Evaluating College Students' Conceptual Knowledge of Modern Physics: Test of Understanding on Concepts of Modern Physics (TUCO-MP)

Bayram Akarsu

Department of Science Education
School of Education, Erciyes University
Kayseri, TURKEY
bakarsu@erciyes.edu.tr

(Received 10.04.2011 Accepted 24.05.2011)

Abstract

In present paper, we propose a new diagnostic test to measure students' conceptual knowledge of principles of modern physics topics. Over few decades since born of physics education research (PER), many diagnostic instruments that measure students' conceptual understanding of various topics in physics, the earliest tests developed in PER are Force Concept Inventory (FCI, Newtonian concepts), Force & Motion Conceptual Evaluation (FCME), Electric Circuits Conceptual Evaluation (ECCE), and Test of Understanding Graphs - Kinematics (TUG-K). Although these tests were generated and tested on the fields, they were mainly interested on freshman physics courses. Maybe only diagnostic test developed above freshman was the one initially used by researchers to investigate college students' understanding of quantum physics concepts but unfortunately, its source or history is not known. The main purpose of this study is to declare of a new diagnostic test and reveal initial results of the diagnostic test of Test of Understanding on Concepts of Modern Physics (TUCO-MP).
Keywords: Physics education, science education, diagnostic tool, modern physics.

Introduction

This paper discusses a new type of assessment instrument that measure student knowledge of major modern physics concepts for instance relativity, wave mechanics, nuclear physics, elementary physics, and statistical physics. A research-based, multiple choice and easy to administer diagnostic test was develop to gather information regarding college students' conceptual learning of modern concepts in physics. It can be utilized for two purposes: 1) Administration at colleges especially in freshmen science courses to collect student knowledge of modern concept prior to taking initial modern physics course (pre-test) and 2) Applying to senior and junior level students to check their learning in the courses (post-test) to evaluate the effectiveness of the course. Additionally, it can be used in AP physics courses at high schools.

Over last three decades, assessing student knowledge of various physics concepts such as Newton's Laws (Thornton et al., 1998), Force and motion (Hestenes et al., 1992), kinematics (Beichner, 1994), electricity (Sokoloff, 1993). The need for generating testing measurements emerged in 1990s when physics education research (PER) was initiated as becoming an independent area of research from the roots of science education research (SER). First versions of instruments for that purposes were generally quantitative and still most of them were quantitative probably because of statistical method prevalence on research among social sciences over 150 years. Also, qualitative method is too young to be developed in another young research discipline. However, some qualitative methods (Otero et al., 2009; Ireson, 1999) do exists in PER.

Description of TUCO-MP (Test of Understanding on Concepts of Modern Physics)

TUCO-MP consists of 30 multiple-choice questions. It was generated in order to investigate college students' conceptual learning of modern physics knowledge including pure knowledge of concepts such as theory of special relativity, real world applications, history of science questions, applied problems and some general knowledge questions for example lasers and radars. TUCO-MP includes various topics, which are typically studied in modern physics courses (Pietrocola, 2005) in sophomore year at various science departments including physics, chemistry, science education and math education. Such subtopics, total number of lectures spent on each item is shown in table 1.

In creating TUCO-MP, several research papers on developing diagnostic tests, modern physics textbooks ((Beiser, 2002; Cuttnell et al., 2009), colleagues' comments, and previous tests on university entrance exams (UEE) were utilized. UEE is a general entrance exam that takes place every year and every graduating high school student who wishes to study in college must take it. In a physics education seminar, nineteen physics professors and three physics educators were asked to review the questions in the test to check their technical, logical sides, and content. They also overviewed it according to the importance of the concepts. Based on their comments, it was revised to the present version.

As stated in Table 1, one item was written for each particular concept according to dedicated number of lectures on each chapter. Although it was noted that several outside sources e.g. textbooks and previous research studies were utilized in providing items, the researchers generated most of them. An effort made to construct a more balanced measurement and to assess the concepts among the students. For example, generating two questions for corresponding concepts increase quality of TUCO-MP. In addition, each question was designed purposely to measure students' pure knowledge of concepts and to make them attractive for them to answer all of the questions.

Selected Concepts of Modern Physics	**Number of Lectures & Question numbers**	**Descriptions (Subtopics)**
Particle properties of waves	*7- lectures* 1, 2, 4, 5, 7, 16, 24,	Review of electromagnetic waves, the double-slit experiments: waves versus bullets, diffraction of X-rays by crystals, photoelectric effect, X-ray production, Compton effect, blackbody radiation, what is light? photons and waves, Doppler effect, special relativity
Wave properties of particles	*3-lectures* 14, 19, 23	Double-slit again: electrons, diffraction of particles by crystals (1927) and by "light crystals"(1999), De Broglie waves, Heisenberg uncertainty principle, wave packets, applying the uncertainty principle
Atomic Structure	*4- lectures* 20, 25, 28, 30	Pre-history: the atomic models of Thomson and Rutherford, Spectral lines, History: Bohr's atom - its successes and failures, Energy levels and atomic excitations
The quantum theory	*7- lectures* 6, 8, 9, 10, 17, 21, 27	Schrödinger equation: a wave equation for matter, wave function and probability, stationary states & expectation values, bound states, particle in a box: infinite and finite wells, harmonic oscillator, barriers and tunneling,
The Hydrogen atom	*2- lectures* 18, 22	Schrödinger equation for the hydrogen atom, quantum numbers, radial probability density, radioactive transitions
Two- level systems	*2- lecture* 26, 29	The Ammonia molecule, lasers, holograms, atomic lasers
Statistical Physics	*2- lectures* 13, 15	Microstates and macro states, temperature & entropy, Maxwell velocity and speed distributions, classical equipartition, quantum distributions: bosons & fermions
Gases of bosons	*2- lectures* 12	Photons and black-body radiation revisited, phonons and the heat capacity of solids, Bose-Einstein condensation (BEC), super fluids
Nuclear Physics	*1- lecture* 11	Models of the atomic nucleus, radioactive decay, nuclear reactions: fission & fusion
Elementary Particles	*1- lectures* 3	The four basic forces, particles & antiparticles, particle interactions and decay, quarks, the Standard Model

Table 1. *Modern Physics Concepts in TUCO-MP*

Methodology

The data collection process took place during second term of 2009-10 academic years at Erciyes University in Kayseri in Turkey. Participants of the study were selected among three different faculties, school of science, school of engineering and school of education.

Disciplines at both faculties were the only students enrolled in modern physics similar content in science education, physics and chemistry.

Taken as a whole, approximately 7500 students are studying in these departments. TUCO-MP was administered to around 2350 students and data collected from 540 among them. Participated students were enrolled in different grades freshman to senior year. Some of them already took a modern physics mandatory course already but all of them studies modern physics topics at high school. Therefore, they are familiar and learned the concepts before. A typical modern physics course offered at the university consists of major concepts in special theory of relativity, atomic models, photoelectric effect, quantum mechanics, photons, and Schrödinger equations.

In order to assess student learning in modern physics courses, a new diagnostic instrument was developed and administered to 540 students. In order to overcome linguistic problems, the test is a 30 multiple-choice questions and was assessed in their primary language (Turkish). English version of the selected questions is included in appendix section. The questions measure their conceptual knowledge of modern physics topics rather than mathematical ability of problem solving. It does not include any types of problem based questions and calculations. However, there are some real life questions to probe their learning of applications of the concepts.

Students were asked to answer questions in the test in 30 minutes and most of them finished it earlier. We strongly believe that allowed answering time is enough for the students to read and answer whole questions in TUCO-MP.

Analysis of TUCO-MP

Following data collection process, the corresponding results according to each department are constructed as illustrated in Table 2.

Faculty	**Depart.**	**Grade**	**N**	**Ave (%)**	**SD (%)**
Education	Physics Education	Freshman	102	36	19.2
Education	Physics Education	Sophomore	45	35	19.2
Education	Physics Education	Junior	177	43	19.8
Education	Physics Education	Senior	99	41	23.9
Science	Physics	Sophomore	38	51	33.6
Science	Chemistry	Sophomore	60	39	20.0
Engineering	EE	Sophomore	19	45	20.2
		Total	540	41	22.3

Table 2. Participating student body and their achievement scores on TUCO-MP

Data analysis of the first version of TUCO-MP has revealed that the developed test measurements reflect reliable and valid data related to accepted value in the research community and statistical terms.

In order to test the quality of test items, we used two standard measures using SPSS: difficulty and item discrimination. Difficulty simply shows how difficult the item is based on the correct response to corresponding question. A difficulty values basically ranges between 0.0 and 1.0 with 0.0 being the worst and 1.0 being the best average. A difficulty level of 0.0 indicates that no one answers the item correctly and 1.0 means that everyone gets it correctly. A difficult value of 0.5 of responses is usually considered as the ideal. Figure 1 is designed according to percentages of correct responses by combined science and education programs. The difficulty level of TUCO-MP items range between around 0.10 (10% in the figure) and 0.75 with an average score of 41 (out of 100), which can be considered a feasible value.

Item discrimination is the single best measure of the effectiveness of an item is its ability to separate students who vary in their degree of knowledge of the material tested, and their ability to use it. If one group of students has mastered the material and the other group had not, a larger portion of the former group should be expected to correctly answer a test item. Item discrimination is the difference between the percentages correct for these two groups (Testing and evaluation services, 2010). Ranking the students according to total score and then selecting the top 27% and the lowest 27% in terms of total score can calculate item discrimination. For each item, the percentage of students in the upper and lower groups answering correctly is calculated. The difference is one measure of item discrimination (ID). The formula is specified as:

ID = (Upper Group % Correct) – (Lower Group % Correct)

Maximum item discrimination difference is 100%. This would occur if all those in the upper group answered correctly and all those in the lower group answered incorrectly. Zero discrimination occurs when equal numbers in both groups answer correctly. Negative discrimination, a highly undesirable condition, occurs when more students in the lower group then the upper group answers correctly. Negative IDs means unacceptable and between 40% and 100% is related to excellent items. Items with 24% or above IDs are usually seen as acceptable. For items on the TOCU-MP, discrimination values of responses are ranging from approximately 0.26 to about 0.63, which are certainly considered acceptable and reasonable values.

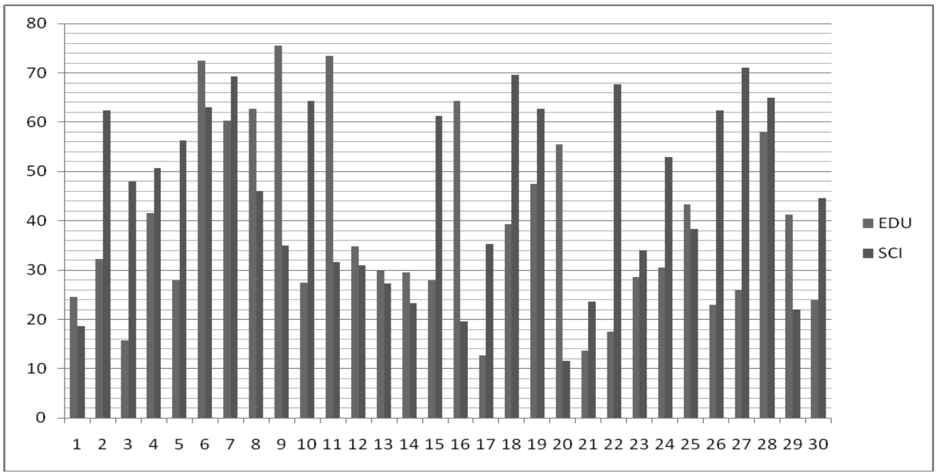

Fig. 1. *Difficulty levels of TUCO-MP items in percentages by each question*

Next, we need to check the items in terms of their validity and reliability corresponding to the quality of the instrument. Validity is the measure of how well each item measures what it should measure. We asked 19 professors at physics department and 3 professors at school of education review the questions at the same university where data was collected. They rated each item with scoring them as 10 being the high and 0 being low for both reasonableness and appropriateness of them. The resultant of their scoring is displayed in Table 3. All of the items were rated as appropriate and reasonable for the students.

European J of Physics Education Vol.2 Issue 1 2011 ISSN1309 7202

	Content		Logical		Appropriate	
Question	Mean	SD	Mean	SD	Mean	SD
1	9.32	1.41	9.12	1.51	9.09	1.57
2	9.12	1.98	9.85	0.52	9.45	1.59
3	9.01	1.87	9.98	0.58	9.55	2.02
4	9.50	1.45	9.00	0.75	9.41	1.42
5	8.98	2.10	9.23	0.15	9.12	0.98
6	9.68	1.65	9.52	1.27	9.87	1.65
7	9.52	1.54	8.20	0.95	9.01	1.78
8	9.32	1.58	9.85	0.69	8.58	1.87
9	9.45	1.65	9.24	1.88	9.87	1.98
10	9.52	1.69	9.45	1.40	9.65	1.85
11	9.48	1.70	9.30	1.26	9.54	1.26
12	9.49	1.87	9.21	0.96	9.89	1.56
13	9.29	1.32	9.20	1.48	9.65	1.41
14	9.32	1.98	9.54	1.56	9.23	1.23
15	9.45	2.30	9.45	0.99	9.12	1.85
16	9.12	1.85	9.47	1.57	9.15	1.45
17	8.65	1.80	9.12	1.69	9.54	1.47
18	8.85	1.65	8.95	1.33	9.36	1.59
19	8.98	1.20	9.12	1.89	9.85	1.65
20	9.12	1.45	9.60	1.88	9.12	1.98
21	9.98	1.69	9.50	1.35	9.25	1.75
22	9.95	1.49	9.48	0.69	9.58	1.32
23	9.80	1.58	9.12	1.03	9.78	1.98
24	9.75	1.54	9.32	1.53	9.23	1.45
25	9.70	1.65	9.18	1.98	9.10	1.99
26	8.95	1.66	9.21	1.43	9.15	2.25
27	9.25	1.53	9.85	0.12	9.19	1.20
28	9.30	1.75	8.98	1.18	9.27	1.30
29	9.20	1.36	8.95	1.90	9.53	1.50
30	9.45	1.35	9.10	1.62	8.98	2.00

Table 3. Validity (Content, logicalness and appropriateness) of the TUCO-MP questions

Reliability refers to how reliable the test items are or the consistency of a measure. A test is considered reliable if we get the same result repeatedly (Marshall et al., 1971). In order to check the reliability of the test items, we utilized a general technique Kuder-Richardson Formula (KR 20) (Triola, 2010). Values can range from 0.00 to 1.00 (sometimes expressed as 0 to 100); with high values indicating that the examination is likely to correlate with alternate forms (a desirable characteristic). The KR20 is affected by complexity, spread in scores and length of the examination. A high reliability score indicates more homogeneous test materials. A typical calculation is given by,

$$\alpha = \frac{K}{K-1}[1 - \frac{\sum_{i=1}^{K} p_i q_i}{\sigma_X^2}]$$

Where K is the number of items in the test, p is the number of students who answered the questions correctly; q is the number of students who answered the question incorrectly. And variance in the denominator is calculated by,

$$\sigma_X^2 = \frac{\sum_{i=1}^{N} (X_i - \bar{X})^2}{N}$$

If KR 20 value ranges between 0.9 and 1.0, it is a reliable, perfect test but it is very rare. If it runs from 0.8 to 0.9 it is very high reliable. Values between 0.7 and 0.8 are considered good and reliable tests. If is below 0.65 it is considered very weak test. When we run the reliability test for TUCO-MP, we calculated KR 20 value for TUCO-MP is around 0.73 that is a very reasonable value.

Discussion

We aimed to generate a qualitative diagnostic instrument for physics and science educators to use for both as pre and post test for any students in college studying modern physics. Teachers or professors can also use this test to get an idea of how students are learning the concepts at any time during courses periods. Besides, we intended to create a useful data collection tool to assess prevalence student ideas regarding concepts of modern physics. We believe we have achieved both goals.

Test-mean score of 41% might be seen low score but compared to the students' grades in a regular modern physics course, it is considered an average score. Averages scored of midterms and finals in modern physics course can be even lower because of difficult concepts related to quantum physics topics (e.g. wave function and hydrogen atom application). Although it is not our goal to discuss how difficult the concepts of quantum physics is (Akarsu, 2010), when evaluating students' achievement scores of TUCO-MP, one should take this into account to make sure the potential explanation of the results.

As indicated in the previous sections, TUCO-MP passed tests of validity and reliability that shows that it can be easily adapted and utilized. Although 0.73 is a very good result for a reliable data collection instrument, test can be revised to reach a higher score. Possible reason for the outcome might be unclear questions (e.g. question 21) as discussed before. Another cause for such low scores of some items in the test might stem from the language because students sometimes learn technical conceptual terms differently therefore if we use it for different meaning then they failed to answer it correctly. We can alter these questions and eliminate students' misunderstandings to get correct responses.

The only items of the test with averages lower than 20% percent of responded correctly were questions 1, 2, 14, 15, 17, 21, 22, and 30. As we predicted above, these questions focus on fundamental concepts of quantum theory so maybe when we prepare questions about it we should be more careful to misguide the students to the incorrect answers. In conclusion, the performance of TUCO-MP implies that additional research on instructional approaches of the concepts is needed to investigate the test. In this article, we provided preliminary results of a new diagnostic measurement tool for concepts of modern physics and hope as more researchers use it to evaluate and to create more effective data collection materials.

Acknowledgement

We would like to show appreciation the following colleagues for their insightful thought about questions in TUCO-MP and their contributions to this study: Dr. Kazım Keslioğlu, Dr. Ahmet Erdinç, Dr. Osman Canko, Dr. Hasan Kaya and other physics faculty members who reviewed and commented on the questionnaire. Also, we would like to express gratitude our research assistant Afşin Kariper and Nagihan Tanık for their contributions.

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Appendix

Sample TUCO-MP questions

Q1. An astronomer measures the Doppler change in frequency for the light reaching the earth from a distant star. From this measurement, can the astronomer tell whether the star is moving away from the earth or whether the earth is moving away from the star? What are the possible explanations?

(A) The earth is moving away from the star

(B) The star is moving away from the earth

(C) The star and earth are moving away from each other

(D) The star and the earth are not moving but materials between them ar

Q6. Which of the following statements is correct for the following Schrödinger equation?

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r},t) = -\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r},t) + V(\mathbf{r},t)\psi(\mathbf{r},t)$$

(A) Ψ is a wave function that represents a particle or a wave

(B) V describes voltage difference

(C) m is the particle's momentum

(D) $\hbar$ is Planck energy

Q7. Which of the following quantities will two observers always measure to be the same, regardless of the relative velocity between the observers:

I- the time interval between two events

II- the speed of light in a vacuum

III-the relative speed between the observers

(A) Only I (B) I and III

(C) Only II

(D) I and II (E) Only III

Q14. Why is it easier to accelerate an electron to a speed that is close to the speed of light, compared to accelerating a proton to the same speed?

(A) Because electron is charged

(B) Because proton is charged particle

(C)Because a proton has larger mass than an electron

(D) Because an electron has more mass than a proton

Q16. A stone is dropped from the top of a building. At the stone falls, what happens to its de Broglie wavelength?

(A) It increases

(B) It decreases

(C) It stays the same

(D) Firstly, it increases and then decreases

Q19.

-Driving a car may be safe.

-Using a cell phone may also be safe

-However, doing both of them at the same time might not be safe

Above statements explain a physics principle with using daily life example. Which physics principle is that?

(A) Principle of electrical attritional force

(B) Compton phenomena

(C) Heisenberg uncertainty principle

(D) Diffraction of light

Q24. Why do α and β decay produce new elements, but γ decay does not?

(A) Because γ is not disturbed by a magnetic field

(B) Because γ carries smaller mass than α or β

(C) Because γ consists of changed particles

(D) Because α and β consists of changed particles