The Grasp of Physics Concepts of Motion: Identifying Particular Patterns in Students' Thinking

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Keywords

Physics concepts in mechanics, Concentration factor, Mental models, Evaluation methods, Multiple-choice test

Cover Page Footnote

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Abstract

We have investigated the grasp of some of the basic concepts of motion by students taking the introductory physics course in Mechanics at United Arab Emirates University (UAEU). We have developed a short research-based multiple-choice test where we were able to extract some information about the state of knowledge of the students. In general, the students were found to have poor understanding. We have analyzed the results of the test using a mathematical function, the *concentration factor*, which may expose some particularly naïve models of basic physics concepts among students and serve to identify particular patterns in the students' thinking. Based on the outcomes and on our own experience, we have pinpointed some possible factors for the students' low performance. We have also recommended several methods which might enhance the students' understanding of the basic physics concepts.

Keywords: Physics concepts in mechanics, concentration factor, mental models, evaluation methods, multiple-choice test.

Introduction

Physics educators all over the world are continuously reporting on the poor and weak level of comprehension of basic physics concepts by students at all levels of study, especially students who are taking the introductory physics courses (Redish, Saul & Steinberg, 1998), (Hammer, 1994), (May & Etkina, 2002), (Malkawi & Obaidat, 2008), (Obaidat & Malkawi, 2008)**,** (Halloun & Hestenes, 1985). The researchers in those studies have investigated several factors that are considered to affect students' attitudes towards the understanding of physics concepts in introductory physics courses. Ineffective instruction methods, students' misconceptions inherited from pre-college about the physical world, negative attitudes toward learning physics, weakness in critical thinking, insufficient mathematical skills, poor problem-solving techniques, poor testing methods, and inconvenient evaluation methods are surely some of the possible factors.

Through a long history of assessment exams and quizzes, the poor performance of students in general physics courses at UAEU has been observed by physics instructors. The students enrolling in General Physics courses at UAEU are mostly majoring in the field of Science with few students majoring in Education or Food and Agriculture. Most of those students are at their first undergraduate level after finishing some general requirements of English and Mathematics. The general physics lectures conducted at UAEU are usually delivered twice a week. The material is explained by the instructors on the board or using PowerPoint presentations. A number of examples and problems are

solved by the instructors during the lecture time. Usually a quiz is given to the students after the end of each lecture. A midterm and a final exam are given to the students during the semester.

It is difficult to completely specify, isolate, and quantify all the factors that influence the observed poor performance of students in General Physics courses at UAEU. Some research work has been done to expose some parts of this important issue at the physics department (Malkawi & Obaidat, 2008), (Obaidat & Malkawi, 2008). The authors in (Malkawi & Obaidat, 2008) investigated the response of students to two different methods of evaluation. The first method is the problem-solving process and the second method is the exercise-solving process. In the exercise-solving process, students are usually directed to the answers using a step by step process. The routine exercise problems, which are usually described to be poor-context problems, involve a division of a real problem into simple sub-problems and thus leading the students step by step to the final and main physical quantity needed to be found in the problem. These exercises imply a quick and linear solution process and students may perceive it as merely a trial-and-error process, and working with formulas in isolation from the physics involved in the problem. The problem-solving process mainly deals with real-world problems and is usually described to be rich-context problems. Solving real-world problems imply deep understanding and realizing of the problem followed by a convoluted solving process that involves thorough analysis and incorporates the physics concepts along with the formulas. In this problem-solving process, the students direct themselves through the solution.

Students taking introductory classical mechanics physics course were found to have a noticeable deficiency in understanding and solving problems that need some ability of scientific thinking. The authors have suggested that students' weaknesses can be minimized by focusing more on real world problems. In (Obaidat & Malkawi, 2008) the authors developed a short research-based multiple-choice test where they were able to extract some information about poor understanding of kinematics and Newton's laws of motion. But that study contained only the first two questions of this current study. Also the number of students involved in that study was nearly half of number of students involved in this study. Much work still needs to be dedicated to study the several aspects related to the issue of poor performance in the introductory physics courses. We believe that initiating serious studies focusing on this issue will revise and enhance the instruction methods and the physics curriculum and eventually will enhance the students' performance.

The multiple-choice exam is a very convenient and practical method of testing the basic concepts in introductory physics courses especially in large classes. Traditional analyses of multiple choice exams focus on the scores, and possibly on the correlation between correct answers chosen by students. Using such analysis it is difficult to extract the information required by physics educators about the students understanding of physics concepts. On the other hand, multiple-choice exams allow physics instructors and educators to examine large populations. If these exams are prepared based on the various reasoning patterns that students might have about the physics problems, valuable information on students' understanding of physics concepts can be obtained by focusing on the way that the student selects wrong answers. In this work we have prepared a convenient multiple-choice exam that can provide this valuable information. In this report we focus on some basic concepts of motion which are discussed extensively in General Physics I (Introductory mechanics course); these are basic concepts in kinematics and Newton's laws of motion. First, we measure the level of understanding and comprehension of very basics physics concepts by first year science and engineering students at UAEU. Second, we analyze each question in detail and check whether students' answers might be based on particular naïve mental models. This is

done since some studies suggest that students develop personal "theories of motion" by generalizing the ideas they acquire from observation of moving objects in everyday situations (Keeports, 2000), (Hammer, 2000). (McClosky. 1983), (Prescott & Mitchelmore, 2005). Third, we pinpoint some of the possible factors that might play a role in the students' performance. Finally, we make some general comments and suggestions that we believe might improve the current students' understanding and performance in concepts of motion and in physics in general. We have applied a very convenient method by which we can extract and analyze information about the state of understanding of physics concepts (Bao & Redish, 2001, July). Using this method we were able to analyze the complete students' responses rather than just counting the number of times they answered correctly. We apply an analytical method for analyzing the concentration of student responses to particular multiple-choice questions. This study was conducted with first year science and engineering students enrolled at UAEU.

It is important to realize that in this paper we do not tackle every one of the possible factors that are considered to affect students' understanding of physics concepts at UAEU. An extensive investigation about some of these factors at UAEU is currently being conducted.

The Concentration Factor

From our research (Malkawi & Obaidat, 2008), (Obaidat & Malkawi, 2008) and experience in teaching physics to first year students, we have learned that student responses to physics problems vary considerably. This variation of responses to physics problems is due to several factors. One factor is related to different students' attitudes toward learning physics (Malkawi & Obaidat, 2008). Other factors may be attributed to different ways of reasoning physics concepts where students apply different mental models (Bao & Redish, 2001, July), (Bao, 1999). The distribution of students' responses to research-based multiple-choice exams can provide valuable information on their state of understanding. Highly concentrated responses in a particular question imply that many students are applying a common mental model associated with the question, whereas randomly distributed responses often indicate that students are guessing or have less systematic reasoning. In order to be able to extract information from such responses we use a function to analyze students' responses. This simple function is called the concentration factor, C, that takes a value in [0, 1]. Large values (close to 1) represent more concentrated responses with 1 being a perfectly correlated response (Bao & Redish, 2001, July). Small values (close to 0) represent less concentrated responses with 0 being a total random guess (Bao & Redish, 2001, July). The concentration factor function is defined for each question as

$$C = \frac{\sqrt{m}}{\sqrt{m} \cdot 1} \left(\frac{\sqrt{\sum_{i=1}^{m} n_i^2}}{N} \cdot \frac{1}{\sqrt{m}} \right)$$

where m represents the number of choices for a particular question, N is the number of students taking the exam, and n_i is the number of students who select the *i-th* choice.

To investigate the behavior of the concentration factor function consider a multiple-choice question with three choices, a, b, and c. Let n_1, n_2, and n_3 be the fraction of students choosing answers a, b, and c, respectively. Defining $n_2 = n_1 + \delta$ and using the

constraint $n_1 + n_2 + n_3 = 1$, we can rewrite the concentration factor function in terms of two independent variables $C(\delta, n_1)$, where $-1 \leq \delta \leq 1$ and $0 \leq n_1 \leq 1$. The minimum value for $C(\delta, n_1)$ is zero which corresponds to the single solution $(\delta = 0, n_1 = 1/3)$. In the plane of (δ, n_1) we show, in figure 1, three particular contours of constant $C(\delta, n_1)$. The smallest contour is shown for $C(\delta, n_1) = 0.2$, the second contour is shown for $C(\delta, n_1) = 0.4$, and the largest contour corresponds to $C(\delta, n_1) = 1$. The allowed values of $C(\delta, n_1)$ do not span the whole space but are bounded by the two dotted straight lines corresponding to the two constraints; $n_2 = n_1 + \delta \geq 0$ and $n_2 + n_1 = 2 n_1 + \delta \leq 1$.
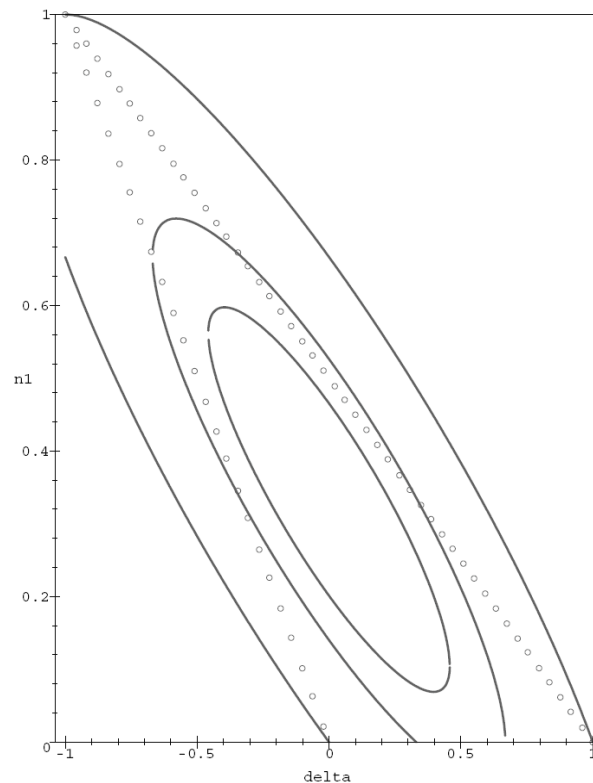

Figure 1. Three different contours of constant $C(\delta, n_1)$. The small contour is for $C(\delta, n_1) = 0.2$, the second contour is for $C(\delta, n_1) = 0.4$, and the largest contour corresponds to $C(\delta, n_1) = 1$.

We find that all the solutions (δ, n_1) lie within the allowed region for which $|\delta| = |n_2 - n_1| \leq 0.46$, while $0.07 \leq n_1 \leq 0.6$. Since the concentration factor function is symmetric with respect to n_1, n_2, and n_3 then we can summarize the result by saying that for $0 < C \leq 0.2$, the possible values for any fraction of students picking a particular choice is bounded $0.07 < n_{1,2,3} \leq 0.6$, and where the separation between any two values, $|\delta| \leq 0.46$. The second contour corresponds to $C(\delta, n_1) = 0.4$. We find that only three small parts of the contour lie inside the allowed region. The three parts are equivalent reflecting the symmetry between n_1, n_2, and n_3. The result can be summarized by saying that for $C = 0.4$ one value, such as n_1, will be large $0.67 < n_1 \leq 0.72$ while at least one of the other two choices should not be very small since $0.28 \leq n_2 + n_3 \leq 0.33$. The separation between any two values, $|\delta| \leq 0.7$. For the largest contour which corresponds to $C(\delta, n_1) = 1$, there are only three discrete solutions which intersect the allowed region. Those three solutions are equivalent and correspond to the case where one of the choices gets the maximum value 1.

The Test

Our test aims to investigate and quantify the students' understanding of basic physics concepts of motion. The test consisted of five multiple-choice questions which tackled five basic concepts of motion out of the many concepts that students learn in an introductory physics course. Since some of the students might have some difficulties with the English language, the five questions were written very carefully and in simple English. These questions tackle the physics concepts directly, such that if a considerable fraction of students miss the correct answer then that might indicate that students hold misconceptions and naïve mental models about these concepts. Two of the questions were taken from the Force-Concept Inventory (FCI) (Hestenes, Wells, & Swackhamer, 1992) with slight modifications in the language to suit the level of students at UAEU. In this study we limit the test to just five questions because this is only a preliminary study that was conducted on several small classes. It was very difficult to arrange for such test for all these classes with different schedules and instructors. Nevertheless, a study that includes several questions on each concept will be arranged in the near future.

The test is shown in the appendix. The first and second questions test the students' understanding of the physical quantities *velocity* and *acceleration*. Many students confuse the two quantities and assume that *large velocity* implies *large acceleration*. The first two questions explore the students' status of thinking in kinematics in two different ways. The third question tests the students' understanding of motion under gravity in the context of one- and two-dimensional motion. Students have difficulty in analyzing two-dimensional motion under gravity as a combination of two linearly independent one-dimensional motions. The fourth question tests the ability of students to extract information from graphs so as to connect between the physical quantities *force* and *acceleration*. Our experience indicates that students suffer a deficiency in reading and extracting information from graphical data. The fifth question tests the ability of students to read and extract information from real data as depicted on a tape. Our own experience indicates that students have a major difficulty in such skills.

The first two questions of the study involved 510 first year science and engineering students who were taking their first course in classical mechanics at UAEU. The last three questions of the study involved 219 students. The students were mainly females and were distributed in 30 sections taught by several instructors. The students were not notified prior to the test and were given 10 minutes to finish the test. The test covered material that was explained to them nearly 2 months prior to the test date.

Results and Discussion

Table 1 shows the percentage of students who answered each question correctly. It is clearly seen from these results that students have a significantly poor level of comprehension of the five basic physics concepts presented in the test. Because those students have been taught by 10 different instructors with some differences in the traditional lecturing method, we might conclude that this poor performance is not directly related to the instructor's lecturing method.

Table 1. The percentage of students who answered each question correctly.

Question	Correct Answer	Number of Students	Percentage of Students with Correct Answer (%)
1	c	510	24
2	b	510	37
3	d	219	64
4	c	219	42
5	d	219	40

As discussed in the "Concentration Factor" section, we have systematically analyzed the concentration function for any multiple-choice question and with specific number of choices in a manner that is different to the method used in (Bao & Redish, 2001, July). Based on the results of the careful analysis of the behavior of the concentration factor, C with a different number of choices we have arrived at a three-level coding system (Table 2) that is very similar to the one obtained by (Bao & Redish, 2001, July). Using this coding scheme, a low level (L) code was given for concentrations values between 0 and 0.2. For a multiple-choice test of only three choices, the L level indicates that either all the choices got an almost equal number of answers or two of the choices got nearly an equal number of answers while the third choice got a different number of answers that is not very far from that obtained for the other two choices. A high level (H) code was given for concentrations between 0.4 and 1.0. The H level indicates that one choice got a very large number of answers while the other two choices (wrong or correct) got a very small numbers of answers. A medium level (M) code was given for concentrations above 0.2 and below 0.4. The M level represents all cases that are not represented by the L or H levels. Thus the M level represents several situations. One of these situations is when two of the choices got a relatively small number of answers while the third choice got a relatively large numbers of answers. Another situation that is represented by the M level is that where one of the choices got a very large number of answers while the other two choices got a number of answers that are nearly equal and not large or small. The M level might also indicate that nearly one of the choices got a large number of answers and one of the choices got a small number of answers, while the last choice got a number of answers that is not large or small. This three-level coding can be easily generalized to a multiple-choice test with more than three choices. Student response patterns are formed by combining the question's concentration factor with the question's score, S which is the percentage of students who answered a particular question correctly. Like the concentration factor, the score has a continuous value with a range of [0, 1]. A three-level coding system is also used to classify the average scores S, where a low level (L) was given for average score between 0 and 0.4, a medium level (M) was given for average score above 0.4 and below 0.7, and a high level (H) was given for average score between 0.7 and 1.0.

Table 2. The three coding scheme for the scores and concentration factor

Concentration (C)	Level	Score (S)	Level
0 ~ 0.2	L	0 ~ 0.4	L
0.2 ~ 0.4	M	0.4 ~ 0.7	M
0.4 ~ 1.0	H	0.7 ~ 1.0	H

Combining the codes for the concentration factor and the score (SC) can provide the student response patterns for each multiple-choice question (Bao & Redish, 2001, July). Each response pattern can be used to evaluate the students' understanding of physics. According to (Bao & Redish, 2001, July), there are five different coding schemes (SC) of the combination the concentration factor and the score. If the results of a question are classified as HH, this implies that there exists only one correct model (concept system).

If the results of a question are classified as LH, this implies that there exists one dominant, but incorrect model. If the results of a question are classified as LM, this implies that there are two incorrect models. If the results of a question are classified as MM, this implies that there are two popular models, one is correct and the other is incorrect. If the results of a question are classified as LL, this implies that the majority of models are represented somewhat evenly.

We believe that a concentration analysis is a very helpful method to detect the students' lack of understanding of the physics concepts. Also by using this analysis, we can check whether there are particular patterns in the students' thinking. If a student consistently chooses distracters that represent a particular alternative physics concept, then the instructor or researcher can make some conclusions about the student's understanding of physics (Bao & Redish, 2001, July), (Bao, 1999), (Hestenes, Wells & Swackhamer, 1992), (Ioannides & Vosniadou, 2002). If this method of analysis is followed by interviews, patterns in the students' thinking can be more easily identified. An important point in this method of analysis is that it helps to identify test questions with ineffective distracters which do not reflect a common student conceptual misunderstanding. This outcome would be identified by an LL response pattern, which indicates that the majority of the students did not find one of the available distracters to be much more attractive than the others.

Table 3 shows the concentration factor and the average score with their levels of the 510 students for each of the five questions. Figures 2-6 show the number of students who chose a particular answer for each question. From the data in table 3, we can see that the first question is classified as LM (SC) which means that students' results in the kinematics question are poor and the majority of the responses are concentrated on a particular wrong answer.

Table 3. The concentration factor and the average score with their levels for all students for each of the questions.

Question Number	Score (S)	Level	Concentration (C)	Level
1	0.2363	L	0.2387	M
2	0.3711	L	0.0832	L
3	0.6438	M	0.3559	M
4	0.4246	M	0.1265	L
5	0.3793	L	0.0690	L

Looking at figure 2, we conclude that many students might hold a misconception that can be summarized by saying that *the object with a larger speed will have a larger acceleration*. From table 3, we also see that the second question is classified as LL (SC) which means that students' results in the question on Newton's laws of motion are poor and their responses are not very concentrated on a particular wrong answer.
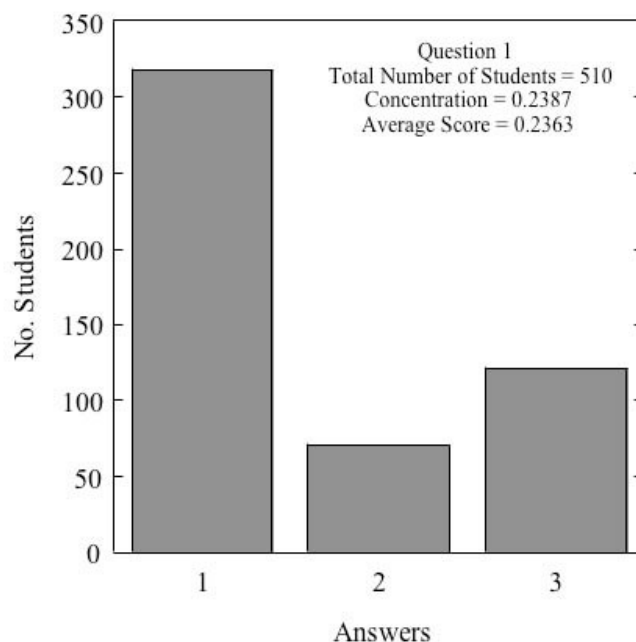

Figure 2. The number of students who chose a particular answer for the first question. Here the numbers 1, 2, and 3 represent choices a, b, and c, respectively.

Looking at figure 3, we find that the students chose mainly two answers; one wrong answer, which is choice (a), and the correct answer which is choice (b). This means that many students thought that the object will stop after the force is removed. Thus we conclude that many students might hold a misconception that can be summarized by saying that *a zero force requires the object to be at rest*. The third question is classified as MM (SC) which indicates that a considerable number of students could not form a clear understanding of free fall under gravity as applied to one dimensional and two-dimensional (projectile) motion. Since a large number of students chose the wrong answers almost equally this indicates that no particular mental reasoning is being held by the students in regards to the subject of fall under the action of gravity. From table 3, we also see that the fourth question is classified as ML (SC) from which we conclude that the majority of the students fail to extract information from graphs to connect between force and acceleration. This could imply a severe deficiency among students in reading and extracting information from graphical data. From our own teaching experience we come to recognize the students' lack of skills to read and interpret information as depicted on graphs.
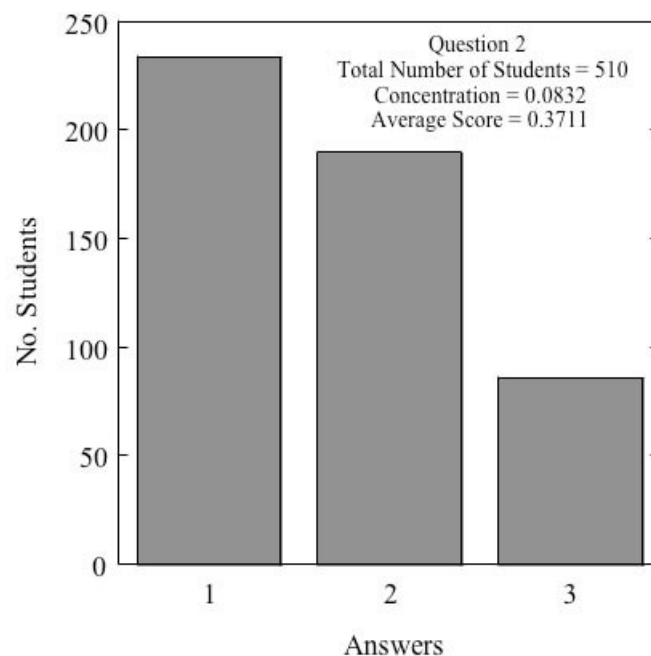

Figure 3. The number of students who chose a particular answer for the second question. Here the numbers 1, 2, and 3 represent choices a, b, and c, respectively.
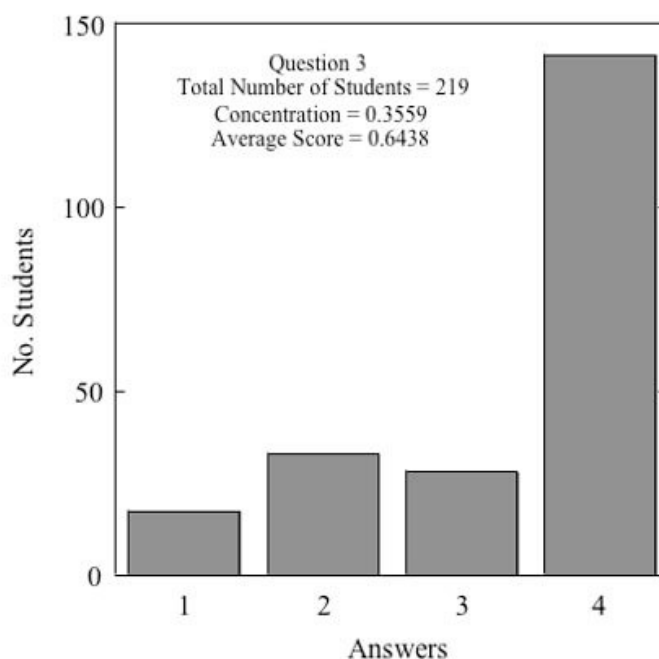
Figure 4. The number of students who chose a particular answer for the third question. Here the numbers 1, 2, 3, and 4 represent choices a, b, c, and d, respectively.
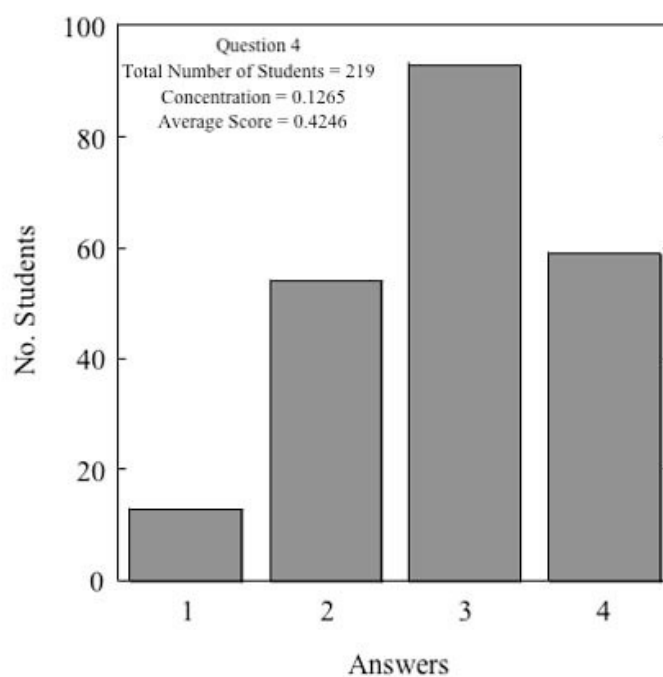

Figure 5. The number of students who chose a particular answer for the fourth question. Here the numbers 1, 2, 3, and 4 represent choices a, b, c, and d, respectively.
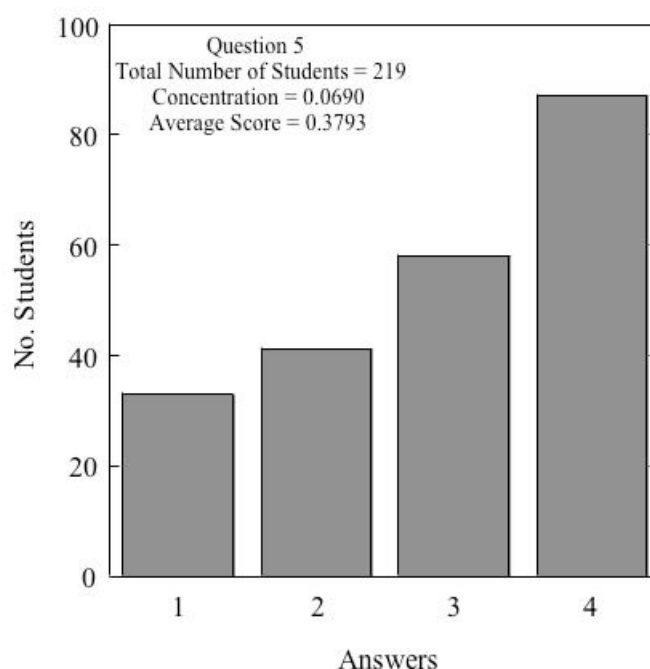
Figure 6. The number of students who chose a particular answer for the fifth question. Here the numbers 1, 2, 3, and 4 represent choices a, b, c, and d, respectively.

From table 3, we also see that the fifth question is classified as LL (SC) which highly indicates that the majority of students lack sufficient skills and capabilities to read, extract, and interpret information from real data as depicted on a tape. The low scores and the very low concentration of answers clearly indicate that students made their choices almost randomly, reflecting an insufficient understanding of dealing with the presented information.

What we have learned from this discussion is that the majority of the students might have wrong and naïve models about basic concepts of kinematics and Newton's laws of motion. They also lack skills to read and extract information from real data and graphs. This study is very interesting since not only were we able to measure the level of understanding of basic physics concepts; we also were able to measure the level of distribution of answers.

Possible Factors Affecting Learning Physics Concepts at UAEU

These results trigger the search for factors that might be responsible for this poor performance and the source of the wrong and naïve mental models that the students have about kinematics and Newton's laws of motion. One possible factor could be the misconceptions and poor attitude toward learning physics inherited from pre-college as mentioned in the introduction of the paper (Obaidat & Malkawi, 2008**),** (Halloun & Hestenes, 1985). (Keeports, 2000), (Hammer, 2000). Another factor could be the total amount of the physics material covered in the course which limits the time spent on discussing the physics concepts compared with problem solving. In order to raise the students understanding of physics concepts, we believe that the traditional way of lecturing physics should be revised significantly, where physics instructors can spend more time on explaining physics concepts rather than spending most of the time on problem solving. This is true because understanding physics concepts is the main key

for enhancing students' attitude toward learning physics which leads to appreciation of solving physics problems. Improving the students understanding of physics concepts can also be enhanced by modifying the home work assignments such that they contain some conceptual questions. We also believe that group discussions on physics concepts could help students grasp the ideas more efficiently (Johnson, Johnson & Smith, 1998), (Michael, 2006). (Abdi-Rizak, 2008). Well designed PowerPoint presentations (Illene, 2007) and experimental demonstrations during the lecture can also provide effective ways of enhancing the students' comprehension of basic concepts of physics. But this method has its own drawback due to the limitations of the lecturer's time, where it is not always possible to conduct such experiments or spend time on every physics concept.

Conclusion

We have investigated the level of comprehension of very basic physics concepts among first year students at UAEU. The study was conducted using well-designed multiple-choice questions that focused on the concepts of kinematics and Newton's laws of motion. By combining the question's concentration factor with the question's score, we have analyzed the results of all the students in each question. We have found that the students' grasp of these concepts is weak. Students' answers showed that many of them might hold wrong mental models of physics concepts such as the object with a larger speed will have a larger acceleration and a zero force requires the object to be at rest. Several factors that were thought to play a role on the students' level of understanding these concepts were discussed.

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Appendix

The test

1. Two blocks each of mass m, move along the x-axis as shown below.

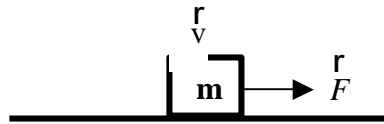If at some instant t, $v_2 > v_1$ then,

a) $a_2 > a_1$
b) $a_1 > a_2$
c) we can not determine which block has the larger acceleration.

2. An object of mass m is moving on a frictionless surface under the action of the force $\vec{F}$ as shown below. After the force $\vec{F}$ is removed,

    a) v becomes zero
   b) v stays the same
    c) v increases

3. Two objects of masses m_1 and m_2 ($m_1 > m_2$) are moving under the action of gravity, starting from the same height, as shown below. The mass m_1 is given an initial velocity in the horizontal direction while m_2 is released from rest.
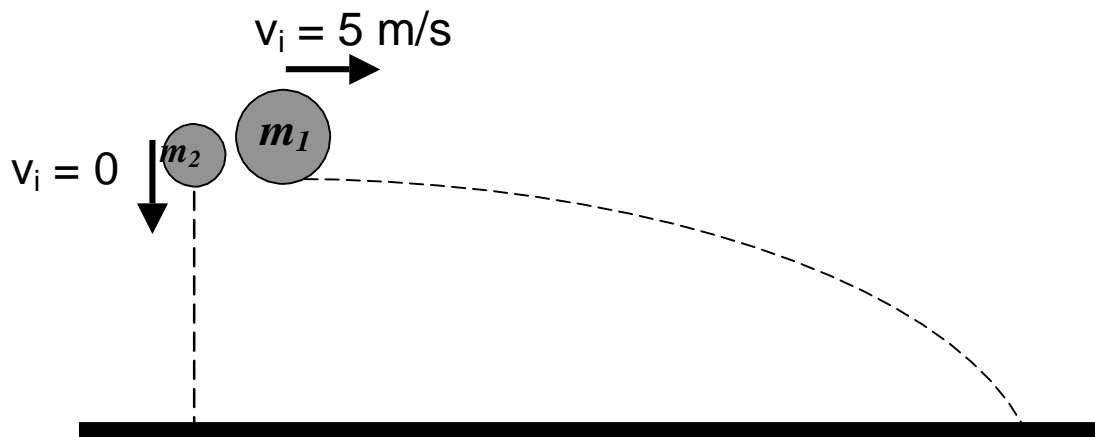

Which statement is correct? (Ignore air resistance)
    a) m_1 will reach the ground first because it is heavier.
    b) m_1 will reach the ground first because it has initial velocity.
    c) m_2 will reach the ground first because it travels smaller distance.
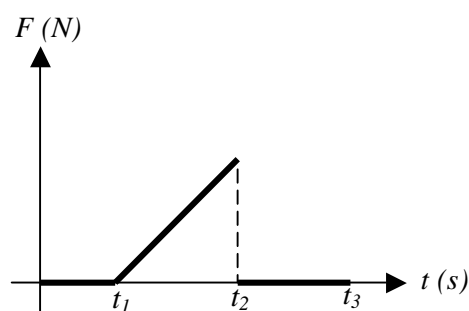   d) Both masses will reach the ground at the same time.

4. The velocity of an object, moving along the x-axis, as a function of time is shown in the graph below.
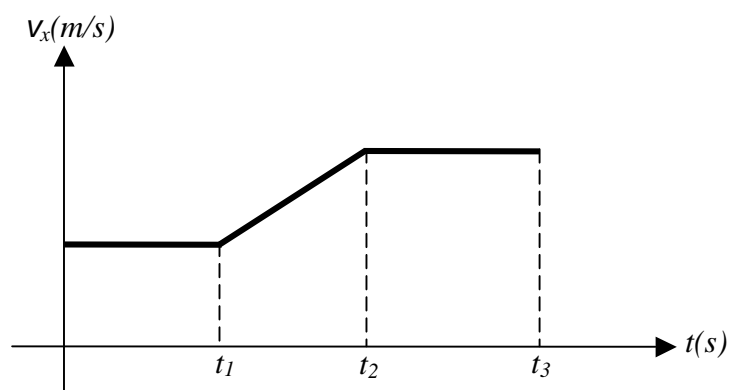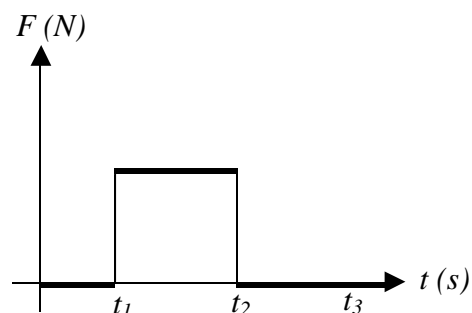

Which graph below represents the net (resultant) force on the object as a function of time?
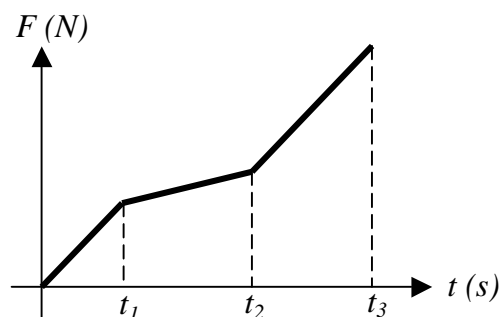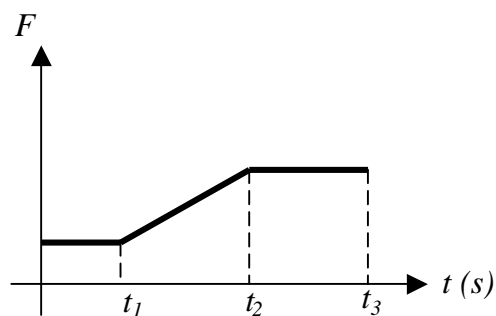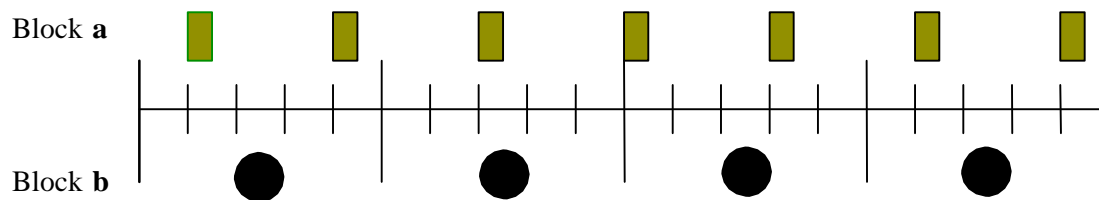

(a)

(b)

(c)

(d

5. The positions of two blocks at successive intervals each of 0.3 seconds, are shown in the figure below. The blocks are moving toward the right.

The accelerations of the two blocks are related as follows:
   a) The acceleration of block "**a**" is larger than the acceleration of block "**b**".
   b) The acceleration of block "**a**" is smaller than the acceleration of block "**b**".
   c) The acceleration of block "**a**" equals the acceleration of block "**b**". Both accelerations are larger than zero.
   d) The acceleration of block "**a**" equals the acceleration of block "**b**". Both accelerations are zero.