2022-05-09

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Recommended Citation

Andrew Cashman & Tom O’Mahony (2022) Student understanding of kinematics: a qualitative assessment, European Journal of Engineering Education, DOI: 10.1080/03043797.2022.2073200

Student Understanding of Kinematics: A Qualitative Assessment

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Keywords: Mechanical Engineering, Phenomenography, Kinematics, Teaching and Learning, conceptual understanding

Abstract

In engineering, kinematics is widely regarded as a fundamental topic due to the part it plays in the wider field of Physics. The literature agrees that students possess a wide range in understanding of the topic and many interventions have been investigated. This study aims to take a second-order approach by understanding and exploring the qualitatively different ways in which students approach solving kinematics problems, so appropriate instruction can be designed.

Phenomenography was used to collect data through ten semi-structured interviews with early stage mechanical engineering students. Following data analysis, four distinct categories of students' approaches were identified; unstructured, framing the problem, strategic, and conceptual. It was found that these categories could be arranged in a hierarchy and were also supported by secondary epistemic factors such as self-awareness and core values, in determining why students employed a particular approach. The findings emphasise the need for approaching instruction from multiple perspectives and suggest a more comprehensive learning experience can be supported. A shift from teacher- to student-centred delivery by linking practical laboratory observations with real world concepts, use of visual aids, dry labs, active and peer-to-peer learning, would be beneficial in supporting students in achieving a higher level of conceptual understanding.

1 Introduction

Mechanical engineering is widely regarded as one of the broadest engineering disciplines as it combines some of the core areas of physics and mathematics in the study of objects and systems in motion (Columbia University, 2020). Within a typical mechanical engineering curriculum, fundamental learning strands are easily identified, one of which is kinematics, the study of motion. This stream forms a key part of the curriculum as it is often a concept that needs to be applied in other areas of engineering and physics, for example in kinetics, the study of forces, where analysis of the interaction between forces and motion may be required. Developing an understanding of kinematics will likely help students to deal with more complex physical problems later in the degree programme and thus, it is vital that they develop this understanding of the basic concepts early on. Rosenquist and McDermott (1987) outline this importance by stating "*kinematical concepts are of sufficient importance to warrant special attention. In addition to providing a basis for the study of dynamics, the concepts of velocity and acceleration are often used to introduce various instantaneous rates, not only in Physics but in other disciplines"* (Rosenquist and McDermott, 1987: p415).

There is a reasonable body of published research investigating pedagogical practices in the teaching and learning of kinematics in higher education. In the 1980's, an extensive study was conducted on the topic of kinematics in the University of Washington to try to understand what aspects students found difficult, with the aim of designing improved teaching methods. Trowbridge and McDermott (1980) and Trowbridge and McDermott (1981) conducted 200 individual demonstration interviews where students were asked specific questions about simple motions they observed. The authors found that a significant portion of the students, who were from a wide variety of courses, had difficulty with the concepts of velocity and acceleration and often even mixed up the two. The authors conclude that "several types of conceptual difficulties were identified". The findings from this research compliment the vast quantity of anecdotal evidence available in both the literature and from the authors' experiences that kinematics is not only a key topic on the engineering curriculum but one which is often hugely misunderstood by students.

While the literature is clear that students have different levels of understanding around the topic, many have attempted to implement different teaching and learning strategies and evaluate its impact. As will be discussed in the next section, one of the criticisms of some of these bodies of work is that the approaches taken are generally first-order and do not account for the perspective of the learner themselves. Furthermore, some of the second-order studies are focused outside of kinematics in the wider topic of physics. Thus, the contribution of this article is that it investigates the qualitatively different ways in which students understand the topic of kinematics and how they approach solving these problems. By firstly characterising the variation in understanding, instructors can make informed modifications to the teaching strategies in order to improve students learning experience.

2 Literature Review

When discussing potential difficulties students may have in understanding a topic, Meyer and Land (2003) provide an interesting insight into the notion of ‘Threshold Concepts’ and ‘Troublesome Knowledge’. Their research seeks to enhance teaching and learning environments, and to do so, the authors review Meyer’s notion of a threshold concept and investigate its link to what Perkins (1999) calls troublesome knowledge. The threshold concept is described as a transformed way of understanding, interpreting or viewing something, without which the learner cannot progress. Having interviewed teaching staff, the authors concluded that a threshold concept can constitute or in its application lead to, troublesome knowledge which is seen as knowledge that is alien, counter-intuitive or incoherent. Perkins (1999) outlines six types or categories of troublesome knowledge:

1. Ritual knowledge – that which feels as though it has routine character
2. Inert knowledge – that which typically is stored in the mind and only used when specifically called upon. Passive vocabulary is a classic example.
3. Conceptually Difficult Knowledge – that which is a mix of misimpressions from everyday experience. Typically seen in mathematics and sciences.
4. Alien Knowledge – that which comes from a perspective which conflicts with our own
5. Tacit Knowledge – that which is mainly personal or implicit at a level of ‘practical consciousness’
6. Troublesome Language – Language itself which can be a source of conceptual difficulty

An interesting finding presented here is the further link made between “conceptually difficult knowledge” and the students own observations and experiences of the real-world phenomena being studied and that the conflict between this and the concepts being presented in teaching, such as kinematics or Newton’s laws, can cause significant difficulties for students.

Price, et al (2021) presents a study which characterised the problem-solving process within science and engineering (S&E) as a set of interlinked decisions but focused on successful experts, rather than students, to help provide a guide for teaching S&E problem-solving. 52 experts across various S&E fields were interviewed and described how they solved typical problems in their work. These interviews were then analysed in terms of the decisions that were made and the authors found that the solution process could be framed around making just 29 specific decisions across seven categories; selection and goals, frame problem, plan process for solving, interpret info and choose solutions, reflect, implications and communicate results. The authors interestingly conclude that “the set of decisions we have observed provides a general framework for characterizing, analysing, and teaching S&E problem solving. These decisions likely define much of the set of cognitive skills a student needs to practice and master to perform as a skilled practitioner in S&E.” (Price, et al., 2021: pg 13)

Walsh et al (2007) carried out an investigation into early years college physics students’ approaches to problem solving using a phenomenographic approach. The findings identified a set of hierarchical categories that described the students’ approaches to problem-solving when presented with various physics problems. At the top of the hierarchy, students used a *scientific approach* where the student qualitatively analysed the problem, were systematic in their analysis and evaluated their solution. Below that level, students adopted a *Plug-and-chug* approach with two sub-categories of structured and unstructured approaches defined. Here, students tended to analyse the problem based on required formulae or variables and related the concepts to the variables involved. Next, students were found to adopt a *memory-based approach* where they typically analysed the problem based on situations or class examples they have encountered previously. Finally, some students adopted *no clear approach* where no apparent strategy was evident and students failed to relate variables as concepts, often taking a random approach to solving the problem. Of the 22 students interviewed, only 2 were seen to apply the scientific approach and the authors concluded that “the majority of students who begin higher level education do not approach problem solving in a strategic or scientific manner” (Walsh et al., 2007: pg 10). This study represents a cohort from a variety of academic backgrounds within the Irish system. While the findings align with those from other researchers, some discussion has been made around the connection between conceptual understanding and problem solving in this domain (Hoellwarth et al., 2005). Hoellwarth et al (2005) studied both conceptual understanding, using the Force Concept Inventory and Force and Motion Conceptual Evaluation tests, and problem-solving ability in both studio and traditional classroom settings. The findings showed that the studio setting, which used an active learning approach, resulted in larger conceptual learning gains while these students performed the same or slightly worse on quantitative final exam problems. Thus, the authors conclude that if we as educators require students to be proficient in both, we need to explicitly teach both conceptual understanding and problem-solving skills, and that the assumption that students will acquire conceptual understanding in the process of learning problem-solving is not valid. More significantly, they conclude that courses where concepts are emphasised produce large gains in conceptual understanding without significantly sacrificing problem-solving ability.

Similarly, Michor and Koretsky (2020) conducted a thematic analysis of junior level engineering students to identify themes and categories that influence their rote or conceptual learning operations. The authors discuss the conflicting body of research around redesign of classrooms to promote deep rather than surface approaches and they conclude that “deep learning improves *qualitative learning outcomes* such as understanding and transferability” (Michor and Koretsky, 2020: pg 48). Biggs (2003) describes a deep approach as being characterised by a students’ focus on meaning and concepts with a link between the content and real life, while a surface approach is where students learn material in an ad hoc manner as needed for assessment rather than making connections between concepts or previous concepts.

The literature exploring teaching and learning of kinematics specifically is extensive. The vast majority of studies focus on the design and implementation of some teaching intervention, the impact of which is then assessed. A limited number of studies firstly sought to explore the level of understanding from the student’s perspective before designing the intervention or teaching strategy modification. A study by Trowbridge and McDermott (1981), specifically investigated student understanding of the concept of acceleration in one dimension. The authors concluded that “*introductory physics students frequently lack even a qualitative understanding of the concept of acceleration as the ratio of Δv/Δt*” (Trowbridge and McDermott (1981): pg 251). Having analysed over 200 student demonstration interviews, the authors were able to summarise the procedures used in solving sample problems into ten categories, further classified into five interpretations of procedure; nonkinematical approach, confusions between position and acceleration, confusion between velocity and acceleration, discrimination between velocity and change in velocity, and qualitative understanding of acceleration as Δv/Δt. They conclude that this hierarchical organisation can be representative of the variation in conceptual understanding of the topic and that a significant number of students, from a variety of courses, confused the concepts of velocity and acceleration. Following on from this study, Rosenquist and McDermott (1987) designed and tested instruction based on the observation of actual motions. Across various student cohorts, a general improvement in understanding of various kinematics concepts was observed, when comparing performance pre- and post-delivery. Interestingly, the authors demonstrated that this type of instruction can help students “distinguish related concepts from one another, and make explicit connections among concepts, their graphical representations, and the real world” (Rosenquist and McDermott, 1987: p 407). This study can therefore be considered an extremely useful benchmark for how to create a deeper conceptual understanding as per Biggs’ (2003) definition of deep and surface learning. The research also argued the importance of kinematics as a fundamental topic in engineering and science, while further demonstrating that many students have significant difficulties in understanding the concept.

Craifaleanu *et al.,* (2014) also studied the teaching of kinematics to early stage engineering students and further validate Reed (2006) claim that anecdotal evidence is used to support a learning assumption, by stating that from the experience of the authors, the traditional approach of teaching kinematics using drawings and mathematical equations to explain the motion of rigid bodies results in students having difficulties in understanding the topic and tend to regard it as excessively abstract. While the research does not explore the difficulties from the perspectives of the students and how they interact with and understand kinematics, the authors assess the use of a Virtual Laboratory of Kinematics as an intervention to overcome the difficulties. While the previous studies do investigate students understanding of the topic, here the authors take a more traditional first-order perspective to study the phenomenon itself, rather than a second-order perspective where one would study the student's perspective and interpretation of the phenomenon. Reed (2006) proposes this second-order approach as research which seeks to understand students' interactions with the topic from their own perspective. Marton (1981) refers to this method as second-order research and the authors describe phenomenography as a method that has this characteristic at its core.

As the literature widely agrees that students experience difficulties within this branch of physics, many tests have been designed to assess conceptual understanding of these topics. Beichner (1994) developed the Test of Understanding Graphs in Kinematics (TUG-K) having collected data from 895 students at high school or college level. The author concludes by stating findings from this test will help teachers modify their instruction to better address difficulties with kinematics graphs. Hestenes *et al.,* (1992) summarise the body of research in this area by claiming it is widely accepted that students have well-established common-sense beliefs about how the physical world works based on their own real-world experiences and that often, these are incompatible with particular concepts within physics. They conclude that instruction must take these beliefs into account to be successful but alarmingly, in the most part, it does not and thus, students resort to "*rote memorization of isolated fragments*". The key implication of this finding according to the authors is that effective instruction on this topic "*requires technical knowledge about how students think and learn*". The study goes on to develop a test called the Force Concept Inventory, which requires students to choose between Newtonian concepts and common-sense alternatives to evaluate their "Newtonian thinking", essentially evaluating the extent of their misconceptions on the topic. Further research (Halloun *et al.,*1997; Thornton and Sokoloff, 1998; Nieminen *et al.,* 2010) has utilised the Force Concept Inventory to assess student performance on Newtonian laws. A study by Desauriers, et al. (2011), used the Force Concept Inventory to compare results between a control group experiencing instruction based on traditional lecturing and an experimental group where instruction was based on the concept of "*deliberate practice*" (Deslauries et al., 2011: pg 862). The deliberate practice concept encompassed both constructivism and formative assessment where a series of challenging questions and tasks requiring students to practice reasoning and problem-solving during class while being provided with frequent feedback. The authors concluded that this approach improved both learning and engagement.

In a more general article, Han and Ellis (2019) investigate methods which could be used to identify what conceptual understanding students already have, whether these concepts are aligned with scientific explanations, and identification of any variations between the two. They argue that once this can be achieved through a qualitative analysis, more informed instructional design can be developed to enhance learning outcomes in science. The authors present phenomenography as an appropriate method in identifying variations in conceptions of and approaches to learning, and the teaching quality and learning environment, all of which account for different learning outcomes. They discuss how the phenomenographic method can be applied in informing instructional design, known as variation theory of learning (Pang and Morton, 2013). Using the four recognised patterns of variation, namely *separation, contrast, generalization* and *fusion*, instructors can manipulate the conditions of how information is presented, in order to focus on the critical aspects needed in order to learn a scientific concept.

van der Merwe and Woolacott (2017) apply phenomenography in an engineering context when they studied the variation in the way students relate to, experience, and conceptualise the topic of Mohr’s Circle. The study showed a hierarchical structure from least to most sophisticated conceptions of Mohr’s circle in the categories of what it does, how it is used, and the visual perspective it provides. This structure, the authors state, is as important as the establishment of the qualitative differences in students’ conceptions themselves as it constitutes a ‘conceptual scaffolding’ of the topic which is pedagogically very useful to instructors. The authors found that the structure suggested how one concept built on another to suggest a conceptual learning pathway outlining along which a student’s typical learning needs to progress in order to master the topic.

This study aims to use a second-order perspective to understand the different ways in which early stage mechanical engineering students approach problem-solving in kinematics specifically. The findings will help characterise the methods a particular cohort of students employ in solving problems, understand the level and influence of their conceptual understanding on this approach, and their use of deep or surface approaches. As concluded by Reed (2006), “*Embracing a methodology like phenomenography will mean that academics no longer need to draw on anecdotal evidence to support their discussion around pedagogic issues and the results can directly inform their teaching practice*” (Reed, 2006: p1). While some similar research has been explored in the literature, further research merit can be developed by characterising the variation in this particular cohort's understanding of a particular topic, and comparing findings with larger or more general research studies. The addition of another perspective from a particular higher education institution, student cohort and module, together with the existing body of research, is likely to enhance and inform the quality of future instructional design in the area of early stage kinematics modules.

The research question for this work is: ***"What are the qualitatively different ways in which students approach solving fundamental kinematics problems in an early stage mechanical engineering module."***

3 Method

3.1 Phenomenography

The research question for this study requires an interpretive/subjective research paradigm to be adopted. Since the question seeks to understand how students learn and acquire a specific type of knowledge, the methodology requires the author to interpret their views and performance on the topic in question. The ontological assumption here is that the reality is created by the different individuals themselves and thus, due to the fact that the authors must interpret the views of a typical student cohort, a qualitative method will be employed to gather information through which an 'interpretive understanding' can be developed. This approach is often referred to as hermeneutics which requires this interpretive understanding to be developed from a certain standpoint (Clegg and Slife, 2009). Mertens (2019) state the assumption in this paradigm is that data, interpretations, and outcomes are rooted in contexts and people. Qualitative methods should allow the researcher to interact with the students to obtain multiple perspectives so that better interpretive understanding can be achieved. This aligns with the second-order viewpoint previously described in the literature review section, which is favourable for this type of research topic.

The primary research method which will be employed is a technique called phenomenography. Phenomenography was originally developed by Swedish researchers in the 1970's to study variations in how students learned and understood concepts (Han and Ellis, 2019). It is now a well-established qualitative research technique which has been adopted across many disciplines, including engineering (Case and Light, 2011; Magana *et al.*, 2012). Phenomenography has a unique second-order perspective, which highlights the collective meaning and variations in a phenomenon, as experienced by people (Marton and Pang, 2008). This perspective will support the author in developing an understanding of how students experience, perceive and understand various aspects of this topic (Marton, 1986). Gray (2004) outline how phenomenological research emphasises inductive logic and through qualitative analysis of data, seeks the subjective accounts and interpretations of participants.

Phenomenography “aims to investigate the qualitatively different ways in which people understand a particular phenomenon or an aspect of the world around them” (Marton and Pong, 2005: p335). Ojo *et al.* (2018) describe it as a rigorous research approach which usually involves conducting interviews in which a number of open-ended questions are put to the students and responses are typically followed up until the subject matter is mutually exhausted. Interview transcripts are then carefully analysed in an iterative process by coding and categorising the extracts into specific themes. As described by van der Merwe and Woolacott (2017), for such a study to be pedagogically useful, the developed insights should “relate to the students collectively and should focus on the qualitative differences in the students’ experiences/conceptions, otherwise the individual idiosyncrasies of a multitude of students are likely to overwhelm and obscure any insights that might be obtained.” (van der Merwe and Woolacott, 2017: p341). This is a key observation and one which justifies the selection of phenomenography as a method within the interpretivist paradigm for this study. The research question here seeks to understand the “qualitatively different ways in which students approach solving fundamental kinematics problems”, and thus insights into the students collectively is required.

As with qualitative studies in general, the rigour of phenomenographic studies can sometimes be questioned. Morse et al. (2002) suggests that researchers take a more responsible, scientific view of validity where verification strategies should be incorporated into a study’s method to identify and correct issues with process and interpretation (Cope, 2004). As part of a full and open account of a study’s method, Cope (2004) suggests its reasonable to expect some reasonable strategies are taken such as acknowledging the researchers own background, justifying and reporting on the interview design, a strategy for collection of unbiased data and analysis of this data with an open mind using a detailed method. To enhance reliability of a phenomenographic study, Cope (2004) suggest multiple researchers would classify the transcripts independently to ensure given a set of data, the outcome space produced would be independent of the researcher. As outlined below, the authors have tried to adhere to this best practice in ensuring reliability and validity in this study.

3.2 Data Collection and Analysis

As the main part of the phenomenographic study, individual semi-structured interviews were conducted with 10 students randomly selected from the cohort. As this study was conducted during a remote teaching and learning phase of the COVID-19 pandemic, the interviews were conducted remotely using standard meeting software familiar to the students. In order to capture data representative of the entire cohort, 5 students from each of the two entry routes to the programme were selected to minimise the potential for skewed data. The first entry route was through the mechanical engineering year 1 programme while the second route was through a common entry engineering programme. As outlined by Hobson and Townsend (2010), a semi-structured interview would allow for the advantages of the structured type interview, such as validity/reliability and coverage of the researcher's agenda, to be coupled with the open-ended questions typical in an unstructured interview which can provide valuable insights which the interviewer may not have considered during the interview design. It is also widely agreed that the unstructured aspects allow interviewers to probe deeper or follow interesting leads and thus, generate a richer dataset. While Trigwell (2000) argues that between 15 and 20 people is the ideal number of interviews, Dahlgren (1995) suggest that as long as the sample is selected to maximise variation, ten interviews should be sufficient to ensure the variation observed is representative of the class. To maximise this variation, the authors selected five students from each entry path using a randomised selection code.

As outlined in Reed (2006), a phenomenographic interview should enable the interviewee to reflect over their experience of a phenomenon. Thus, questions should not be leading and should be open-ended. Another key aspect of a well-designed interview is to develop a 'shared definition' of the phenomenon early on in the discussion (Bowden, 1996 p 58). Therefore, the interview was designed with two distinct sections. Firstly, a number of questions sought to explore how the students related to the topic, and what they found interesting, confusing, helpful or important and to develop that 'shared definition' of the topic. The second section focused primarily on their understanding of kinematics and to do this, a number of sample kinematics problems were presented where the student was asked to "think aloud" about how they approach the problem, how they would solve it and identify appropriate theories or methods which could be employed. Through these problems, the authors can explore some of the misconceptions and troublesome knowledge highlighted in the literature. When students displayed confusion, prompts were used to support them and help identify which aspects in particular were the issue. In some instances, students chose to use a pen and paper to assist in their development of a solution, while others chose to simply verbalise their approach. These problems are outlined below and were sourced from Meriam *et al.* (2020).

Q1. A team of engineering students designs a medium-size catapult which launches 4-kg steel spheres. The launch speed is v_0=24 m/s, the launch angle is θ=35° above the horizontal, and the launch position is 2m above ground level. The students use an athletic field with an adjoining slope topped by an 2..4m fence as shown. Determine:

a. **the time duration t_f of the flight**
b. **b. the x-y coordinates of the point of first impact)**

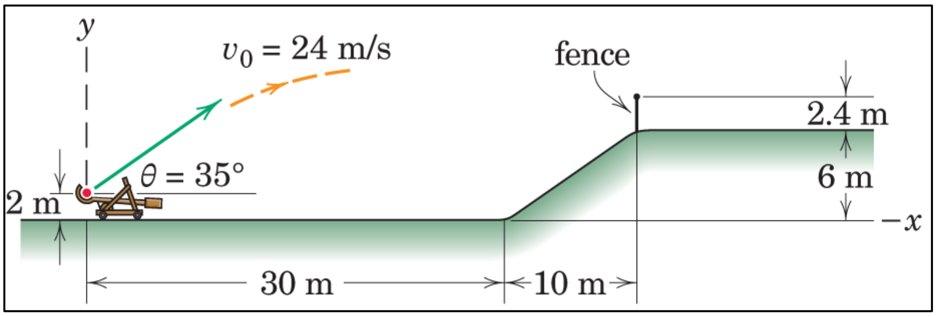


Figure 1 Accompanying Image for Question 1 (Meriam et al., 2020)

Q2. When the effect of aerodynamic drag is included, the y-acceleration of a baseball moving vertically upward is $a_u = -g - kv^2$, while the acceleration when the ball is moving downward is $a_d = -g + kv^2$, where k is a positive constant and v is the speed in meters per second. If the ball is thrown upward at 30 m/s from essentially ground level, compute its maximum height h and its speed v_f upon impact with the ground. Take k to be 0.006 m^{-1} and assume that g is constant

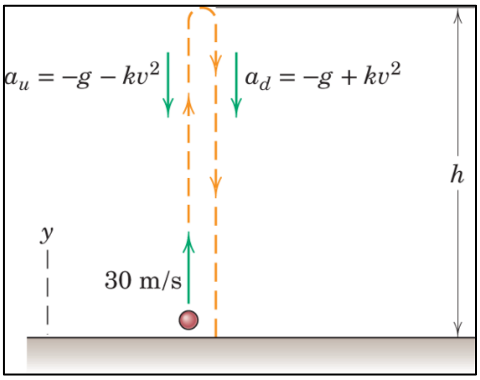
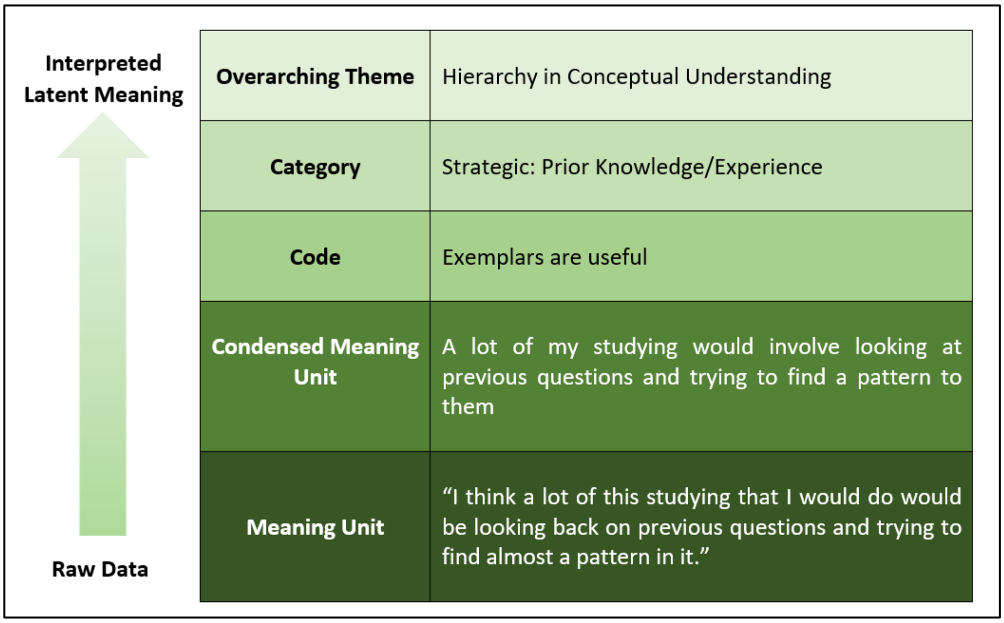


Figure 2 Accompanying Image for Question 2 (Meriam et al., 2020)

Q3. A car starts from rest and accelerates at a constant rate until it reaches 60 mi/hr in a distance of 200 ft, at which time the clutch is disengaged. The car then slows down to a velocity of 30 mi/hr in an additional distance of 400 ft with a deceleration which is proportional to its velocity (i.e. a=-kv). Find the time t for the car to travel the 600 ft. Note: There are 5,280 ft in 1 mile.

Two pilot interviews were completed with 3rd year students who had completed the module previously in order to test the interview protocol and questions. These interviews were not used in the data analysis and only minor modifications were required to the design. Cope (2004) identifies appropriate interview design as a key aspect of validity in the phenomenography process and in this instance, the final interview was justified based on investigative goals, informed research and reflection and adaption following pilot interview.

The interviews were allowed to run a natural course to completion and ranged from between 20 and 30 minutes, with an average duration of 25 minutes until the content was exhausted. Once the ten interviews were completed, transcripts of the recordings were created and together, these transcripts would form what Marton (1981) describes as the 'pool of meanings', in which all of the interviewees conceptions and experiences about the topic are represented. Many analytical variations have been presented in the literature but for this study, the author followed the procedure outlined by Erlingsson and Brysiewicz (2017), where firstly transcripts are read multiple times such that the analysts obtain a detailed understanding of the discussion. The creation of and familiarisation with the transcripts is a long process which took a number of months to complete. Next, 'meaning units' are identified where small sections of the text with a particular meaning are isolated. These are then condensed into equivalent shorter statements where the core meaning is still represented. Each condensed meaning unit then gets assigned a 'code', which is a descriptive label, and finally the codes and meaning units together are grouped into 'categories' where commonalities exist. Categories should answer questions about who, what, where or when and should be "an expression of manifest content" (Erlingsson and Brysiewicz, 2017: p2). Depending on their aim, some studies can go further and create themes based on the categories created. This process can be seen in the example in Figure 1.



Overarching Theme	Hierarchy in Conceptual Understanding
Category	Strategic: Prior Knowledge/Experience
Code	Exemplars are useful
Condensed Meaning Unit	A lot of my studying would involve looking at previous questions and trying to find a pattern to them
Meaning Unit	"I think a lot of this studying that I would do would be looking back on previous questions and trying to find almost a pattern in it."

Figure 3 Example of analysis

The following sample from a transcript is used to demonstrate the data analysis process:

I: *…based on the information there in in the problem would anything jump out at you as to what to do next kind of a thing?*

S3: *I mean, yeah, I mean if I went, if I went at it, I'd probably give you an actual answer for it but to just do that sort of working through my head that, that takes a bit like.*

I: *Absolutely yeah, this is 10 times harder talking about answering the problem than actually answering it, I fully get that, and that's a common theme I've had in the other interviews as well. So let's say we had the luxury of, you know, a pen and paper in front of you and you were going to sit down like literally what would be the first things you’d do. You know, in terms of the solution, what would you start doing?*

*S**3:** I’d definitely take down what I knew anyway, so like the initial velocity, then break it up into its cos theta sine theta to sort out angles and kind of work from there, then like.*

*I**:** OK, OK, very good. And so…*

*S**3:** Like I mean it, it like it brings back to like the kinematics question too or the…. That, that had a kind of elevated kind of base or plane, so I suppose you'd be following close enough to the same sort of implementation like.*

*I**:** OK, so would you kind of look to go back to like similar problems you did before that, that's kind of what you mean there is it?*

*S**3:** That's what I mean, and basically, when you did examples like the worked examples, that's kind of… I kind of work with all of that and then kind of work through that way.*

From the transcript section described above, seven condensed meaning units were created as shown in Table 1. These were then coded before being finally categorised.

Table 1 Data Analysis Steps

Condensed Meaning Units	**Codes**	**Categories**
If I went at it, Id probably solve it for you	uncertain re method	strategy for solution formulation
but just doing it in my head takes a bit	uncertain re method	
If I'd a pen and paper in front of me, I'd take down everything I knew anyway	formulate the problem	
break up the initial velocity into components and work from there	useful data	
It brings back to kinematics questions too like	prior examples	Familiarity/benefit of exemplars
to the elevated plane, so I suppose you'd follow the same approach	prior examples	
When you did worked examples, that’s what Id use to work through the solutions	prior examples	

3.3 Research Ethics and Integrity

As this research involves human participants, one of the key ethical considerations involves ensuring no harm, both physical or psychological, comes to any person and that ultimately, the benefits of the research should far outweigh the risks involved. To adhere to this requirement, it is essential that awareness is raised around respecting the dignity, wellbeing and values of the participants and that the benefits are equitable within the body of research. Careful consideration of ethical and research standards has been given to this work and an application to the institutes research ethics committee for ethical approval was made and granted, ensuring the research adhered to the institutes Code of Good Practice in Research. Prior to conducting interviews, voluntary informed consent forms were sent to each participant for review, to ensure they were well informed regarding their participation, highlighting the benefits and risks, and inform them of their right to withdraw at any stage up until a predefined date. Information on data management was also outlined which described how their data would be anonymised, stored and analysed.

In order to adhere to research best practice, it is essential that sources of bias are identified and reflexivity applied to ensure recognition and awareness of these biases does not influence the research process or outcomes. An important step in identifying these sources of bias is in reflection of the researcher themselves. The primary author and interviewer in the research, is an instructor on the module and thus, had knowledge of the students prior to interviewing, had perceptions about their abilities, strengths and weaknesses and this was initially flagged as a source of bias in interviews. Likewise, the students were likely to have had preconceptions of the interviewer and what they may be looking for or wanting to hear. As outlined by Breen (2007), insider research must be recognised when the researcher is positioned within the group being studied, which is the case for this project. Insider research can result in a loss of objectivity due to a greater familiarity with the research, a phenomenon known as insider knowledge. Role ambiguity can also occur where the role of researcher and instructor are interchanged, while finally entanglement is also possible, where everyday activities between instructor and class may impact the research due to an over-involvement and having over-rapport with the cohort (Adam, 2013). As outlined above, reflection prior to and during the research process is a key exercise in ensuring rigour and validity in the research findings. During the data analysis phase, initial coding and thematic categorisation was independently reviewed by the 2nd author, an important step in ensuring reliability in the research findings. All data is also made available during the peer-review process and following publication.

4 The Outcome Space

Having analysed the data, it could be argued that a dual outcome space exists where conceptual understanding and problem-solving process are separated. Many students highlighted the challenges of “getting started” and identifying the appropriate method which should be used for a given problem, while actually formulating a solution was viewed as a secondary, separate challenge. Student 1:

I: *what bits do you find most difficult or most challenging about it?*

S1: *Amm, probably the circular stuff or finding out where you start like ‘cause you know, I suppose they are one part of the same equation ahh, but like at the same point, it's like which one do you start with. So when you see the first question, it's like oh no!*

I: *Yeah yeah, that's interesting now, I’d be similar. OK so identifying the kind of the correct approach, so you're saying to me is the one of the biggest challenges. Am, this probably you've possibly half answered this question, but what aspects do you think are most important in like, working with a kinematics problem?*

S1: *Probably, I think once you get into it, the problems themselves, but ones that I've encountered so far aren't that difficult like you work away through it, probably yeah, but it's just knowing like where to start saves like a lot of time rather than figuring, getting halfway through or using the wrong formula, then taking double the length.*

Student 3, although demonstrated a strong fundamental understanding of kinematics, also differentiated between understanding the concept and formulating a solution by successfully executing a process:

I: *Do you find certain aspects more difficult than others?*

*S3**:** Well, I definitely found the kinematics harder than kinetics or kinetic so far 'cause I did, 'cause with the energy problems where there was the energy on one side equal to the other, we did a bit of that before and I found the relative motion angular velocity bit, angular motion, a bit hard like, just hard to see where you are coming from, with the point of view that you were looking at and attacking the problem from, if that makes sense.*

I: *OK so and like do you, do you find that a challenge to kind of, at the outset, figure out how to attack the problem, as you said?*

S3: *Yeah, that's…. that's probably the hardest part of the whole module like because once I get started, you can kind of, not go off the template but go off of other examples you've done and kind of, you know, use the knowledge you had. But it's just getting the start off is the hardest bit.*

It was determined however, that rather than having two separate outcome spaces for concept and process, they were inextricably linked and that students who demonstrated a strong fundamental understanding of the topic valued the importance of exploring the concept and corresponding methodology, before executing the problem-solving process, whereas other students merely moved straight to some process-oriented phase. Thus, this differentiation is reflected in a hierarchy within a single outcome space and parallels can be drawn between this observation and the link between conceptual understanding and problem-solving identified by Hoellwarth et al. (2005), discussed in section 2. While a number of sub-categories of interest were also identified, four primary categories were defined relating to the qualitatively different ways that students approach solving fundamental kinematics problems; ***Unstructured: (Trial-and-error), framing the problem, strategic, conceptual***.

1. Unstructured: “Trial-and-error”

Starting on the lower end of the scale for conceptual understanding, some students used an unstructured approach where they identified the variables provided in the problem and haphazardly applied those within various equations, until some unknown value was revealed. Walsh, *et al. (*2007), described this type of approach as “no clear approach” as students did not try to approach the problem using any clear strategy but rather analysed the problem based on the variables and data provided. These students were found to employ a trial-and-error approach in many instances, where they might begin using certain equations and upon hitting some obstacle, restart the problem using a different approach. In trying to formulate a solution, some process of elimination was observed at the outset to try to narrow the trial-and-error range.

These students were found to rarely solve the problems presented correctly. For example, when presented with a projectiles question (Q1), student 6 stated:

I: *Just maybe, as I said, think out loud to me there about what you see in that question and how you might go about solving it?*

S6: *Yeah, amm, I kinda just eliminated what it isn't, so it's not relative or curvilinear. I was kind of stuck between is it constant or variable motion. I believe it's constant 'cause I don't think anything is changing. Maybe acceleration, but I don't think so. It's launched with 24 meters per second velocity and the thing that was going to trip me up was the angle of 35 degrees. So I think you'd have to split it into its different force components.*

After describing that they would start the solution by doing a crude sketch, when asked what they would do next, they replied:

S6: *Amm, I kind of just write down what I do know and then what I don't know. What I'm trying to find out is T so I'll write down what I do know so I know the speed.*

I: *OK.*

S6: *I know the position it is and the angle and then I'd write down all the formulas I would need that involve T and then kind of work backwards there from what I need to get, T, and if I don't have….. if I need to get T, you need to get this and if I don't have that, how do I get that.*

When presented with a more challenging variable acceleration problem where a ball was thrown vertically upwards (Q2), the student failed to evaluate the concept presented at the outset and incorrectly assumed it was a constant acceleration problem.

S6: *Ah, I think what I need to determine is H which I'm used to being as S, yeah, so amm and then A is given to me as constant.*

I: *Yeah.*

S6: *So, I feel like to determine the time it takes to get up to the top and then once I have the time I could have subbed it into a formula and then I can get S. I think that there's probably another easier way but that's the way my brain went, is trying to see how long it gets to take to get to the top.*

Similarly, at the outset of the projectile problem (Q1), student 2 failed to evaluate the concept and instead used a process of elimination:

S2: *Straight away, just when I saw like it was kinda like a catapult and I saw the angle I was going like you know this is being flung. It wasn't even a case of like looking at…. well obviously with the angle there but like, catapult, straight away you're thinking like this is being thrown and you know you're not going to… but you're not going to whip out curvilinear. But anyway, not curvilinear motion or any of those things you know, as I said, it's kind of nearly a process of elimination.*

The trial-and-error approach was also observed when student 2 was presented with a question which was a two-part problem without a supporting diagram (Q3), having started using an incorrect approach and being prompted towards the correct approach, the student reflected:

S2: *Sure, yeah, and sometimes I feel as well like you know, you might think it's one, but then obviously, as you're working through the solution, you can go, OK, this isn't going to work, obviously. No, that's different. You know when we're just trying to reach the question because even though sometimes I might think I know what's going on in the question, I'd be half way through an A4 page of trying something else before I'd say OK, this isn't the approach I'm going to take here.*

I: *Yeah. Yeah and you restart then, is it?*

S2: *Yeah*

I: *So on that like if you're working through a problem and you hit a wall or whatever, what's your kind of strategy, I guess, in terms of how to get out of that hole?*

S2: *If I hit the wall, I'd literally just go back to OK, what's the topic? Is it variable or, well, sorry no, I'd look at it and be like, OK, it wasn't constant, let's see if it's variable and, and then look at what I've obviously done so far.*

It was observed, that while in some instances, students in this category made progress through a solution, often they required significant prompting to redirect their approach. It was clear that these students didn't place any value in fundamentally understanding the concept being presented and linking that to a specific methodology.

2. Framing the problem

In this category, students tended to value previous examples and sought to identify familiarity within the problems presented and engage in an exercise where they attempted to frame the problem against something they encountered in the past. While they generally didn't appear to possess a fundamental understanding of the concepts, instead these students preferred to immediately try to make a link between the problem presented and previous examples or questions they had encountered in order to replicate the approach. In some instances, students were able to successfully solve problems in this way, however there was an extreme dependency on having an exemplar to work from. Student 1, when probed about why they had selected a certain method simply stated:

S1: *My thinking was just on previous questions.*

Similarly, Student 5 stated:

S5: *Ya, Amm well first I thought it was at the start was amm, I can't remember, I'd have to look back at my notes now but the type a question where you're just…. the duration of the flight that… we did before in a test anyway with a golf ball going over trees and seeing what was the distance actually*

I: *Yes, exactly.*

S5: *There's another one anyway, it's a general one anyway and there's definitely a certain type of equation to use first.*

Interestingly, these students seemed to focus on these problems in the context of an examination, or a 'me vs. the question' approach and only valued the solution relative to this situation. Understanding the underlying concept was not valued. For example, when student 5 was questioned on what their approach to developing the solution further might be, they expressed a desire for examinations that require memorisation tasks, rather than demonstrating conceptual understanding by stating:

S5: *Ammm, yeah, to be honest from we're doing this online all the time, it's … you don't learn as much as when you are in class like you know, going to an exam hall where like you've to learn it and know it off the top of your head, you know, like in tests online you kinda, ya, I might look back at the test like or like if if you got stuck I mean like I feel in first year, I know… I still know the stuff that I learned, but in first semester or… in last semester this year I've kind of forgotten half of what I've learned or been tested on if you get me*

Similarly, student 1 viewed the problems presented as a solvable task in a 'me vs. the question' mindset. This mindset suggested that developing a fundamental understanding wasn't valued or important because it was simply an exam question which had to be solvable:

S1: *…..Plus I think in the questions, there's always something in the questions with no diagram. There's always something in it to give it away, to give you a bit of a hand because I think they are a bit harder…*

This mindset would explain why students went on to sometimes employ a process of elimination type approach in actually developing the solution. For example, when discussing how to solve question 2, student 1 suggested:

S1: *Yeah, well first I'd wipe away the SUVAT 'cause the ball realistically just goes straight up and straight back down so there's no distance moved at all or displacement like. So, it'll be just zero for everything. So I'd just wipe that out straight away. So, and it doesn't really look like circular motion, so that would leave me with the varying acceleration.*

3. Strategic

In this category, students typically attempted to formulate a solution by applying a strategic approach to linking the variables and data provided with equations which could be used. This was by far the most populous group and for the most part, students were extremely process oriented. Again, a fundamental understanding of the concept was not explored at the outset in order to select an appropriate method, however students did typically make good connections between the variables given and how they could be applied to the underlying theory. While students didn't always solve the problems presented, in many cases they were able to arrive at a correct solution with minor prompts from the interviewer. While an understanding of the concept and its real-world link was not typically demonstrated, students did often show a sound understanding of how and when specific equations could be used. The solutions typically needed to be constructed through this strategic approach which sometimes required a number of paths to be explored. These strategies appeared to have been built on a combination of linking previous examples with memorised process steps and could be viewed as a combined approach of categories 1 and 2. Student 7 articulated this quite clearly by stating:

S7: … *I think a lot of this studying that I would do would be looking back on previous questions and trying to find almost a pattern in it.*

They went on to demonstrate an appreciation of the potential limitations of this approach, and demonstrated a desire for a higher level of fundamental understanding:

S7: *As you know, if this question is a rectilinear motion question and it asks for this, I do it this way you know, and I would do it like that, but obviously that only gets me so far. There's… a lot of it is figuring out kind of in the moment with what you're given because it would be quite rare to get two almost identical questions, especially in, in kinematics.*

Similarly, student 8, when asked about how they would begin a solution to problem 2, reinforced the reference to combining a procedure with previous examples by saying:

S8: *I'd definitely take down what I knew anyway, so like the initial velocity, then break it up into its cos theta sine theta sort of angles and kind of work from there then like.*

I: *OK, OK, very good.*

S8: *Like I mean it it like it brings back to like the kinematics question too or the…. That's, that had a kind of elevated kind of base or plane, so I suppose you'd be following close enough to the same sort of implementation like.*

Student 10 also evidenced that this approach lacked a fundamental conceptual understanding and was more about trialling strategies to help one arrive at a solution. When discussing their correct approach to the projectile question, they displayed a further insight by saying:

***S10:** And when you break down into X&Y movements and it becomes a lot easier to understand and to analyse, amm but if it came to like, you know, circular motion, it's harder to do that, and it's less like the answer. The strategy that you would take would be less obvious because there are more options for it.*

The limitation of this approach however became clear with student 10 on the second problem where they were unable to select an appropriate method. An unfamiliar problem was posed and since they didn't appear to possess a conceptual understanding, they presented with significant uncertainty as to how to solve it.

***S10:** Amm yeah, it would I suppose with this as well because there are two new equations that I like I wouldn't be familiar with using. It would have confused things a bit more, umm, so it might add a bit of a complication into how I would answer it and how I would choose to answer it.*

4. Conceptual

In this category, students possessed a fundamental understanding of the core concepts within the topic. Not only were they generally able to solve the problems posed, they did so by first focusing on developing clarity around relating the problem to a fundamental concept. From there, they were able to successfully identify and justify an appropriate methodology before finally developing a solution. As opposed to students in the other categories, they seemed to value the importance of developing a conceptual understanding at the outset before using that to progress the solution.

Having determined the correct approach in problem 2, student 3 outlined that they combined the general description of the problem with the nature of particular formulae to develop an understanding of what type of problem they were presented with:

***S3: …**I'd read all the, the text there and just get a bit of background and then I just read into the formulae then. The formula, like I can understand the formula better than I can understand the writing like.*

Student 9 demonstrated strong knowledge in solving each problem presented and frequently tried to develop a real-world link to each problem. After correctly identifying a variable acceleration approach was needed, they stated:

***S9:** ...Well, I would've assumed that because going up, it's going to be slowing down, so like if you think of it throwing a ball up in the air, it's not gonna be travelling forever, It's gonna slow down eventually and come back down and like yeah so I think that's what is it, yeah.*

When pressed about the possibility of something slowing down at a constant rate, they then identified the specific aspect of the problem which made it variable acceleration:

***S9:** But then yeah, so then I think that's where like the velocity squared and the equations will come in sort of because it's slowing down the velocity will be changing and then yeah, I think.*

While 4 distinct categories emerged from the data, it should be noted that in many instances, students were found to move between categories, depending on the nature of the problem presented. Typically, in more challenging or abstract concepts such as variable acceleration problems, students were observed to step back into lower categories, whereas in simpler problems, they were more likely to conceptualise the problem and operate in a higher category.

Even though they may not currently possess a higher conceptual understanding, some students did demonstrate a perceived value for achieving it and demonstrated a desire to do so. For example, student 4 stated:

S4: *Almost every question is different, you know, like it's not always the same, so it's very hard to like 'cause you can't just copy and paste it or it's like, I'm trying to get the understanding of what was done in the question and why are we going to apply that over like…*

5. Additional categories

Further to the categorised levels of conceptual understanding, the outcome space was also populated with some secondary categories which it was felt played a role in why students were in a particular category and ultimately, how they solved a given problem. Many referenced a desire to link the problems to real-world scenarios to attempt to develop their understanding. Student 5 when asked about their interest in the topic stated:

S5: *I do yes, it's kind of new to me so everything is kind of interesting really, but it's interesting enough now like looking at a few questions seeing when stuff will move and under what force and calculating like the maximum force that you can apply without anything moving or so,like the crate on a truck was one question. Its actually kind of interesting, whether it will slip or not, with friction.*

When probed on the specific question relating to variable acceleration of a ball thrown upwards, they seemed to try to make a real-world link again:

I: *When you say speed, is it the speed that's changing as it goes up which is the trigger for you?*

S5: *Yeah, so as it goes up, yeah, 'cause its battling up against gravity and its going to be slowing down.*

Significantly, the level of understanding of most students was also directly impacted by their own values. Students operating at the lower conceptual level tended to perceive the problems as simply an obstacle to overcome in the form of an exam question that needed to be solved, rather than valuing the development of their own fundamental understanding of the concept. When struggling to solve the final problem, student 1 articulated this view that ultimately, it was a task which was presented simply to challenge them, in a 'me versus the question' view:

S1: …plus I think in the questions, there's always something in the questions with no diagram. There's always something in it to give it away to give you a bit of a hand, because I think they are a bit harder.

In contrast, other students placed a lot of value in breaking down the problem in order to fundamentally understand what concept they were dealing with before formulating a solution. For instance, student 4 stated during one problem:

***S4:** You know, like it's not always the same, so it's very hard to like 'cause you can't just copy and paste it or it's like, I'm trying to get the understanding of what was done in the question and why are we going to apply that.*

Likewise, student 2 stated:

***S2:** Like you know, if I have my like equations next to me and I go right, Ill try this. That didn't work, will this go, you know? Right, it's not something you learn off, you know that's kinda, that's what I like you know, if I have to think that about every problem. Every problem is different.*

Interestingly, two additional sub-categories were noted which had directly impacted how students solved a given problem. Firstly, all ten students referenced the use of visual aids as being beneficial. When probed about how these sketches or graphs were beneficial, many suggested that it allowed them process the given information into a referenceable form which could then allow them to consider the problem at hand conceptually. For example, when discussing the value of making a sketch at the beginning of a problem, student 6 stated:

***S6:** So if I just read it on a page of like, I don't know what heads or tails, I have to really look at it and see can I understand what's happening in order to tend to solve it.*

Student 7 suggested visual aids allow them to consider other aspects of the problem, rather than committing to memorisation of information:

***S7:** Definitely, it's, I might imagine it as kind of freeing up space in my head, if that makes sense. You know, just so like if I have it written down, it's there, it's not going anywhere. If I need to reference it again, I can look back at it and I can concentrate on thinking about other things then.*

Others used visual aids as a reminder of key information, such as student 9:

***S9:**…we're gonna get highlight the important parts of it instead of having to look at constantly.. look back to the question and see what's going on, like get the values from that.*

Secondly, it became clear that students were very self-aware and many openly admitted to carrying baggage in terms of previous mistakes or a former inability to solve a problem. In some instances, students in the higher levels were restricted from correctly progressing forward out of fear they had made a similar mistake or through a lack of confidence. Student 9, even though they had successfully solved each of the three problems presented, referenced a lack of confidence in each question relating to whether they had it correctly solved or not. Student 7 seemed to doubt themselves with the more complex tasks and on a variable acceleration problem stated:

S7: *I don't know if it's just something to trip up on for me like amm, I'm not 100% sure what about it is, I think it's probably a lack of clarity in my head on where to go like. The first part there I know exactly, I'd know the equations that I can use. I'm very comfortable using them and I can, I'm very happy getting out the time in that 1st 200 feet whereas I'm not as confident using the variable acceleration equations probably.*

These additional categories of *values*, *real-world link* and *self-awareness* can be viewed as a collective theme linked with Jaber and Hammer's (2016) concept of the epistemic affect, the emotions associated with the practice of doing science (Michor and Koretsky, 2020). Jaber and Hammer (2016) use the terms epistemic affect and epistemic motivation to refer to feelings and drives connected to epistemic experience and objectives in the doing of science. They state "It is an epistemic affect to be troubled by a discrepancy in reasoning or evidence; it is an epistemic motivation to want to resolve it" (Jaber and Hammer, 2016: pg 5)

Due to the relatively small number of participants in the study, the authors have presented the outcome space in Table 2, including the codes within the categories previously discussed and overarching themes defined.

Table 2 Outcome Space. Themes, Categories and Codes for Each Student

	Hierarchical Conceptual Understanding				Epistemic Affect			
Student	**1. Unstructured**	**2. Framing the Problem**	**3. Strategic**	**4. Conceptual**	**Self-Awareness**	**Real-World Link**	**Values**	**Visual Aids**
S1		Previous examples Problem as exam question Some process of elimination Difficulty Identifying Method						X
S2	Restart with new approach (trial and error) Trying to apply variables given Lack of conceptual understanding							X
S3				Strong conceptual understanding Problem-solving strategy				X
S4			Process oriented Previous examples			X	Valued understanding process	X
S5		Previous examples Problem as exam question Difficulty identifying method	Trying to develop link between variables and equations			X		X
S6	Process of elimination Testing variables Trial and error Lack of conceptual understanding				Awareness of limitations		Valued real-world link	X
S7			Process oriented Previous examples Trying to develop link between variables and equations		Awareness of limitations			X
S8			Process oriented Previous examples Trying to develop link between variables and equations			X		X
S9				Real-world interpretation Conceptual understanding Problem-solving strategy	Awareness of limitations	X		X
S10			Process oriented Previous examples Trying to develop link between variables and equations		Awareness of limitations	X		X

A summary of these findings is presented in graphical form in Figure 4.

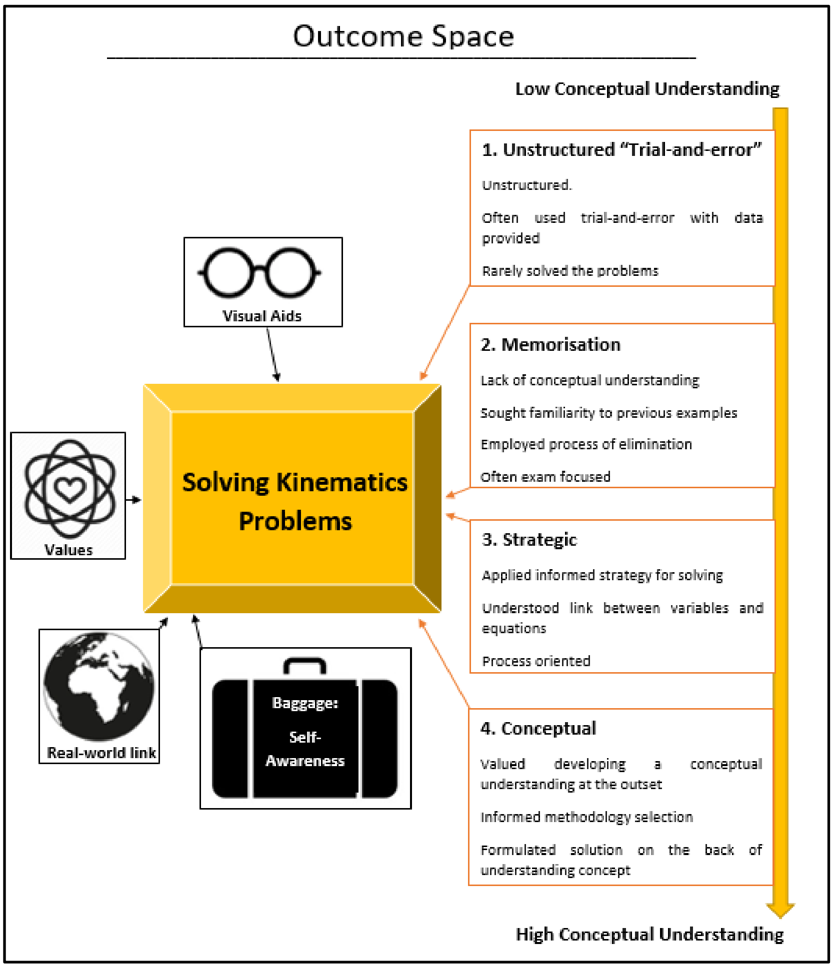


Figure 4 The Outcome Space

5 Discussion

The findings from this research provide an interesting insight into the ways in which students solve fundamental kinematics problems. As outlined in section 2, many authors have previously studied this, or similar areas, and some of the findings from this study align with the literature. It was evident that one of the most challenging concepts aspects of the problems discussed during the interviews was how students related to the concept of acceleration, and in particular, the concept of variable acceleration. A significant study by Trowbridge and McDermott (1981) highlighted the concepts of velocity and acceleration and confusing the two as being a common issue amongst students. This was also noted on numerous occasions within this study, and in particular, it was felt that the concept of variable acceleration was more likely to be treated as velocity than a constant acceleration problem.

The findings presented by Hestenes *et al.,* (1992) attempted to qualify the reasons why students misunderstood problems associated with Physics and outlined that their own common-sense beliefs about how the physical world works is based on their own experiences and instruction needs to account for these in order to help develop a conceptual understanding. Interestingly, the authors conclude that when instruction does not account for these beliefs, students often resort to "rote memorisation of isolated fragments". On reviewing the outcome space from this study, it is clear that this aligns with category 2: framing the problem. Thus, building on findings from Hestenes *et al.,* (1992), it can be concluded that when students are not 'supported' in progressing to categories 3 and 4, they 'resort' to category 2. Findings from this research, linked with findings from the literature, would suggest that instructors need to firstly accept that a variety of beliefs of how the physical world works exists within a cohort and these are intrinsically linked to how students will understand a concept. Furthermore, instruction must attempt to build on these beliefs to help students achieve a higher conceptual understanding and that this could be done by using instruction based on observation of actual motions (Rosenquist and McDermott, 1987) and emphasising a real-world link, as highlighted in this study.

The identification of a hierarchical structure representing the variation in conceptual understanding is not new, as previous authors in related topics have identified similar findings (Walsh, 2007; van der Merwe and Woolacott, 2017). Strong similarities were noted in the findings when compared with Walsh (2007) although variations also exist. The base and top levels of the hierarchy displayed similar properties with *no clear approach* and *unstructured: trial and error* both exhibiting no clear structure or procedure, students randomly using variables in a trial and error approach. At the top level, the *scientific approach* and *conceptual* approach both saw students carry out solutions in a systematic or informed manner and built on underlying conceptual understanding. While variations in the descriptions or definitions of the middle layers was observed between the two studies, similarities were still noted in the identification of a memory-based approach, developing further into a more strategic approach where variables and appropriate equations are linked. The majority of students in both studies were categorised in the middle layers of the hierarchy with most taking a systematic or *plug and chug* approach. Thus, the performance of early stage students in a physics programme can be seen to be largely relevant to a more specific branch of kinematics. Additional findings here however should be noted in the identification of the epistemic affect and motivations which can significantly influence how students solve kinematics problems. When assessing the findings against those presented by Price *et al.* (2021), the importance of underlying conceptual understanding in the problem-solving process can be seen. The early stages of the process require framing of the problem, identifying approximations and simplifications which can be made, and decomposing the problem into sub-problems. In the lower categories in this study, students tended to skip these stages and attempt to progress the solution without due consideration.

Importantly, the findings here suggest we must go beyond understanding students' beliefs but also consider their values and motivations. In this analysis, it has been observed to have a significant impact on how students approach solving kinematics problems based on whether it is simply getting the particular correct answer, a particular exam result, getting a degree, or whether they in fact value understanding a concept first and foremost or the ability to make real-world links with the problem. As described by Jaber and Hammer (2016), this work has highlighted the importance of including students' epistemic drives and motivations when considering instructional design.

If effective instruction aims to ensure students can develop a higher level of conceptual understanding of this topic, while also achieving strong problem-solving skills, then the findings noted should be considered in parallel with the research of Hoellworth (2005). While there is significant evidence that a more 'student-centred' approach can successfully achieve higher conceptual understanding, motivation and engagement levels which ultimately result in higher summative assessment scores (Wendorf, 2018), Hoellworth (2005) have noted that through the use of a studio-based rather than traditional lecture-based instruction, significant increases in conceptual understanding can be achieved but not at the expense of problem-solving. Importantly, the authors also state that explicit attention must be given to both concepts and problem-solving if the desired outcome is proficiency in both. The use of practical instruction to demonstrate real-world concepts can be integrated within a more student-centred process, where students would be required to explore their findings and observations. A stronger link between these practical assessments and the in-class activities should be developed using general active learning approaches. Kirshner and Huisman (1998) explore the use of 'dry labs', where non-laboratory practicals are carried out, often using simulation tools and software. While traditional 'wet labs' are recognised as being important to compliment theory, they are often used for the wrong reasons and the authors state they often provide a "poor return of knowledge considering the amount of time and effort invested by staff and students". The authors argue that dry labs serve a distinct purpose which are functionally different from traditional practicals. Goodwin-Jones, *et al.* (2016) also discuss how practical laboratory sessions are often designed to reinforce the theory presented in lectures into practice. Their study revealed how there is often a significant disconnect in the overall instructional design and timings between the two where timetabling constraints often result in a large time gap between the theory and practical sessions, and students struggle to connect the learning. Some successful active learning approaches have been explored in projects such as SCALE-UP (Student-Centred Active Learning Environment for Undergraduate Programmes) (Beichner, 2008). This approach requires small hands-on activities, simulations or interesting questions and problems to be solved in teams, while the instructor roams. The lectures are class-wide discussions where these activities are explored and peer-to-peer learning is employed. When assessed using the Force Concept Inventory method, this approach proved significantly better than traditional instruction methods. Burke (2015) explored the flipped classroom model in the SCALE-UP project where students engaged with content prior to a lecture, with active learning strategies employed in the lecture session in a studio classroom design. The authors conclude that this approach can engage students in the learning process, encourage more participation and accept more responsibility for their learning, a key aspect of student-centred learning.

As outlined in the 'dry lab' approaches previously discussed, integrating peer instruction could provide a valuable avenue through which these practical demonstrations could be explored, critiqued and defended by students, to students. This approach, rather than persisting with individual, in-class or exam type problems, would ensure students divorced the process from the concept when exploring real-world problems, ensuring students focused on the latter. As described by Pederson and Liu (2003), a student-centred approach would ensure students worked to provide a response to a central question, rather than to meet objectives set by a teacher in the more traditional, teacher-centred approach. This approach could support students in moving to the categories of higher conceptual understanding, rather than employing techniques such as memorisation likely to result from teacher-centred approaches.

While a number of important findings have been outlined, it is also important to discuss some of the limitations associated with the research. As previously outlined, insider research does pose a potential to influence the data generated, primarily due to the strong rapport between instructor (interviewer) and cohort and it should be acknowledged that some bias could be introduced. It should also be acknowledged that the data was generated from 10 students, within a single module, in a particular institute and while efforts were made to diversify the interviewees, the authors did note that often students who tended to be struggling with the topic declined the interview invitation. This could result in potentially stronger or more confident types of students being over-represented in the data. The small sample size must also be acknowledged, although saturation was observed in the interviews where no new themes were emerging from the data.

To ensure rigour and validity was maintained throughout the research process, a reflective journal was kept throughout the project and proved to be a useful medium through which the authors could engage in critical reflection prior to, during and after the analysis was completed. Reliability was maintained by further independent reviews of the coding and categorisation steps in the phenomenographic process, while all raw and analysed data was made available to the anonymous reviewers during the publication review process. The authors acknowledge that further similar studies across other student cohorts, in other institutes would help develop a broader, more diversified understanding of how early year students solve kinematics problems and would add to the overall literature on the topic to support the evolution of instruction.

6 Conclusions

This study aimed to investigate the qualitatively different ways in which students understand the topic of kinematics so that more effective instruction can be designed. The outcome space from the analysis reveals four primary categories which can be viewed in a hierarchy, where students vary their approaches to solving these problems. It is clear that to cater for a diverse cohort of students, instructors must firstly recognise this variation, and secondly design instruction to cater for this range of learning perspectives. Many authors, such as Felder and Silverman (1988), have emphasised the benefits in student learning from addressing a topic from multiple perspectives. Furthermore, it is clear that we must go beyond simply considering instructional design but also consider and promote the development of students' value systems and promote the valuation of underlying conceptual understanding, rather than treating any given topic as a means to an end in an assessment. An appreciation of student's history is also evidenced as having an important role to play, as they can be observed to bring some significant baggage which sometimes leads to self-doubt and a resulting inhibition to progress through a problem.

A shift from teacher-centred to student-centred delivery would help students to develop higher levels of conceptual understanding and encourage them to move out of the lower categories where techniques such as framing of the problem are employed. Practical laboratory-based, or studio-based instruction linked to real-world problems, coupled with more student-led and peer instruction, can enable students to critique their own fundamental understanding of physical concepts with laboratory observations, visual aids and social learning activities. Development of enhanced instructional design for early stage kinematics students will be a focus of future work based on the findings presented.

7 Acknowledgements

The authors wish to acknowledge the support of the Teaching and Learning Unit, Munster Technological University in facilitating the research work, as well as the institutes research ethics committee for the prompt review and approval of the authors' ethical approval application. The authors also wish to thank the authors of Meriam et al. (2020) for approving the use of the figures used in the interview in this publication. Finally, the authors would like to sincerely thank the anonymous reviewers for their time, detailed reviews of the work and constructive suggestions which ultimately enhanced the quality of the final paper.

8 Supplementary Material

All raw data and files used to process the transcripts are available at: 10.6084/m9.figshare.15141033

9 References

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