), Questionnaire II (Relevant to the dual wave/particle nature of matter, or emphasizing its wave-like characteristics) and Questionnaire III (Contrasting perspectives those that addressed the uncertainty principle (indeterminacy issues), randomness, or the probabilistic nature of quantum mechanics).

IV.1 QMCSQ Part I

1. In Quantum Mechanics courses we say that light behaves like a particle, as well as like a wave. When does light behave like a wave and when does it behave like a particle? What would you say are the simplest "particle-like" and "wave-like" properties that light could show?
2. In Quantum Mechanics courses we say photons behave like waves, as well as like particles. What would you say are the simplest ‘particle-like’ and ‘wave-like’ properties that these photons could show?
3. Suppose you were to perform the photoelectric effect experiment using sodium as the target metal. You find that at your present light intensity with 300nm light, you have about 1000 electrons being ejected per second. **You are making observations of both the number of electrons being ejected per second and the kinetic energy of these ejected electrons.**

   a) Describe what you observe when you turn the intensity down and down until it is 1/1000th of its current value. (Include qualitative graphs of the number of electrons ejected per second vs intensity, and max KE vs intensity, to support your words. Label any important points on your graphs.)

b) Describe what you would observe as you vary the color of light over a broad range (from far IR to far UV). (Include qualitative graphs of the number of electrons ejected per second vs frequency, and max KE vs frequency, to support your words. Label any important points on your graphs.)

c) Describe the effect of varying the target metal (the work function of the metal)

d) From the observations in parts a and b, what inferences or conclusions can you make about the nature of light? List at least 2 inferences for part a and 2 for part b. Include the reasoning that leads you to these inferences.

4 A photon of yellow light (wavelength = 550nm) is Compton scattered through 90 degree by a free electron. Could you notice the color change of the photon? why? Explain your reasoning.

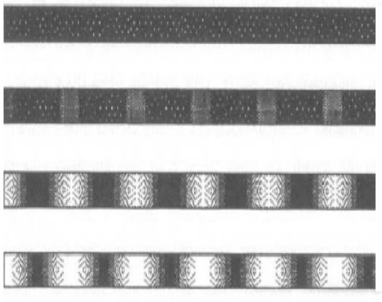
5 **Double-slit experiment with high intensity light beam:** A monochromatic light gun is set to fire thousands of photons per second. The screen at the back detects the photons that make it through the slit(s).

(a) When both slits are uncovered, what will the pattern look like?

(b) When the intensity of the gun is altered so that only one electron is travelling at a time. What will the pattern look like?, Explain where on the screen the next photon will land? How does this pattern compare to the two single slit patterns?

(c) A detector is added to the left slit. This will be able to detect whether the electrons went through the left side or the right slit. It will not block the electrons. Sketch and explain the result? How does this pattern compare to the two single slit patterns?

6 The patterns that appear in photographs (shown below) of a-d are the typical interference pattern that appear after different periods of time, from a few minutes (the top pattern) to a few hours (the bottom one) obtained in double slit experiment when monochromatic light is projected through two adjacent narrow slits. Based on this figure answer the questions raised below. Explain your reasoning in each case. You may use drawings, picture and sketches to explain your answer.



a) Explain briefly what is discovered in figure (*a*), and how the occurrence of white 'dots' in it can be explained. What can you say about the behavior of light in this situation?

b) Explain briefly what is discovered in figure (*d*), and how the occurrence of white 'stripes' in it can be explained. What is the process or course of events that causes the phenomenon?

c) What can you say about the property of light in of this situation?

d) Why the shape and form of a typical interference pattern began to emerge in the distribution of the dots after longer periods of time?

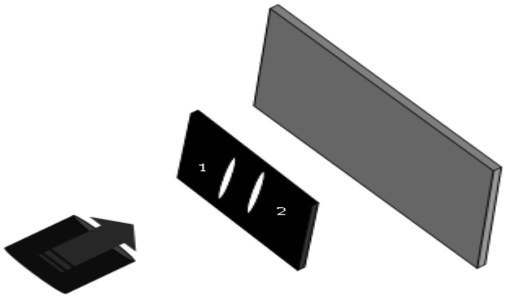
e) Do you think that the interference patterns that appear will be changed if the first slit is closed and the second is then opened for the same period of time as the first case? What will happen then when each slit is opened for half the time but never **both** at the same time?

IV.2 QMCSQ Part II

1. You have learnt about water waves, surface waves, micro waves, sound waves and light waves in your Wave and Optics Course. In 1924 Louis de Broglie proposed that microscopic entities or objects are also waves. What do you mean when you say "microscopic entities are waves"? What would you say are the defining properties of a wave?

2. We say that electrons, protons, neutrons and other microscopic objects behave like waves, as well as like particles. What would you say are the simplest 'particle-like' and 'wave-like' properties that one of these objects could show?

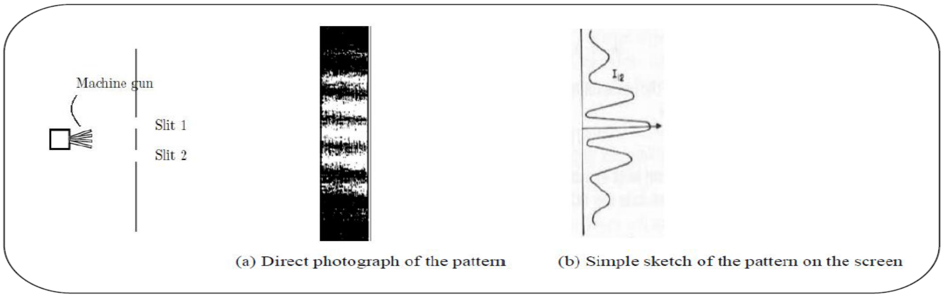
3. Anelectron gun is set to fire thousands electrons per second. The screen at the back detects the electrons that make it through the slit(s). Predict what will happen on the screen for any possible change on the experimental setup and explain your reasoning and/or sketch the result in each case.



a) If only the first slit (S1) is blocked off and if the electron gun is fired for hours, what will the pattern look like? Sketch and explain the reason.
b) If only the second slit (S2) is blocked off and if the electron gun is fired for hours; what will the pattern look like? How does this pattern compare to the previous one?
c) When both slits are uncovered and if the electron gun is fired for hours; how does this pattern compare to the two single slit patterns? How does this pattern compare to the single slit patterns?
d) When the intensity is reduced so that there will only be one electron going through the slits at a time, predict where the next electron will hit the screen?
e) When the intensity of the gun is altered so that only one electron is travelling at a time, what will the pattern look like?
f) A detector is added to the left slit. This will be able to detect whether the electrons went through the left side or the right slit. It will not block the electrons. What will the pattern look like? How does this pattern compare to the two single slit patterns?

4. A beam of monochromatic electrons is incident on a mask that contains two very narrow slits. Suppose the direct photograph in (a) and/or a simple sketch in (b)

shown below depicted the pattern observed on a photographic screen placed far from the slits after some hours.



(a) Direct photograph of the pattern (b) Simple sketch of the pattern on the screen

Suppose this experiment is repeated with a single change made to the original setup. For each possible change described below predict and compare the changes on the pattern that will be seen on a photographic screen placed far from the slits. Explain your reasoning in each case.

a) The speed of electrons is increased
b) If the electrons are replaced with elementary particles, with each particle having the same kinetic energy as each of the original electrons but a higher mass.

IV.3 QMCSQ Part III

1. If you know exactly the initial condition (say, for example, you do measure the position of an electron and you find it to be at a certain point P) can you determine where was the electron just before you made the measurement? Can you predict with 'certainty' the future states resulting from it?
2. In quantum mechanics, you cannot predict with certainty the outcome of a simple experiment to measure its position. Is it a peculiarity of microscopic world, a fault in the measuring apparatus, lack sophisticated technology, or what?
3. Recall the simple double-slit electron interference experiment; can you determine the impact point of an electron on the screen before the instant of impact? Can you track the particle position without destroying its interference pattern?

4. The double-slit experiment illustrated several fundamental concepts in quantum mechanics. Explain what each of these is and how they are demonstrated in the experiments: (a) Intrinsic Randomness and probability and (b) Heisenberg's Uncertainty Principle
5. In Quantum mechanics, the degree to which a physical variable can be precisely measured is subject to some uncertainty. What does this meant to you? Do you think that repeated errorless measurements of the variable will always give precisely the same value? Why? Can you describe mathematically the Heisenberg uncertainty relations? What is the meaning of Δx and Δp?
6. Do you think that the Heisenberg Uncertainty Principle is generally applied to macroscopic objects such as electrons, photons, cars and tennis balls? If not, why don't we see the uncertainty principle on larger objects such as cars and tennis balls?