How do the Students Describe the Quantum Mechanics and Classical Mechanics?

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Abstract
The major goal of physics education researchers is to identify the student difficulties in learning of conceptual and mathematical basis of physics. In order to answer the research question, phenomenographic approach was used in the design of this study to analyze data from the open ended questions with 15 upper undergraduate level students (aged 21-23) in physics departments in Turkey by using representative convenience and purposeful sampling techniques. We have administrated a questionnaire with two open ended questions which covers the basic properties of quantum mechanics and classical mechanics to learn the ideas of students. We have reported the results set of categories that describe the participants' approaches to understanding the quantum mechanics and classical mechanics.

Keywords: Quantum Mechanics, Classical Mechanics, Phenomenographic study.

Resumen
El principal objetivo de los investigadores en educación en física es identificar las dificultades de los alumnos en el aprendizaje de las bases conceptuales y matemáticas de la física. Para responder a la pregunta de investigación, en el diseño de este estudio se utilizó el enfoque fenomenográfico para analizar los datos de las preguntas abiertas, con 15 estudiantes de nivel superior de pregrado (21-23 años) en los departamentos de física en Turquía mediante el uso de representaciones convenientes y técnicas de muestreo representativo. Se administró un cuestionario con dos preguntas abiertas que cubre las propiedades básicas de la mecánica cuántica y la mecánica clásica para aprender las ideas de los estudiantes. Hemos reportado el conjunto de resultados de categorías que describen los enfoques de los participantes para comprender la mecánica cuántica y la mecánica clásica.

Palabras clave: Mecánica Cuántica, Mecánica Clásica, Estudio fenomenográfico.

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I. INTRODUCTION

The major goal of physics education researchers is to identify the student difficulties in learning of conceptual and mathematical basis of physics. On the other hand it may help to instructors to improve the students' understanding of physics and related concepts. For an exact quantum mechanics teaching, numerous mathematical manipulations and deep understanding of conceptual structure are equally important and necessary. Quantum theory is a successful theory of physics which describes, correlates and predicts the behaviors of [1] atomic systems. Not being able to see atomic systems in our daily lives, not reasoning physical situations intuitively and not stating all of them with basic algebra make quantum mechanics (QM) abstract, counter-intuitive and highly formal. In addition to these special characteristics, its highly philosophical and interpretive structure which is totally different from classical mechanics (CM) implies that it is a new paradigm of physics.

A fundamental difference between CM and QM is that, in CM, the state of the dynamic system is completely specified by the position and momentum of each component of the system. Because of this reason, in principle, the position and momentum of a particle can be measured and determined exactly at each instant of time [2]. In other words the position and momentum of the particle at one instant of time one completely specified by the position and momentum of the particle at a previous instant, namely the CM is deterministic. In this way one can specify the state of a particle in the macroscopic world, because one can see and touch such a particle. Therefore it is possible to measure the position and momentum of particle simultaneously. Because of this reason, the CM has commutative mathematical structure [3].

On the other hand, there is no assurance [4] of our intuition in the world on the atomic and subatomic scale where we cannot see or touch any particle directly. In QM, according to "Heisenberg's Uncertainty Principle" no a priori assumption is made about the possibility of measuring or determining exactly the position and the momentum of the particle at the same time. In other words, the mathematical structure of the QM is commutative algebra [2].

The content of QM in under graduate level courses include learning of experiments and mathematical background of theories, Hermitian operators, the solution time dependent-independent Schrödinger equation corresponding different potential function, one-dimensional potential well problems etc. Every topic includes special concepts of Quantum theory which are different from classical mechanics concepts. Because of this reason the students ideas regarding to quantum mechanics and classical mechanics are different. The quantum mechanics concepts are relatively abstract from the concepts of classical mechanics so the students have many difficulties regarding to the quantum mechanics concepts. According to Styer [5] the students have some misconceptions about quantum states, measurement, identical particles, the dimension of the wave function and some other concepts. In addition to these results, many studies have been shown there are another students' difficulties relating to the concepts such as wave particle duality [6] atoms [7], probability [8].

In the present study, phenomenography [8, 9, 10] was chosen as the strategy of methodology to answer the research questions. Phenomenography, which has become the focus of the education researches, aims to understand the various ways in which different people experience, perceive or understand the same phenomenon [11, 12, 13] The core of using this method in educational research is to understand why some students are better learners than the others. According to the phenomenographic approach, there are a limited number of qualitatively different ways in which different people can experience the same phenomenon, but different people will not experience a given phenomenon in the same way.

II. METHOD

In order to answer the research question, phenomenographic approach was used in the design of this study to analyze data from the open ended questions with 15 upper undergraduate level students (aged 21-23) in physics departments in Turkey by using representative convenience and purposeful sampling techniques.

The reason for convenience sampling techniques was to increase the credibility of the research. We have administrated a questionnaire with two open ended questions which covers the basic properties of quantum mechanics and classical mechanics to learn the ideas of students. The questionnaire was performed during 20 minutes with 15 upper undergraduate level students who attended the quantum mechanics course in physics department in Turkey.

III. RESULTS AND DISCUSSION

A. Descriptions of the categories about classical mechanics

In order to help the students with their difficulties in understanding quantum mechanics and classical mechanics concepts, we need to carefully investigate the students' description regarding to two important theories in physics.

TABLE I. Classification of the students' responses about classical mechanics.

Main Categories	Subcategories	Explanation Categories
1) The CM has a holistic point of view This is because:	1.1. The CM systems decomposed in many subsystems.	
	1.2. Atoms, molecules and other systems have the same electrons.	complementary
	1.3. The hydrogen atom consist of one proton and one electron which are the point particles.	complementary macro systems
2) The predictions of CM is deterministic.	2.1. A state at time t can be specified at a previous instant to unique.	unique, constancy macro systems
	2.2. The measurement results are unique, that is, it has the same value before measurement.	constancy
	2.3. The system and the observer obey the	measurement

	same physical law.	determinism
3) The mathematical structure of CM is different from QM.	3.1. All of the observables in CM described with observable commutative algebra	measurement, unique, constancy
	3.2. The space in CM is Euclidian	macro systems
	3.3. The equation of motion is second order differential equation.	

The analysis of responses to the open – ended questions revealed a hierarchical set of categories that describes the participants' approaches to understanding the both of these theories. One of the open ended question was "How do you describe the classical mechanics?" By means of this question, we identified students' description about classical mechanics. The Table I presents the classification of students' responses.

We have reported the category results in two parts which are CM (see Table I) and QM (see Table II). In all components of the first category of CM the students mentioned about philosophical insight of CM. Responses in this category indicates that the CM associated with macro system and Newton's second law F = ma. On the other hand the students' responses indicated that in CM each motion of particle has been understood individually. Category 1.1 describes responses stating that the CM systems decomposed in many subsystems. Moreover this category includes students' responses such as; "The motion of the system can be described with Newton's second law, because all of the particles are identical of which the system are composed". Category 1.2 includes those students who denoted that atom, molecule and other systems have the same electron. All the students explained their responses in terms of the "complementary".

Category 1.3 deal with responses stating that the hydrogen atom consist of one proton and one electron which are the point particles. This category consists of two parts in which the students explained their answers in terms of "complementary" and "macro systems". In the main category 2 the students generally stated that the CM is deterministic with its foresight. Category 2.1 includes those students who denoted that a state at time "t" can be specified at a previous instant to unique. This category was further subdivided to two explanation categories in which the students explained their answer in terms of "unique", "constancy" and "macro systems". In category 2.2, we have confined the students' answers under the concept of measurement. Their responses stated that the measurement results are the same value before the measurement process. It is interesting to note that some of the students were awarded of the measurement process not to change the system in classical mechanics. Category 2.3 deal with responses which is stated that the results of physical laws. In this category the students mentioned about the relationship between observer and the physical systems in terms of measurement and determinism. The last main category was determined as the mathematical structure of CM. Category 3.1 deals with responses stating that in CM all of the observables described with commutative algebra. As an example, one student wrote;

> "*In CM the position and the momentum of a moving object can be specified simultaneously. Because of that reason these observables can commute with each other in CM*".

Category 3.2 describes responses that the mathematical structure of CM based on Euclidian space. They stated their answers in term of macro systems and denoted that the CM investigated the macroscopic world.

Category 3.3 deals with the responses about the equation of motion. Some responses in this category said that the equations of motion are second order differential equations. The student explained their answer in terms of "Newton's law" and "causality principle". Some of the students make an accurate analysis of the Newton's second law.

B. Descriptions of the categories about quantum mechanics

The second open ended question was "How do you describe the quantum mechanics?" By means of this question, we identified students' descriptions and description ways about quantum mechanics. The Table II presents the classification of students' responses.

We have reported the students' answers about QM in three main categories. In all of components in the first category the students mentioned about the perspective of QM and the relation between subatomic systems and Schrödinger wave equation.

Category 1.1 deals with responses which are stated that gravitational effects neglected between subatomic particles. Some of the students emphasize the laws between the subatomic particles and the motion of the particles explained with QM very well. Generally they explained their answer in terms of "micro system" and "mass and force".

Category 1.2 includes those students who denoted that the wave function and Hamiltonian described all of the system. All the responses in this category were used wave – particle duality.

In category 1.3 the students mentioned about high speed motion in QM. In this category they confused the QM with special theory of relativity. Because of this reason they mostly stated that the high speed motion can be explained only with QM.

Category 2.1 deals with responses which stating that the physical magnitudes calculated with probability wave function. The students mostly explained their answer in terms of operator concept and probability. Here is a typical response of students as an example of this category.

Quantum physics is the physics of possibilities.

In category 2.2 we have collected the students' answers under the concept of measurement. In this category they mentioned about the relation between observer and quantum mechanical systems. They stated their answer in terms of "measurement" and denoted that the quantum mechanical systems and the observer are not independent from each other. Category 2.3 deals with responses stating that the measurement results are the only one which is a lot of the different states before the measurement, *i.e.* superposition principle. They explained their answer in terms of "superposition principle" and "wave - particle duality". Category 2.4 included explanations that measurement affected on the system which we have not encountered in classical mechanics. This result indicated that the students are aware of the measurement process in QM. This category was further subdivided to include those who explained their answer in term of "superposition" or "probability". In the main category 3 of QM the students generally mentioned about the differences of the mathematical structure between the QM and CM.

The students explanations were summarized in Category 3.1 contained the mechanical variables of QM which are explained with non – commutative algebra. The students stated their answer in terms of "uncertainty principle" and "measurement". Category 3.2 was similar to the category 3.1 except students' responses included the relation between momentum and the position operator which can not be determined simultaneously.

TABLE II. Classification of the Students' Responses about quantum mechanics.

Main Categories	Subcategories	Explanation Categories
1) The subatomic systems were described by QM and the motion of the system are determined with Schrödinger equation.	1.1. Gravitational interaction neglected between subatomic particles.	micro systems mass and force
	1.2. Wave functions and Hamiltonian described all of the system.	wave-particle duality
	1.3. High speed motions explained with QM.	relativity
2) The foresight of the QM based on probability theory.	2.1. The physical magnitudes calculated with probability wave function.	operators probability
	2.2. The system and the observer are not independent from each other	superposition wave- particle duality
	2.3. The measurement result is the only one of a lot of the different states before measurement.	superposition wave- particle duality
	2.4. The measurements affect the system absolutely.	superposition probability
3) The mathematical structure of QM is different from CM.	3.1. The mathematical structure of the QM is non-commutative algebra.	uncertainty principle measurement
	3.2. The momentum and the position can not be determined simultaneously	uncertainty principle measurement

IV. CONCLUSİONS

This research indicates that upper class undergraduate physics students explain their knowledge on the quantum mechanical nature of atomic systems and the classical behaviors of the macroscopic world indirectly. On the other hand, the students explained and interpreted the whole phenomenon (QM and CM) by means of its concepts. Moreover, the present study indicates that the students have some difficulties to identify the differences between QM and CM.

We suggest that teachers should be able to use these descriptions of probable learning pathways, to improve curricula and to design new learning experiences. Teaching quantum mechanics should also aim to give the students some understanding of how, fundamentally, this part of physics differs from classical mechanics.

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