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A Graphical Insight into Real-Time Relation between Displacement, Velocity and Acceleration-Validation using Diagnostic Test

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Abstract - A diagnostic test was designed to identify the student's misconceptions in kinematics and their understanding of kinematics graphs at the undergraduate level. It is observed that students have conceptual difficulty with major kinematics concepts and related graphs of vector quantities like displacement, velocity and acceleration and their relationships with each other. Problems based on the concepts of integration and differentiations are easy to solve in mathematics, but students have difficulty applying and interpreting the concept while solving kinematics graphs. We developed a diagnostic tool called Kinematics Concepts Test (KCT) covering all concepts of kinematics to identify and characterize student alternate conceptions. The test includes 23 items of multiple choices which were selected from a total of 37 items. The test instrument was validated for difficulty level, reliability and consistency. The statistical indices were calculated for each test item and for the complete test.

Keywords - Kinematics Concepts Test (KCT)

I. Introduction

The importance of graphical and info-graphic representation to interpret data is growing steadily. A graph representing a physical event gives indication of trends and insight which cannot easily be understood in the tabular data form [3].Mokros and Tinker report that graphs help scientist to use their powerful visual pattern recognition skill to see the trends [10]. It helps in visualizing, representing and recapitulating data, interpreting the relationships between variables. The skill to interpret the graphs is related to the understanding equations and related mathematical concepts. In kinematics it has been observed that student's response on differential kinematic quantities on a question posed in verbal representation and graphical representation often have strikingly different results [4]. Students find it difficult to differentiate between the concepts of displacement, velocity and acceleration. They find it difficult to make the graph when verbal description of the situation is given. Students often make association of kinematical variables, their graphical representation and shape of path of motion of objects [2]. They could not differentiate slope and path of the motion. It appears that interpretation of graphs as taught in mathematics classes in schools is not adequate for students to apply in real life to understand physics [5].

It was observed that students have a serious difficulty understanding the implication and importance of the direction of velocity of the object. They consider many times that if velocity is increasing in negative direction then object is slowing. They have confusion about the relation between direction of motion and sign of the velocity. Students often think that zero velocity implies zero acceleration. They do not understand that it is possible that velocity is zero acceleration can be nonzero and if acceleration is zero velocity may not be zero.

As far as understanding of functional relationship between velocity and acceleration is concerned, students think erroneously that if an object moves with high speed then its acceleration is high and if an object moves at low speed then its acceleration is low. They have difficulty in deciding whether the body is slowing down or speeding up looking at the direction of velocity and acceleration. Understanding the concept that the direction of both acceleration and velocity together decides whether an object speeds up or slows down is hard for the students. Most of the students intuitively believe that body having positive velocity cannot have negative acceleration and body cannot have negative velocity and positive acceleration simultaneously. Most often negative acceleration creates confusion in students' mind.

During this study it has been observed that the meaning and calculation of area under the curve was the most difficult concept for students to understand. They could not find out whether the displacement is increasing or decreasing from velocity time graph. This requires the ability to understand first level integration graphically. When students were supposed to find change in velocity from acceleration time graph, instead of finding out area under the curve they considered the change in acceleration over the time interval. Students could not relate the sign of area under the curve on velocity time graph with the sign of displacement.

Students find it difficult to draw position time graph from acceleration time graph or interpret the acceleration time graph in terms of displacement. This requires the concept of double level integration. Students even find it difficult to create acceleration time graph from position time graph or interpret position time graph in terms of its acceleration. This requires the understanding of graphical representation of mathematical concept of double differentiation.

The presently available multiple-choice tests instruments do not cover questions on concepts of double differentiation and double integration which is very important to understand Newton's laws of motion. Generally, items included in the presently available tests are distance, displacement, velocity, acceleration, based on concept of single level derivative and integration. Many multiple choice conceptual survey instruments have been developed, especially in the areas of heat and thermodynamics, mathematics, electricity and magnetism, and quantum physics. In the area of kinematics graphs there are only two concept test instruments. The TUGK(Test of Understanding Graphs in Kinematics)is a 21-item survey on beliefs or understandings of kinematics graphs[1]. The popular FCI and MBT are excellent mechanics concept assessment tools based on the earlier research [8, 9]. Surprisingly, there is less research work done on students' difficulties with the interpretation of kinematics graphs. This research study was an attempt to develop new useful survey tool in line with few existing studies and to find additional misconceptions if they exist.

II. Construction of the KCT

We designed the KCT based on topics of kinematics included in the curriculum for first year undergraduate study. The test included a combination of qualitative and quantitative questions from the calculus-based undergraduate physics mechanics curriculum, which probed for student's ability to conceptualize and calculate

a. Velocity changes from real trajectories, graphical representation.

b. Change of magnitude and direction of acceleration from velocity and position graphs

c. Relate graphical and visual representations with verbal description or vice versa

a. Understand Position changes from Velocity graphs.

b. Derive Change of magnitude and direction of position and velocity from acceleration graphs

All test items or questions were intended to investigate students' conceptual understanding of kinematics and related graphs. The concept test is based on the following list of kinematics concepts:

C1: Velocity and Acceleration as rate.

C2: Velocity and Acceleration as vector in one dimension (i.e. direction of the velocity and acceleration)

C3: Change in position as area under the velocity-time graph and change in velocity as area under the acceleration-time-graph.

C4: Acceleration from position time graph.

C5: Position from acceleration time graph.

C6: Concept of average and instantaneous values

This list of concepts is in good agreement with the concepts identified in other studies [11].

The content validity for the KCT was analyzed by five senior teachers teaching mechanics at undergraduate level. The consistency of the test instrument was evaluated by using more than 346 student's responses from three different colleges in Pune. The statistical analyses showed that the test is reliable and valid. The objective of implementation of this test is to investigate alternative conceptions in kinematics.

Pre-testing is very critical for developing an effective questionnaire - the questionnaire for the test was standardized, tested, and assessed by pre-testing it. Responses in pre testing were collected from participants from actual sample source. Final questionnaire which will not be edited significantly further was used for pre-testing.

We have used face to face interview method and paper pencil method for pre-testing and to get feedback on answer options and to find out how people are responding to answer options and wording. From the analysis of the results of pre-test and we could find out the issue with duration of the test and it was corrected.

The selection of final questions was based on the following criteria:

1. The test should be short enough to retain interest and long enough to be comprehensive

2. The students have sufficient time to think and answer carefully.

3. The questions should be independent and there should be minimal progressive learning during the test which will help the student to answer later questions.

4. The sequence of questions should be such that different type of questions are randomly mixed in sequence

5. The language of the questions should be easy and concise – this was tested during the soft testing of the questionnaire on a small sample

6. The questions asked should be a part of the syllabus under study

7. The difficulty or complexity level of the questionnaire should be of the level of first year undergraduate studies

8. For difficulty level of individual test items following validity criteria were required and tested[6] [7]:

- Difficulty index (> 0.3)
- Discrimination index and (> 0.3)
- Item point biserial coefficient(> 0.2)

9. For the complete test, the following validity criteria were required and tested:

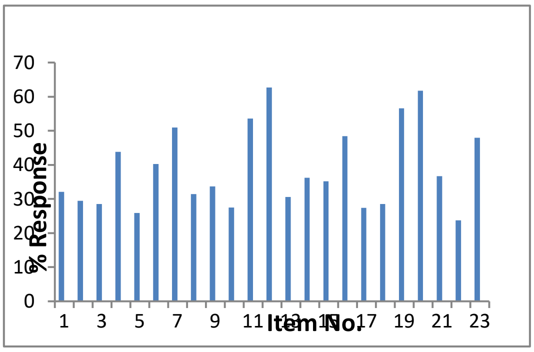
- Kuder-Richardson reliability index (> 0.7 or > 0.8)
- Ferguson's delta (> 0.90)

10. The answer list should be such that the wrong responses point to the underlying misconception.

11. Students had to give the test in one uninterrupted sitting, so as to prevent any manipulation of responses.

12. Corresponding to each objective there are at least 3 or more questions.

The test was administered to students of first year science undergraduate degree students from three different colleges. Student's responding correctly on different items of the test are shown in Figure 1.



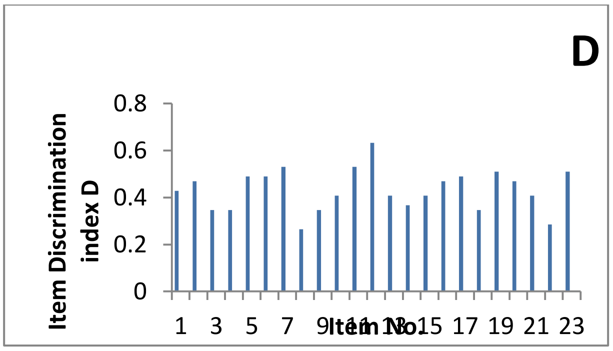


Figure 1 Results of content survey on KCT   **Figure 2.KCT item discrimination indices**

The final version of KCT was administered to the first-year undergraduate students from calculus-based physics and mathematics class as a pilot survey. The content validity was checked again with a group or senior teachers teaching mechanics at undergraduate level for more than ten years.

III. Validity of the Tests

The tests were validated using following procedure:

The test was shown to 5 senior teachers who were teaching these courses for at least 10 years

The test was assigned to 25 postgraduate students who studied these courses at their undergraduate level and studying in the postgraduate classes. The in-depth interviews with the students gave no hint of students misunderstanding or misinterpreting the questions in the test.

Statistical Evaluation of the test tool

The reliability index of the test, as measured by the KR-21, for diagnostic test on general kinematics concepts is 0.712. The diagnostic test on general kinematics concepts is a reliable instrument and considered to be sufficient for group measurement. The average difficulty index P_{mean} = 0.386728indicates that the test is moderately difficult. The D_{mean}value of the test is 0.429, so the discriminatory power of the test is considered to be good.

Table 1

The average reliability index, difficulty index and discrimination index of the diagnostic tests

Average Index	Possible values	KCT	Free Fall
Item difficulty index (P)	[0,1]	0.3885	0.44435
Item discrimination index (D)	[-1,1]	0.43	0.54133
Point biserial coefficient (r_{pbs})	[-1,1]	0.385	0.4839
KR-21 test reliability (r)	[0,1]	0.7171	0.70153
Fergusson's delta (δ)	[0,1]	0.952	0.96772

IV. Result and Discussion

Kinematics studies the trajectory or path of motion of any geometric object and their differential properties like velocity and acceleration to describe the motion. An understanding of motion is a key to understanding many concepts in physics.

The detailed analysis of students' response on each item and their difficulties were given on basis of the test responses and group discussion with the students. The main objective of this is to explain

(a) Could the students understand the item correctly?

(b) What are the students' conceptual misunderstandings about this item?

The test questionnaire is given in Appendix I

Following difficulties were observed in conceptual understanding in kinematics

Item 1: This item is based on the application of kinematics equation. Discussion with students, suggested that they often confused with a concept of average and tried to calculate the mean velocity, when they were required to interpret the v/t graph of an object in terms to the distance covered. Mathematically, finding the mean value is equivalent to determining the area under the curve and dividing by the interval. It shows that students just apply kinematics equations without considering the fact that kinematics equations are applicable only when acceleration is constant. This shows that students find the concept of area under curve and use of kinematics equations difficult.

Item 2: The item is based on mathematical concept of first level integration. In this graph acceleration is positive and decreases uniformly to zero with time. In this item most of the students gave the incorrect response. Some students have chosen the option in which velocity is increasing and was negative, shape of the velocity/time graph matches with the shape of acceleration/time graph. When discussed with students it was found that they believe that if acceleration is increasing then velocity will also increase. Many students have chosen the option in which acceleration (slope of velocity time graph) is positive and decreasing to zero, but velocity is negative. It was found that students have difficulty applying mathematical concept integration to kinematics graphs.

*Item 3:*The given position time graph is parabolic in shape representing constant negative acceleration motion and slope at each point of the graph should be negative and increasing from zero with time. Many students have chosen the option in which the shape is parabolic and slope increases from zero with time but is positive, which corresponds to the motion of a particle thrown vertically upward. It is observed that students have difficulty in relating direction of motion with the slope of the graph and converting verbal description into graphical representation. Some of the students have chosen the graph whose shape is straight line, probably because its shape matches with the shape of the path. It was noticed that students have difficulty in understanding the implication of negative acceleration; they consider negative acceleration means velocity decreasing with time.

Item 4: In this simple application of kinematics equation to find velocity and acceleration, the error could only be due to mistake in calculation or wrong application of formula used.

*Item 5:*In this item students had to select the option which represents the motion of an object speeding up uniformly in negative direction. The item is based on the principle of area under a curve. Area under acceleration/time graph is a measure of change in velocity. The correct option is B, the area associated with the motion is negative and increasing linearly with time and thus the object is moving with increasing speed uniformly in negative direction. In case the area is positive then velocity is positive and if area is negative then velocity is negative. After discussion with students it was observed that even if they understand the meaning of area under the curve they do not understand its direction.

Item 6: In this item velocity as slope of displacement time graph and displacement as a vector quantity are the concepts under test. Most of the students could not relate the position time graph slope with the measure of velocity. Some students have made error in discriminating between displacement and distance. Some students did not consider the period in which the person stops so the displacement will be zero.

Item 7: This item describes an object moving in straight line and the position/time graph of is motion is given. This item is simple application of calculation of slope and its direction (velocity as a vector). Students had to select the region of the graph in which the object is moving with uniform positive acceleration. Some students have chosen the option in which displacement is increasing linearly in positive direction. Students find it difficult to interpret position time graph for change in velocity and change in acceleration.

Item 8: In this item, the speed time graph for a body in motion is given and the respondents were required to calculate average acceleration over a time-period of 10 seconds. The concept of average v/s instantaneous acceleration is tested. Most of the students have calculated instantaneous acceleration. This suggests that students have difficulty in differentiating between average and instantaneous kinematical variables.

Item 9: This item describes the position/time graph of an object moving in a straight line and students had to choose the corresponding acceleration time graph from given four options. The item is based on the concept of double differentiation. This item is introduced in the questionnaire to check the understanding of the concept of relation between both the direction and magnitude of acceleration with change direction and magnitude of velocity). Most of the students have chosen the graph with shape similar to the shape of position time graph.

Item 10: In this item students had to identify a correct position time graph moving with uniform positive acceleration was to be selected by the students. This item involved the concept of double integration. Most of the students have chosen the position time graph in which displacement is positive and increasing linearly. During discussion with students it was found that they believe that if velocity is positive and uniform acceleration is also positive and uniform. Some students have chosen the option with positive constant acceleration when velocity is positive and increasing because they consider acceleration positive only if velocity is increasing.

Item 11: In this item students had to identify the graph corresponding to movement of an object with negative acceleration and slowing with time. This item is based on the concept of differentiation and student should understand the concept of direction of slope because acceleration is the slope of velocity time graph. Most of the students have chosen the option in which the slope of the graph is negative and constant but in this option object is changing direction. The responses to this item show that students do not have concept of slowing down and speeding up and change of direction of motion.

Item 12: In this item students had to identify the graph corresponding to motion of an object speeding up in negative direction. This item is based on the concept of differentiation. Some students have chosen the option in which slope is negative but decreases with time. Some students have chosen the option where slope is constant but negative. Most of the students have chosen the option in which slope is positive and increasing but the position is in negative quadrant. The responses to the item show that students find it difficult to differentiate between the direction of motion and direction of velocity.

Item 13: In this item, students had to compare the displacement of the particle in a given interval of time. The correct option is where the area under the curve is highest. Most of the students have chosen the option velocity is increasing.

Item 14: In this item students had to interpret the graph. Most of the students answered that the object is stationary at the beginning and then it moves forward and then finally stops because the graph slopes in forward direction. Some students answered that the object moves along a flat surface, and then falls down along a slope. Probably they considered the shape of the graph as representing the path of motion. The responses of the students show students have difficulty in interpreting the position time graph in terms of the direction of displacement.

Item 15: This item is introduced in the questionnaire to the understanding of relationship between change in velocity and sign of acceleration. In this item students had to interpret the graph verbally by selecting the correct description of motion in terms of its velocity. To solve this item student should have proper understanding concept of area under the curve. If the graph is extended beyond point B the acceleration will become negative but velocity will be positive and decrease in parabolic shape. To do this body will not have to change the direction of motion only its magnitude will decrease. Majority of students chose the option (C) i.e., 'The object is moving with zero velocity at time represented by point (B)'because they believe that if acceleration is zero, velocity will also be zero. Many students have chosen the option 'The object is moving with decreasing velocity between points A and B'.

Item 16: Students had to find the time interval in which particle is moving in positive direction with highest acceleration. Some students have chosen the interval with slope 5 m/s^{2} but the velocity is negative. This suggests that students have difficulty with understanding the relation between velocity and direction of motion.

Item 17: In this item, students had to calculate the displacement and distance travelled by the particle between 0s to 6s.They had to calculate area under the curve to calculate change in position. This is negative in the interval from 1s to 4s so while calculating total area under the curve this fact should be taken into account for calculation of displacement. Distance travelled is the total magnitude of area under the curve.
*Item 18:*In this item students had to identify the graph for the object which had smallest change in velocity during the five seconds interval. To answer this item concept of area under the curve should have been used. Most of the students have chosen the option in which acceleration is decreasing. Some students have chosen the option in which acceleration is constant.

Item 19: In this item alternative which represents the motion of object speeding up positive direction was asked. The item is based upon the concept that velocity is positive when direction of motion is positive and if the velocity is increasing the object is said to be speeding up.

Item 20: In item 20, ruled graph of the velocity a car was given and students had to calculate the distance travelled by it during the first four seconds.

Item 21: This item was included in the test to check students understanding about calculation of slope concept of positive and negative slope. The responses to this item show that some of the students cannot differentiate between positive and negative slope.

Item 22: In item 22 students were supposed to find average acceleration from the graph. This item is also based on concept of area under the curve. The correct answer is D; average acceleration can be calculated by finding out change in velocity during a fixed time interval which is area under the curve.

In item 23, students had to interpret the graph in terms of magnitude of displacement and acceleration at a given point A given on the graph. To answer this item student must understand the mathematical concept of integration in terms of graphs. The correct answer is at point A acceleration is positive and increasing because the velocity time graph has positive gradient. The displacement at this point is also increasing because the velocity is negative and object is slowing down.

V. Conclusion

Teachers rarely present formally the conceptual meaning attached to the equations to the students in the classroom. This is the reason why students construct different mental models for qualitative and quantitative aspects of concepts in physics. To enhance their problem solving skills, students must develop better qualitative knowledge and should learn to apply it to new situations. Knowledge of a particular topic is often considered as the measure of students understanding of concepts of the topic. The examinations are usually based on qualitative and quantitative knowledge, students are rarely asked to integrate their qualitative knowledge with quantitative knowledge.

It is necessary that the teacher must understand the prior knowledge of the student and his personality and provide him with planned multiple learning paths.

In most cases, students were unable to differentiate kinematics concepts and they had difficulty in interpreting time relationship of these kinematical variables which is the key to understanding of graphs in physics. Most of the students were unaware of the fact that these equations are applicable only if acceleration of the body is constant. In some cases students had problem deciding the value of initial velocity. They had difficulty understanding the connection between direction of motion and the sign of velocity and displacement. Students had difficulty calculating the slope of graphs. Since a slope of these graphs at any point can be positive, negative or zero, it is able to indicate both the magnitude and direction of a velocity or acceleration. Students have difficulty constructing, interpreting and using graphs with time as the variable plotted on the x-axis. Students make wrong interpretation of correlation between the kinematical variables, their graphical illustration and the paths of motions of objects. They get confused between slope of the graph and the path of the motion. They often read graph as the path of motion of the body. Students have difficulty interpreting the meaning of slope and height of velocity and position time graph while comparing their speeds in different intervals of time. Students have difficulty accepting that it is possible to have zero velocity and non-zero acceleration and vice versa. Zero acceleration with non zero velocity is the situation when after speeding up the velocity of the body starts reducing instantaneously. Zero velocity and non-zero acceleration is the situation when body is changing direction. Both the cases are very significant for study of motion of the body. Students have difficulty accepting that the direction of acceleration and sign of velocity together determines the change in speed of the object. Students have difficulty understanding that a moving body can have a positive velocity and negative acceleration or negative velocity and positive acceleration simultaneously. Students do not understand the concept of area under the curve. They do not understand that integration between two time limits is the area under the curve. Hence they are unable to predict displacement from velocity graph and velocity from acceleration graph. Students have difficulty predicting position time graph from acceleration time graph which is based on the mathematical concept of double integration. Students have difficulty predicting acceleration time graph from position time graph which is based on the mathematical concept of double differentiation.

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