Undergraduate students' difficulties with motion of objects on horizontal and inclined surfaces

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Abstract. The purpose of this study was to investigate the conceptual knowledge of the motion of two objects on an inclined and/or horizontal surface, in undergraduate physics students at the Central University of Technology, Free State (CUT), Bloemfontein campus. The study was conducted with 103 introductory to physics students in B.Ed. (FET) Natural Science programme in the faculty of Humanities as respondents. A pre-test was administered to test and investigate the students’ existing knowledge and was based on the concept of problem-solving. The results indicated that the majority (more than 80%) of students had major difficulties with where and how to start in order to solve the problems. They lacked basic knowledge of free-body diagram and vector analysis, as a result, they could not apply or deduce equations to solve. A follow-up remedial intervention was conducted to clear up the confusion and to assist them to acquire necessary and basic skills and knowledge of vector analysis, viz., free-body diagram, finding vertical and horizontal components of vectors, equilibrium conditions as well application of Newton’s Second law of motion. With this skill, they were introduced to deriving equations to calculate the acceleration of the objects and the tension of the wire connecting them (mathematical skills). A post-test was administered and the results indicated a great improvement (more than 70%) in the vector analysis and mathematical application of vectors in problem solving. Follow-up interviews indicated deficiencies and confusion from their previous learning, although some students (about 30% of the 70%) indicated that they need to be taught the concept first before the test. Their reasoning was they forgot the concept.

Keywords: Conceptual knowledge, motion, horizontal and inclined plane, problem solving, free-body diagram, vectors

1. Overview
Introductory university physics courses emphasize problem solving [1] and students actively construct a knowledge hierarchy on a foundation of qualitative understanding. Physicists often apply mathematical knowledge, but attach physical meaning to mathematical symbols and rules such as numbers, variables and relations [2]. Mathematical concepts are re-interpreted in the physics context [3].

It has been reported that many cognitive scientists and physicists have done work on the students’ conceptual knowledge and understanding in introductory physics but only few incorporated this concept
in the teaching and learning [4]. Maloney [5] and Phage [6] reiterated that students bring with them their own opinions on the study of physics and these opinions and ideas are conflicting with the actual physics practices.

Tuminaro and Redish [7] provided evidence showing that students’ inability to transfer their existing mathematics knowledge to physics is the major source of students’ errors. Most of the studies were on problem solving - e.g. [8, 9] - or interpretation of specific aspects such as the slope of graphs - e.g. [11]. There are few research studies [11, 10] on students’ applications of mathematics knowledge in physics.

One of the fundamental and phenomenal challenges that students experience is problem-solving, which requires undergraduate students’ analytical and interpretational skills (prior learning, mathematical applications, etc.), [1]. Studies [11] have reported that even if students succeed in problem-solving, that does not necessarily mean that they have developed general problem solving skills and/or have a thorough understanding or learning of the concept. They further argue that a common misconception of the teachers is that they seem to believe that the more problems students solve, the better their understanding of the concept (an efficient instructional delivery rather than efficient instructional learning).

Leonard et al [11] emphasize the importance of conceptual analysis of a situation emanating from deep-rooted understanding and proficient ability to solve problems, a cognitive measure. Research by Langbeheim, [12] has shown that project-based learning promotes student interest in science and improves understanding of scientific content through (a feasible classroom practice, challenging yet fulfilling for both students and teachers), evidence demonstrated from student work. Campbell, [13] has argued that students believe that they did not learn science best via textbook-based instruction.

2. Pedagogical Knowledge on the study of motion on a surface

Many students find it difficult to study science, particularly physics, because they find it abstract in nature. One of the fundamental and phenomenal challenges students experience is problem-solving, which requires undergraduate students’ analytical and interpretational skills. One concept that requires such skills is motion (whether there is or there is not) within an object, due to the impact of force or forces acting on or by such an object.

Physics education research is into instruction for introductory university physics courses that emphasize problem solving [1]. Students actively construct a knowledge hierarchy on a foundation of qualitative understanding. Friction has been reported to of vital and significant importance in daily life environment, e.g., playground slides [14]. Slides form a basis for and is a good example for the investigation of friction and motion on both inclined and horizontal planes.

This paper deals with what skills do first-year undergraduate physics students need to be able to solve problems on motion and its causes of an object. It has been reported that even if students succeed in problem-solving, that does not necessarily mean that they have developed general problem solving skills and or have a thorough understanding or learning of the concept [11]. Leonard et al [11] further argue that a common misconception of the teachers is that they seem to believe that the more problems students solve, the better their understanding of the concept. This is regarded as efficient instructional delivery rather than efficient instructional learning. Leonard et al [11] emphasize the importance of conceptual analysis of a situation emanating from deep-rooted understand and proficient ability to solve problems, a cognitive measure.

Research has shown that project-based learning promotes students’ interest in science and improves understanding of scientific content. Evidence from student work further demonstrates that project-based learning is a feasible classroom practice, challenging yet fulfilling for both students and teachers [12].

Campbell [13] has argued that students believe that they did not learn science best via textbook-based instruction, However, students’ knowledge and understanding of force and motion concepts does increase through demonstration as compared to textbook-based instruction.

The study, therefore, is aimed at investigating the difficulties that undergraduate physics students experience with the motion of objects on inclined and horizontal surfaces.
3. Research questions and objectives

3.1 The objective of the study was to determine:
- establish the difficulties encountered by students when analyzing the motion of horizontal and/or inclined planes
- determine effective teaching and learning strategies required to enhance students’ comprehension of conceptual analysis of motion on horizontal and inclined planes.

3.2 Research questions
- What difficulties were encountered by students when analyzing the motion of horizontal and/or inclined planes?
- How and what effective were teaching and learning strategies required to enhance students’ comprehension of conceptual analysis of motion on horizontal and inclined planes?

4. Research Methodology

The study was conducted using a mixed methods approach, which entailed an open-ended questionnaire and follow-up focus group interviews. The researcher's journey through this process was also a focus of a qualitative and quantitative analysis of effective and enhance strategies for comprehension and interpretation in the study of kinematics and dynamics in introductory physics. Initial data were gathered by a pretest indicating students' understanding of force and motion concepts, their subsequent understanding of these concepts and their ability to generalize their understandings and then classroom-based assessments was evaluated using a posttest approach.

To prepare the students, a revision on kinematics and dynamics was done with them in class as an intervention measure. A questionnaires made of questions (populated from previous exam questions and tutorial exercises) on motion of an object on both horizontal and inclined planes were distributed to the respondents. After the questionnaires were collected, follow-up interviews were used to probe students’ reasoning behind their solutions. These interviews were conducted using the focus group approach, which allowed for the triangulation of pertinent data necessary to draw conclusions from the study.

4.1. Sampling
Participants (convenience sampling) were comprised of 103 first year undergraduate physics students in the B.Ed (SP & FET) Natural Science Specialization programme at a University of Technology (UoT), an institution of higher learning under the Department of Higher Education and Training (DHET) in South Africa. The programme is aimed at training prospective science teachers to be able to teach Natural Sciences in the Senior Phase (SP) (Grade 7 to 9) and to teach Physical Sciences in the Further Education and Training (FET) Phase (Grade 10 to 12).

The admission criterion is that students should have passed both Mathematics and Physical Science with a minimum of 50% and above. In their underlying and all undergraduate physics course, vectors play a significant and critical role of their basic learning and science literacy. Hence, a need to probe their conceptual understanding and problem-solving skills of vectors.

Participation in the research was voluntary and participants’ consent was obtained. Participants were made aware that their details will be confidential, and the results obtained will be strictly for research purpose and that it will not impact on the formative and or summative assessment. The study will be used to enhance the teaching and learning of and increase the performance in of the study of motion, viz., kinematics and dynamics both in the undergraduate introductory and high school physics.

4.2. Data collection
The questionnaire involved ability of students to identify all the forces acting on an object on horizontal and inclined planes and consequently able to represent them fully on a vector diagram. They also had to be able to split a given vector into its vertical and horizontal components.

Derivation of coefficient of friction or equation of friction and any other equation were also expected to be deduced or derived from such a vector diagram. Derivation of equations to be worked with or to
assist with problem-solving involved application and use of Newton’s Laws of motion especially on the equilibrium or resultant of vectors (forces).

4.2.1. *Object on a horizontal plane.*
The Free-body diagram for an object on a horizontal plane showing all the forces acting on an object and its corresponding equations had to be represented as below.

![Free Body Diagram](image)

**Figure 1.** Free Body Diagram.

Respondents also had to state the difference between static and kinetic friction and represent a definition and equation of coefficient of friction.

4.2.1.1. *A typical scenario of an inclined was also questioned.* Examples of problem-solving exercises and expected solutions

**Procedure**
- Students have to draw a rough diagram of the problem
- Draw all the forces acting on it
- Use Newton’s Laws to deduce equations to solve
- Apply mathematics to solve the equations (simultaneously)

Examples of problem-solving exercises and expected solutions

4.2.1.2. *Example 1.1.* Examples of problem-solving exercises and expected solutions. If the coefficient of kinetic friction between a 35-kg crate and the floor is 0.30, what horizontal force is required to move the crate to the right at a constant speed across the floor?
Solution:

\[ F_a = F_f \quad F_f = \mu_k F_N \]
\[ F_a = \mu_k F_N \]
\[ F_N = mg \]
\[ F_a = \mu_k mg \]
\[ F_a = (0.30)(35)(9.8) \]
\[ F_a = 102.9 \text{ N} \]

**Figure 2.** Solution to Example 1.1.

4.2.1.3. **Example 1.2.** Suppose the same 35 kg crate was accelerating at 0.70 m.s\(^{-2}\). Calculate the applied force. The coefficient of friction is still 0.30.

\[ F_{\text{NET}} = ma \]
\[ F_a - F_f = ma \]
\[ F_a - \mu_k F_N = ma \]
\[ F_a - \mu_k mg = ma \]
\[ F_a = ma + \mu_k mg \]
\[ F_a = (35)(0.70) + (0.30)(35)(9.8) \]
\[ F_a = 127.4 \text{ N} \]

**Figure 3.** Solution to Example 1.2.

4.2.2. **Object on an inclined plane.** Examples of an inclined plane involved analysis of problem over and above what they did in solving horizontal plane problem:

Procedure:
- First identify the two surfaces, viz., the ground and the incline
- Split weight into its vertical and horizontal components of the incline
- Show mathematically how the angle on the ground is equal to the angle below the incline, made by weight and its weight component.

![Diagram showing forces and angles](image)

**Figure 4.** Expected Analysis.

4.2.2.1. Example 2. A person pushes a 30-kg shopping cart up a 100 incline with a force of 85 N. Calculate the coefficient of friction if the cart is pushed at a constant speed.

![Diagram solving example 2](image)

\[
F_a = F_f + mg \sin \theta \\
F_f = \mu_k F_N \\
F_a = \mu_k F_N + mg \sin \theta \\
F_N = mg \cos \theta \\
F_a = \mu_k mg \cos \theta + mg \sin \theta \\
F_a - mg \sin \theta = \mu_k mg \cos \theta \\
\mu_k = \frac{F_a - mg \sin \theta}{mg \cos \theta} \\
\mu_k = \frac{85 - (30)(9.8)(\sin 10)}{(30)(9.8)(\cos 10)} = 0.117
\]

**Figure 5.** Solution to example 2.

5. Results
5.1. Analysis of results
In accordance with Hake [16], most physicists would agree that a low score that through FCI test, students’ lack of understanding the Newtonian mechanics, including vectors can be determined. Hence the table below indicates the respondents’ pre-test and post-test performance scores. In the pre-test, there were fewer respondents, 38 as compared to post-test with 103 respondents.
### Table 1. Results obtained.

| Problem 1.1 | Pre-test (n = 38) | Post-test (n = 103) |
|-------------|-------------------|---------------------|
| No. of respondents | % Correct | No. of respondents | % Correct |
| 16 | 42 | 89 | 86 |
| 11 | 29 | 79 | 77 |

| Problem 2 | Pre-test (n = 38) | Post-test (n = 103) |
|----------------|-------------------|---------------------|
| No. of respondents | % Correct | No. of respondents | % Correct |
| 5 | 16 | 84 | 82 |

Average 11 29 84 82

#### 5.2 Discussion of results

The results in Table 1 depict the average performance scores of respondents per problem during the pre-test and post-test. These results indicate poor performance in the pre-test, and further show that there are several factors for this underperformance as reiterated and highlighted in the conceptual framework (literature review). The factors are also accounted for by the interview responses, such as having learnt to pass in high school, expecting to be taught the concept or topic again, lack of conceptual and mathematics knowledge, inability to link or relate or use mathematical skills to solve the force and motion problems. These factors and problems were revisited, dealt with and addressed during remedial intervention hence an improved performance in the post-test.

Table 2 shows that the effect sizes (w-values) in problems 1.1 was large, implying that performance was practically significantly different. This meant that students could remember, comprehend and use conceptual knowledge constructively.

**Table 2. Results obtained**

| Task | Problem 1.1 | Problem 1.2 | Problem 2 |
|------|-------------|--------------|-----------|
| Average % | 65.3 | 53.5 | 40.8 |
| Effect sizes (w) | 0.58 | 0.52 | ≤ 0.24 |

Cohen’s effect size:

\[ w = \frac{\chi^2}{n} \]

The \( w \)-values are interpreted as follows:
- \( w<0.3 \) is a small effect
- \( 0.3 \leq w \leq 0.5 \) is a medium effect
- \( w>0.5 \) is a large effect
The performances and Problem 1.2 indicated a medium effect, meaning participants answered differently. This implied that students struggled to add and to use knowledge used in solution of problem 1.1. The effect size of the problem 2 was smaller (insignificant), implying students had difficulty with what they have to do and the conceptual understanding. The questions were answered similarly, either both correct or both incorrect, forgetting that they had to find and use weight components.

6. Limitation of study
The study is limited to introductory physics students at Central University of Technology, Free State, an institution under the Department of Higher Education and training in South Africa, therefore no generalised conclusion can be made.

7. Conclusion
In the physics domain, the majority of participants were unable to transfer and integrate their correct conceptual (kinematics and algebraic) knowledge and skills on the representation and analysis/interpretation of motion on horizontal and inclined planes. Student knowledge and understanding of force and motion concepts do increase through demonstration as compared to textbook-based instruction. Participants reveal the mathematics knowledge, but lack the necessary physics knowledge and conceptual understanding, e.g. in the kinematics and dynamics (Newton’s equations and Laws). Various teaching strategies could be implored which would motivate students and learners to learn to understand and know to be competent in the concept for a lifelong learning. In this way, constructivist and scaffolding approach will be implemented towards learning and introduction of new concepts. Student and learners’ attitude and interest in the subject will also be enhance.

8. References
[1] Van Heuvelen, A. 1991. Overview, case study physics. American Journal of Physics, 59(10), pp.898-907.
[2] Redish, E.F. & Gupta, A. 2009. Making meaning with math in physics: A semantic analysis, GIREP 2009, (Leicester, UK)
[3] Meredith, D.C. & Marrongelle, K.A. (2008). How students use mathematical resources in an electrostatics context. American Journal of Physics, 76, 570-578.
[4] Arons, A.B., Gould, H. and Gould, M. 1991. A guide to introductory physics teaching. American Journal of Physics, 59(2), pp.189-190
[5] Maloney, D.P. 1990. Forces as interactions. The Physics Teacher, 28(6), pp.386-390.
[6] Phaje, I.B. (2015). An analysis of students’ knowledge of graphs in mathematics and kinematics. Potchefstroom: North-West University. (Dissertation – M.Sc.).Potgieter, M., Harding, A. & Engelbrecht, J. (2008). Transfer of algebraic and graphical thinking between mathematics and chemistry. Journal of Research in Science Teaching, 45, 197-218
[7] Tuminaro, J. & Redish, E.F. (2004). Understanding students’ poor performance on mathematical problem solving in physics. In J. Marx, S. Franklin, & K. Cummings (Eds.), American Institute of Physics: 2003 Physics Education Research Conference. (pp113-116).
[8] Freitas, I.M., Jiménez, R., Mellado, V. (2004). Solving Physics Problems: The Conceptions and Practice of an Experienced Teacher and an Inexperienced Teacher. Research in Science Education 34: 113–133, 2004.
[9] Redish, E.F. (2005). Problem solving and the use of math in physics courses. Proceedings of the Conference on World View on Physics Education: Focusing on Change, New Delhi, India.
[10] Woolnough, J. (2000). How do students learn to apply their mathematical knowledge to interpret graphs in physics? Research in Science Education, 30, 259-267.
[11] Leonard, W.J., Gerace, W.J. and Dufresne, R.J., 1999. Concept-based problem solving: Making concepts the language of physics. University of Massachusetts Physics Education Research Group Technical Report.
[12] Langbeheim, E. 2015. A project-based course on Newton’s laws for talented junior high-school students. Physics Education, 50(4), p.410.

[13] Campbell, M. 2006. The effects of the 5E learning cycle model on students' understanding of force and motion concepts. University of Central Florida, Electronic Theses and Dissertations

[14] Pendrill, A.M., Ekström, P., Hansson, L., Mars, P., Ouattara, L. and Ryan, U., 2014. Motion on an inclined plane and the nature of science. Physics education, 49(2), p.180.

[15] Hake, R. 2002. Lessons from the physics education reform effort. Conservation Ecology, 5(2).