PROBING STUDENTS' UNDERSTANDING AND SCIENTIFIC THINKING OF EQUATIONS OF MOTION IN KINEMATICS

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ABSTRACT:

Research alludes to the prioritisation of both content knowledge and scientific thinking for effectiveness of learning. Since course success is dependent on pass rates, teachers of late have resorted to training students to answer questions in a stereotype way to ensure that students are able to answer questions in a similar format in formal assessments. This paper explores the various scientific processes that students experience whilst engaged in problem solving in physics. In particular, we have focussed on equations of motion in kinematics involving the motion of 2 bodies, for which there appears to be many inconsistencies in the way these types of problems are tackled.

Early in the semester, before the onset of classes, a pre-test was administered to 111 first year university students engaged in physics studies. This research is then preceded by an inquiry-based instruction in class, specifically aimed at techniques in problem solving in physics. Once a substantial amount of time has been devoted to problem solving techniques in kinematics, a post-test, in the exact format as the pre-test was again administered. Concurrently, with these tests an epistemological survey, developed by Hammer (1994) was also administered at the same time as that of the pre and post-tests. The pre and post-tests were evaluated by using a modified rubric developed by Steinberg et al. (2009). The results indicate a mean score of 2.45 for the pre-test and a mean score of 2.82 for the post test, indicating a positive shift in scientific thinking after purposeful instruction. Likewise the epistemological survey indicates that the students have a favourable understanding of science from the differences between the pre and post epistemological survey of results.

Key words: kinematics, scientific thinking, inquiry-based instruction and epistemological

1. Introduction

Students generally loose interest when exposed to a traditional format of instruction in science. To inspire young scientific minds, prioritisation of both scientific thinking and scientific content needs to be put in place for academic success (Steinberg et al., 2009). In many schools and universities of today, there is a huge emphasis for syllabus coverage and tests with little cognisance given to the understanding of the content. Schools are pursuing a traditional mode of instruction. This mode of instruction places little emphasis on the development of scientific skills in the minds of these students. In this instance, very little time is devoted to the understanding of how to analyse and think scientifically about real world problems in science (Williams et al., 2004). Devoid of such scientific thinking tools will engender these students with a belief that the nature of science is skewed and not in line with what is expected of experts in the field of science (Steinberg et al., 2009; Songer & Linn, 1991). For science education to be successful, there needs to be a counterview of this scenario, where scientific thinking becomes part of everyday lifestyle decision making (Kuhn, 1993(a)).

For this paper, we focus on the nature of scientific thinking amongst undergraduate physics students at a university who have been exposed to many years of traditional teaching at schools. The trajectory from this point in time is to introduce them to an inquiry-based form of learning. We have focussed our attention to mechanics, and in particular projectile motion, where there appears to be many inconsistencies in the way these problems are solved. In order to understand how students can be trained to think scientifically, we are informed by research of Koshowski (1996) that there are 2 approaches, namely domain-specific and domain-general approach to scientific thinking. Zimmerman (2000) has clearly enunciated these approaches (and cited by Williams et al., (2004) as well):

In the domain-specific approach of thinking, students are adapted to new ways of knowledge assimilation with the hope of overcoming the challenges they face, from misconceptions, language barriers, etc. (Williams et al., 2004), and In the domain-general approach to scientific thinking, the focus is on experimental design and hypothesis, where reasoning skills about casual relationships in the transferability of knowledge from one discipline to another is developed (Williams et al., 2004; Zimmerman, 2000). An example of this is when one uses an algorithm from mathematics to solve a problem in physics.

Thus, to achieve scientific reasoning skills in both cases may be difficult. Williams et al., (2009) has combined both these approaches into one theme. This they have done by linking science to real world contexts, a general strategy for thinking science with a scientific method. Thus the focus of this paper is on the development of metacognition (students thinking scientifically) skills through an inquiry-based approach.

2. Research Question

To understand the nature of the students' scientific thinking in the context of Equations of Motion in Mechanics.

3. Conceptual framework

According to Paul & Elder (2012), scientific thinking is defined as follows:

"Scientific thinking is that mode of thinking – about scientific subject, content, or problem – in which the thinker improves the quality of his or her thinking by skilfully taking charge of the structures inherent in thinking and imposing intellectual structures upon them".

With this in mind, and inherent in this definition, are problem solving and communication skills, which are pre-requisites for effective scientific thinking. Communication is essential when discussing solutions to complex problems in science. Other researchers such as Kuhn (2010) have alluded to scientific thinking as "knowledge seeking". In this sense, it means that they seek knowledge, acknowledging that their existing knowledge is lacking or incorrect and thus something new is learnt.

Our research focusses on an inquiry-based learning approach as a way of developing scientific thinking. According to Ingelsrud & Leonard (1988), there are 3 broad definitions of inquiry-based teaching, and they are (Udo Westerneng, 1993):

The pedagogical methods of teachings. Teaching students different methods that are used in science, and Science is conducted by a scientist.

In respect to the above, we aim to use various pedagogical methods to teach science until students have the tools to help them to think robustly and scientifically about a whole range problem, both professionally and personally (Williams et al., 2004).

In respect to an inquiry – learning approach, Bell et al., (2010) has postulated the following criteria that are relevant to this approach:

Creating their own questions

Providing supporting evidence to answer the questions Explaining the evidence that was collected

Finding a connection between knowledge and the investigative work Creating a compelling argument and justifications for the explanations.

These statements are in line with Zimmerman's (2000) arguments, in their dichotomy discussions when domain-specific and domain-general arguments were presented. These arguments tend to align more towards the domain-general criteria of scientific thinking, mentioned above.

4. Context of the Study

This research made use of students from the Bachelor of Engineering Technology (BET) program. The minimum criteria for admission to this program is a level 5 (60%) for Physical Science in the National Senior Certificate examinations. Many of these students come from various high schools within the Gauteng and surrounding regions and consists of largely black South Africans. It has come to our attention that, after administration of the pre-test on a 2-body diagram problem in kinematics, that students lack the strategy in solving such problems. It was then decided to change our strategy of teaching from one of a traditional mode of instruction to an inquiry-based mode of instruction.

5. Validity and reliability of the pre-and post-test

The question chosen for the pre- and post-test was taken from the grade 12 Physical Science National Senior Certificate Examination paper. This question was officially approved by the Department of Basic Education and was moderated by their team as part of their validation process. The general decline in performance of grade 12 learners in Physical Science, and such poor performance is also consistent with the question that was chosen for this research.

6. Research Methodology

3. sample of 111 students were administered a pre-test, given below. After an inquiry-based instruction, students were then given a post-test (same as the pre-test) towards the end of the semester. Concomitant to these tests, an epistemological survey by Hammer (1994) were also given to these students. The pre- and post- tests were intended to reflect the students' beliefs and perceptions of the nature of learning and understanding science (Steinberg et al.,

2009). On the other hand, the epistemological survey was intended to measure the students' approaches to problem-solving, prior to traditional instruction. The purpose of this intervention was to indicate if students thinking was aligned to what is expected from experts in the field of science.

For the data analysis, a completely modified rubric of the nature of the one used by Steinberg et al. (2009) for astronomical studies, was adapted for this study. In this respect, the rubric scale ranged from 1 (uses the incorrect equation of motion to solve the problem) to the other end of the scale 5 (uses the relevant equation of motion to solve the problem completely). Likewise the epistemological survey ranged from 1 (least favourable) to the other end of the scale 5 (most favourable) answer. Statistical measures, in the form of mean scores, were used to evaluate both sets of data.

PROJECTILE MOTION: Pre-test

An air balloon is ascending (moving upwards) from the ground and once it is 50.0 m above the ground, its speed is 20.0 $m.s^{-1}$, ball A is released from the air balloon. One second later, when the air balloon is Δ m above the ground and travelling at a speed of 11.2 $m.s^{-1}$, ball B is released. Both balls, A and B, strike the ground at the same time. If the ground is taken as the reference and upward motion is treated as positive,

1) Calculate the time taken for ball A to reach the ground, and

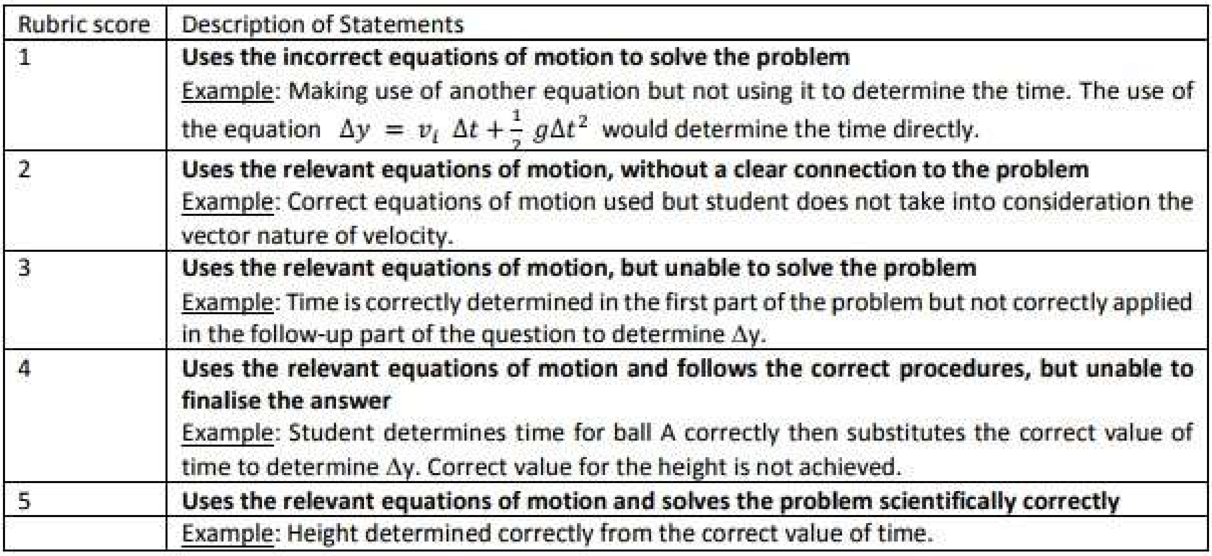
2) Determine the height from which ball B is released.

7. Pre-Test evaluation

The pre-test, as indicated above has been administered to the students. The same test, as a post-test was given to the students towards the end of the semester. The test comprised of a 2-body problem in projectile motion. When such a problem appeared in the NSC examinations, the performance of the students in that question was appalling, with only 11% (Diagnostic Report of DBE, 2015) of the candidates getting the question correct. In respect to our question, the answers reflect a lack of deep conceptual misunderstanding for 2-body problems in mechanics. During the class sessions, students were very eager to know how such problems were solved and if their answers were correct. Unfortunately, we were not willing to disclose the answer for this problem without them having a sound conceptual understanding of it.

To assess the students’ answers, we have used a rubric, as shown in Table 1 below. Students are awarded a score, based on the scientific principles as indicated in the table below.

Table 1: Rubric used to evaluate the students’ responses to both the pre-and post-tests.



Rubric score	Description of Statements
1	**Uses the incorrect equations of motion to solve the problem** Example: Making use of another equation but not using it to determine the time. The use of the equation $\Delta y = v_i \, \Delta t + \frac{1}{2} g\Delta t^2$ would determine the time directly.
2	**Uses the relevant equations of motion, without a clear connection to the problem** Example: Correct equations of motion used but student does not take into consideration the vector nature of velocity.
3	**Uses the relevant equations of motion, but unable to solve the problem** Example: Time is correctly determined in the first part of the problem but not correctly applied in the follow-up part of the question to determine Δy.
4	**Uses the relevant equations of motion and follows the correct procedures, but unable to finalise the answer** Example: Student determines time for ball A correctly then substitutes the correct value of time to determine Δy. Correct value for the height is not achieved.
5	**Uses the relevant equations of motion and solves the problem scientifically correctly**
	Example: Height determined correctly from the correct value of time.

Example: Height determined correctly from the correct value of time.

In Table 2, we have the results of the students’ evaluations using the rubric in Table 1 of the pre-test.

Table 2: Frequency tally and the corresponding percentages obtained by students in the pre-test

Rubric score	Frequency tally- number of students with scores within the rubric scale	Percentage score (%)
1	15	14
2	56	50

3	26	23
4	3	3
5	11	10

Table 2 reveals that bulk of the students have obtained a rubric score of 2 for the pre-test and a small percentage of students have obtained the correct answer. The average mean score for the pre-test is 2.45.

8. Instruction

The outcome of the pre-test results has implored us to re-visit our teaching strategies. Previously, our mode of instruction was traditional in nature, meaning that students achieved success through replication and memorisation of concepts and solutions without a deep conceptual understanding. Mechanics and topics within it such as projectile motion has since been taught using an inquiry-based mode of instruction, where emphasis is placed on the development of higher metacognitive skills (scientific thinking). In this method, students were not given any answers to problems but were carefully guided as to how to obtain them through a scientific method. For example, in the aspect of theory instruction, students are not taught concepts but are first referred to real life phenomena that students are familiar with, then instruction proceeds from definitions of variables that are relevant to the phenomena. In respect to problems, students are given elementary problems as a warm-up exercise and then are exposed to a variety of problems of varying complexity as part of their classwork or tutorial exercises. When these students fail to resolve a particular problem, they then ask the question, “What is the method of solving this problem?” instead of asking what the answer is. In this way students learn physics as part of their lifelong learning endeavours.

9. Post-test Evaluation

Towards the end of the teaching of the mechanics section, after implementing an inquiry-based instruction, students were then given the same question as the pre-test. Students’ responses were then evaluated using the same rubric, as shown in Table 1. The average rubric score for the post-test was 2.82, showing a shift of 0.37 from the pre-test rubric score. Likewise, the results for the post-test is given in Table 3 below.

Table 3: Frequency tally, corresponding percentages and shift in percentages for the post-test results

Rubric score	Frequency tally	Percentage score (%)	Shift in percentage (%)
1	5	12	-2
2	43	39	-11
3	44	40	+17
4	4	4	+1
5	15	14	+4

Large majorities of students (40%) have used the relevant equations of motion to correctly determine the time in the first part of the problem but were unable to resolve the rest of the problem to determine the correct height of the ball. Of the 111 students that have completed the test, 26 of them had a rubric score of 3 in the pre-test and this has shifted to 44 students achieving such scores in the post-test. This may be regarded as encouraging when considering fewer students had a rubric score of 1 (less by 2%) and 2 (less by 11%), respectively. In the ideal scenario, 4% (rubric score of 5) have achieved maximum benefit from an inquiry-based instruction mode of teaching.

Table 4: Shifts in the rubric scores for each of the 111 students. Here - - - , - - and – represents shifts in rubric scores of 3, 2 and 1 place downwards, respectively, 0 represents no shift in rubric score and +, ++ and +++ represents upwards shifts of 1, 2 and 3 respectively, upwards from their original rubric scores.

Shift in rubric score	Frequency tally score	Percentage shift (%)
_ _ _	2	2
_ _	5	5
_	7	6
0	54	5
+	32	3
++	4	4
+++	5	5
+++	2	2

Focussed inquiry based instruction have benefitted 43 of the 111 students, for which there were an upward shift in the rubric score. For the vast majority of the students, the rubric scores remained unchanged (54 of 111 students) and for 14 of them, the instruction had the opposite effect.

10. Epistemological Survey

The epistemological survey, which was given in conjunction with the pre and post-test, was done to determine the students' beliefs and approaches to problem solving. In this respect, the epistemological measures survey of Hammer (1994) is a good tool for that purpose, because the students' responses to the survey could provide a yardstick as to whether their understanding of science is in line of what is expected by experts in the field (Steinberg et al., 2009). Results from the survey, which scaled from 1 (least favourable) to 5 (most favourable), reveals that students have a favourable approach to science. The average mean score for the survey is 3.5. Of interest is the students' response to item 5 (61%), where creativity is being regarded as a useful skill, appears to be strongly supported by many students. Other items, such as item 7 (75%), which appears to be unfavourably supported; this is not surprising since it was for a pre-test evaluation. In this respect, it seems that students struggle to make connections between science and real life experiences. Quite interestingly, for item 16, 76% of the students have vehemently supported the understanding of concepts and its interconnectivity, rather than merely memorising formulas and definitions.

These perceptions also concurs with the students' responses to item 10 (59% in favour), in which students consider science laws to have little significance to everyday life experiences. In the pre and post-test, it has come to our surprise that students' beliefs about science is slightly lower than their pre-test perceptions. The average mean score for the post-test is 3.4. On the positive side of things, some items such as items 7 and 10 have shown a shift to being more favourable from their pre-test perceptions.

EPISTEMOLOGICAL BELIEFS ABOUT SCIENCE

Table 5: Table shows the pre-test and post-test mean scores for the various items of the questionnaire

No	Item	Mean scores	
		Pre-test	Post-test

1	When real life experiences differ from what is learned in a science text book, the real-life experience should be ignored in order to learn the science well.	2.3	2.9
2	It is very hard to understand scientific ideas in an intuitive sense; they should just be taken as given.	2.5	2.2
3	Knowledge in science consists of pieces of information, each of which applies primarily to a specific situation.	3.8	3.3
4	To know science is to be able to recall equations, laws, definitions and theories.	4.0	2.8
5	Creativity is a useful skill that is often utilized in learning science.	4.3	3.2
6	Learning science is a matter of acquiring knowledge that is specifically located in the definitions, principles, and equations given in class and/or in textbook.	2.8	3.1
7	In learning science, it is not necessary to make connections between science concepts and real-life experiences.	1.5	2.8
8	A significant problem in science courses is being able to memorise all the information that is needed.	2.9	2.7
9	In solving problems in science, if a calculation provides a result that is significantly different than what was expected, the calculation should be trusted.	2.2	2.2
10	Science laws have little to do with everyday life.	2.1	3.4
11	Being able to recall formulas and definitions about a topic in science shows an understanding of that topic.	3.6	2.4
12	Often, a scientific principle or theory just doesn’t make sense. In those cases, you have to accept it and move on, because not everything in science is supposed to make sense.	2.4	2.6
13	Each field of science has its own set of theories, equations and definitions, few of which have connections with the other fields of study.	2.9	3.0
14	What is observed in real life doesn’t always match scientific theories because those theories only apply to laboratory situations.	2.5	2.9
15	A good textbook is the most useful tool in learning science.	3.7	3.2
16	When learning science, understanding the concepts and the connections between them is more important than memorizing formulas and definitions.	4.5	4.2
17	The most crucial thing in answering a question or solving a problem in a science class is to find the right definition to use.	4.0	3.9
Average mean score		3.5	3.4

11. Discussions and Conclusion

From the two sets of evaluation tools (student reasoning in their explanation of answers and student self-assessment epistemology survey) used to measure student thinking about the nature of science, the benefits accrued from an inquiry-based instruction cannot be overlooked. In this scenario, there has been an improvement in the overall averages between the pre and post-test evaluations. However, in the epistemological survey, there was a slight decrease in the overall mean score. This could imply that students' conceptual understanding of school science may be found wanting. Although these students might have had good grades at high school, they might not have understood the basic laws that underline the phenomena (McDermott, 1993, & Erceg et al., 2013). These students have attained success from the traditional quantitative problem solving methods (McDermott, 1993), but show lack of scientific thinking in problem solving activities.

Students' understanding of the nature of scientific thinking in the context of equations of motion is superficial, but through an inquiry-based format of instruction, we have seen some beneficial results. On the issue of a 2-body problem, students are successful in solving a single body problem but lack serious insight when two or more problems are combined into a single problem. They have excellent memory to replicate solutions to similar problems but once variables are tweaked poses a serious fundamental challenge to even the brightest of the students. Our remedy to this situation, also echoes the thoughts of Kuhn (1993 (a)) when he says that one should connect the content of science to phenomena that the student is familiar with, thus moving from the known to the unknown.

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