Enhanced conceptual understanding in first year mechanics through modelling

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Abstract

As part of the National HE STEM programme, we have developed and implemented a modelling curriculum in first year mechanics to overcome well known conceptual difficulties. By modelling, we mean more than just the development of mathematical equations to describe the evolution of a physical system; we also mean the use of multiple representations both to understand the problem at hand as well as to develop a solution. We have developed a structured approach to both teaching and assessing the use of such representations through the ACME protocol: Assess the problem, Conceptualise the Model, and Evaluate the solution. This paper describes the implementation of this protocol within a conventional lecture setting during a single semester of the 2011-12 academic session and demonstrates the impact on conceptual understanding of 42 students though pre-course and post-course testing using the Force Concept Inventory (FCI). Detailed analysis shows that on virtually every question in the FCI student performance improved, with questions 4 and 15, relating to Newton's third law, showing especially large gains. The average FCI score rose from 17.7 (out of 30) to 22.5, with the distribution of post-instruction scores being statistically significantly different (p=0.0001) from the distribution of pre-instruction scores.

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Introduction

The teaching of mechanics is perhaps the most widely investigated topic in physics education research. Historically, the investigations by psychologists such as Larkin et al[1] and Chi et al[2] into problem solving in the 1980s were based around mechanics problems in physics and the observation that graduate students hold similar alternative conceptions to five year olds[3] led ultimately to the development of the Force Concept Inventory (FCI) as a method of testing students understanding of the Newtonian concept of force[4,5]. The FCI uses many of those misconceptions, for example that a force must exist in the direction of motion, as alternative answers to the questions and is therefore very effective as a test of understanding. Many different concept inventories have since been developed and Bates and Galloway[6] have summarised those applicable to the physical sciences, especially the FCI.

It is a general finding of physics education research that conventional lecturing has little effect on students' conceptual understanding and the FCI has been instrumental in showing this in mechanics[7]. It might seem rather obvious to state that students need to be intellectually active rather than passive observers in order to learn effectively, but whilst this might have been known for some time within the field of educational psychology, it took some time for physics education research to establish the same within higher education by direct empirical observation of student understanding, or misunderstanding, across the spectrum of introductory undergraduate physics[8]. Consequently instructional strategies based on interactive engagement are considered essential to foster student understanding[9].

This paper is concerned principally with teaching introductory mechanics and fostering conceptual understanding through an emphasis on models and modelling. Modelling has been promoted by Hestenes[10] in particular as a general method of promoting understanding. Hestenes identified four elements to a model:

- a set of names for the objects and agents that interact with them
- a set of descriptive variables representing properties of the objects
- a set of equations which describe the structure and evolution of the model
- an interpretation and extension of the model to other situations

Modelling thus defined is a systematic method of constructing new knowledge about a specific problem, but not all modelling instruction is necessarily effective. For example, Chabay and Sherwood[11] put computational modelling in VPython at the heart of their strategy, with limited success. The idea that students must first understand the physics before constructing a computer model is attractive and one of us has likewise reported on the introduction of modelling in VPython into the UK curriculum[12]. However, as judged by the FCI, the construction of simple mechanical models around Newton's second and third laws had little effect on conceptual understanding, despite evidence that students employed model-based reasoning. Students tended to place more emphasis on the computation than on the physics and the last stage of Hestenes' sequence, which is crucial to consolidating learning gains, is somewhat curtailed.

Model-based reasoning is a phrase used by Nersessian[13] to describe the kind of image-based spatial reasoning often employed in the construction of models. A simple example might be the use of a free-body diagram to identify the forces acting on an object. In this respect modelling is similar to problem solving. Indeed, in order develop a quantitative solution to an unseen problem it is necessary first to understand the phenomenon under consideration and this is done essentially by constructing a model. Therefore in constructing a general theory of modelling education we can use all the elements of the cognitive psychology of problem solving[14], which include the use of representations both to understand the problem and to reason about the solution, as well as an ability to use multiple representations such as diagrams, graphs, mathematical equations and qualitative verbal explanations.

There is an important difference between problem solving and modelling, however. Problems in undergraduate physics generally require specific answers which are either right or wrong, but models can vary enormously in both their complexity and in their details. That is, two people constructing a model of the same phenomena could use different representations, offer different descriptions, and differ in the emphasis placed on particular aspects. Both instruction and assessment therefore have to recognise these very personal differences whilst at the same time formalising to some extent the process of modelling. Our solution to this difficulty has been to develop a modelling protocol. In this paper we describe this protocol as well as our approach to teaching first year mechanics through an emphasis on models and modelling. We analyse the gains in conceptual understanding through the FCI and show that this approach leads to both a general improvement in conceptual understanding of the force concept as well as specific, and spectacular, gains in relation to Newton's third law of motion.

Methodology
Students were tested both before and after instruction using the standard 30-question force concept inventory test[15]. Additionally, students were asked prior to the course to answer a few free-form questions in order to gain some insight into two questions on the FCI that had been shown to cause particular problems[16]. Data collected over three years prior to instruction in mechanics showed that questions 15 and 26 were answered correctly by only a small minority of the class, and the purpose of the free-form answers was to have students explain their thinking on these two questions. Question 15 asks about the magnitude of the force with which a car pushes on a truck relative to the force exerted by the truck on the car when both are accelerating. The free-form answers reveal that students are associating the acceleration with a nett force and are therefore applying Newton's second law rather than the third. Question 26 asks what happens to the speed of a box that is initially being pushed across the floor at constant speed by a person who then doubles force applied to it. In a strict Newtonian view the box will accelerate, but over the previous three years between 84 and 90% of students consistently thought that the speed will settle at a constant, though larger, value. The free-form answers show a belief that the resistance opposing the motion will also increase. Unfortunately, the students did not say why they believe this and we shall attempt to shed light on this in the coming year. Some answers indicate that the starting point was a belief that the final velocity is constant and the idea that the resistance increases then serves as an explanation. This is not the same as reasoning that as resistance increases the final velocity must be constant, but as yet there is insufficient data to come to a firm conclusion.
In addition, about ten willing students were interviewed both before and during the lecture course (about two thirds of the way through) to determine student attitudes to this method of teaching. The first set of interviews were used to elicit some information on the students approach to learning new physics and their process of problem solving in the broad sense. In the second interview, the students were asked specifically about the modelling approach and encouraged to give feedback about their experiences during the semester.

The lecture course on mechanics was delivered within a conventional lecture setting over a period of nine weeks, but the format emphasised conceptual understanding over mathematical development, as well as a modelling approach to solving problem. That is, diagrams, graphs, equations and verbal explanation were all used to describe the concepts. In reviewing the psychological literature on concepts Machery[17] has shown that there is no single model of a concept. A great deal of emphasis is placed on the process of categorisation. Deciding that an object belongs to category A depends crucially on our concept of A, but this is not what most physicists would understand by the term 'concept' or the associated phrase, 'conceptual understanding'. Fortunately, as Machery shows, there is a school of thought that regards a concept as embodying theoretical knowledge, which corresponds much more closely to the idea of concept as used in physics.

Our approach, therefore, to teaching a concept was to draw on a multiplicity of representations, each of which on its own can be used to describe the theoretical knowledge but which, when used together, provide different perspectives and help to avoid misconceptions. For this reason the lectures were delivered in a double lecture slot. This also allowed sufficient time within each session for student interaction and discussion, as well as practical demonstrations. For example, in one session a motion sensor was used to demonstrate the motion of toy bus rolling down an incline and bouncing off an elastic band at the bottom. This provided an opportunity for students to discuss and analyse the situation within the class, build a model and receive immediate feedback. This was then given as an assignment to allow for a more detailed model. Of particular interest is the difference in acceleration when the bus moving down the slope compared with motion in the opposite direction. The motion sensor records the acceleration and from this the magnitude of the frictional force can be calculated. Figure 1 shows an example of a student generated model.

The idea of constructing models was introduced at the beginning of the course and the modelling protocol, ACME, was used both to build models within the lecture and as the basis for student-built models. ACME stands for: **A**nalyse the situation; **C**onceptualise (or **C**onstruct) the **M**odel; **E**valuate the outcome. It is based Hestenes' idea of what constitutes a model in physics[8], as well as the cognitive psychology of problem solving. The first two elements in Hestenes' structure, identifying objects and agents as well their properties and interactions, correspond to the analysis, the third, the mathematical equations, to the construction of the model, and the last, the interpretation, to the evaluation. Hestenes' four components are augmented in the ACME protocol through the use of representations. The identification of objects and agents, together with their interactions can usually be represented by one or more diagrams. In many problems the properties of various agents and bodies are specified at the outset, but the construction of a diagram tests whether students correctly understand the relationships between the objects and agents

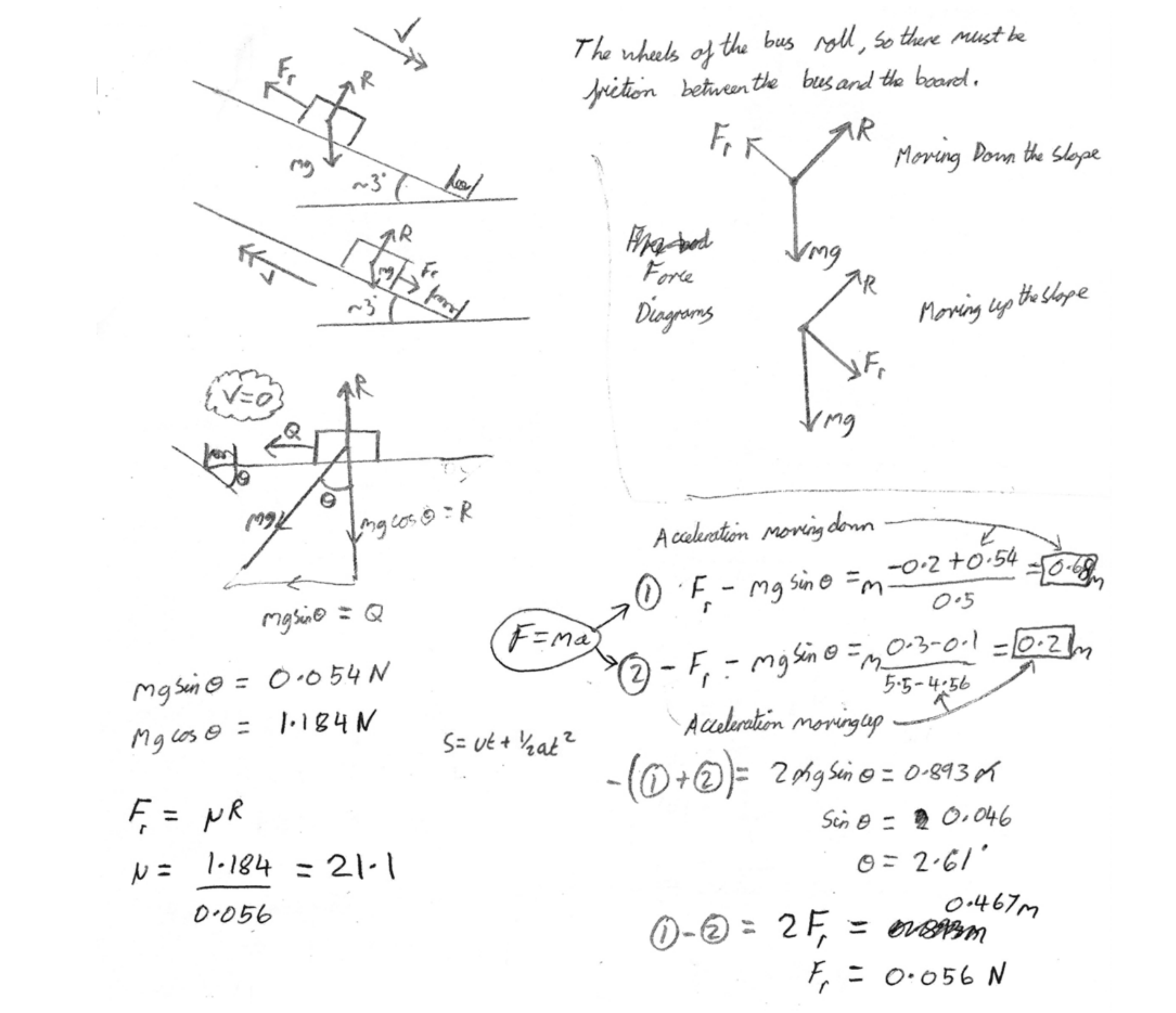

Figure 1: A student-generated model of a toy bus rolling down an incline. A diagram of the bus on the ramp is used to assess the problem and force diagrams are used to help construct the mathematical equations.

and which objects and agents can be ignored. We take also the mathematical equations to be a representation which can be augmented by diagrams or graphs illustrating the evolution of the model. For the purposes of assessment each representation is worth up to three marks, corresponding to; completely absent (0 marks), present but not very effective (1 mark), almost complete, but with room for improvement (2 marks) and complete (3 marks).

A typical model constructed by a student will be marked out of 12, corresponding to a diagram for the assessment, a set of equations, a representation depicting the evolution (motion diagram or graph), and the verbal description representing the evaluation. More complex models may require more representations and will attract more marks. For the model depicted in Figure 1 the four representations envisaged in the marking scheme were slightly different. The evolution of the motion is not required as data from the motion sensor is given as part of the problem statement. Instead, analysis of this data constitutes part of the assessment of the problem, with the identification of the forces constituting a second representation. It is noticeable that this analysis is missing in Figure 1 and only the drawing of the body on the ramp is given in the assessment. Other students took the slope of the velocity-time graph and explicitly represented the acceleration as a function of time as part of their assessment of the problem and this particular student lost three marks for showing none of this. The force diagram is not strictly necessary and wasn't envisaged as being so in the marking scheme, as it is possible to go directly from the sketch of the bus on the ramp to the set of equations. The force diagram could thus be regarded as part of the assessment of the problem, but there is sometimes a difficulty in deciding when the assessment of the problem ends and the construction of the model begins. The model arises naturally out of the assessment so there is likely to be some overlap, but as long as there is a representation marks can be awarded. This student clearly felt the need for an extra level of abstraction and the force diagram seems to be part of the construction of the model as it is used to derive the set of equations that lead on to the evaluation of the frictional force. Therefore the force diagram was taken to be an extra representation in its own right and marks were awarded for it. The written evaluation of this model is not shown.

Results

The FCI was taken by the majority of the 70-strong class both before and after instruction. However, matched pre- and post-instruction tests were obtained from 42 students and the following analysis concentrates on these. The mean score of these 42 students increases from 17.7 out of 30, with a standard deviation of 5.7, to 22.5 with a standard deviation of 5.0. The reason for this is shown in Figure 2, in which the percentage of correct responses for each question is displayed. It is clear that as well as the very noticeable improvement in questions 4 and 15 there appears to be a general improvement all the questions. A two-tailed t-test of the distributions of scores has been performed, both with and without data from questions 4 and 15 in order to see whether these two questions are responsible for any differences observed. It is perhaps not surprising that removing questions 4 and 15 from the pre-test data has little effect on the mean score (17.2 as opposed to 17.7) as very few students answered these questions correctly. However, the post-test average is reduced to 21.0 from 22.5. However the t-tests reveal both sets of post-test data to be significantly different from the corresponding pre-test data to a confidence level of $p=0.0001$.

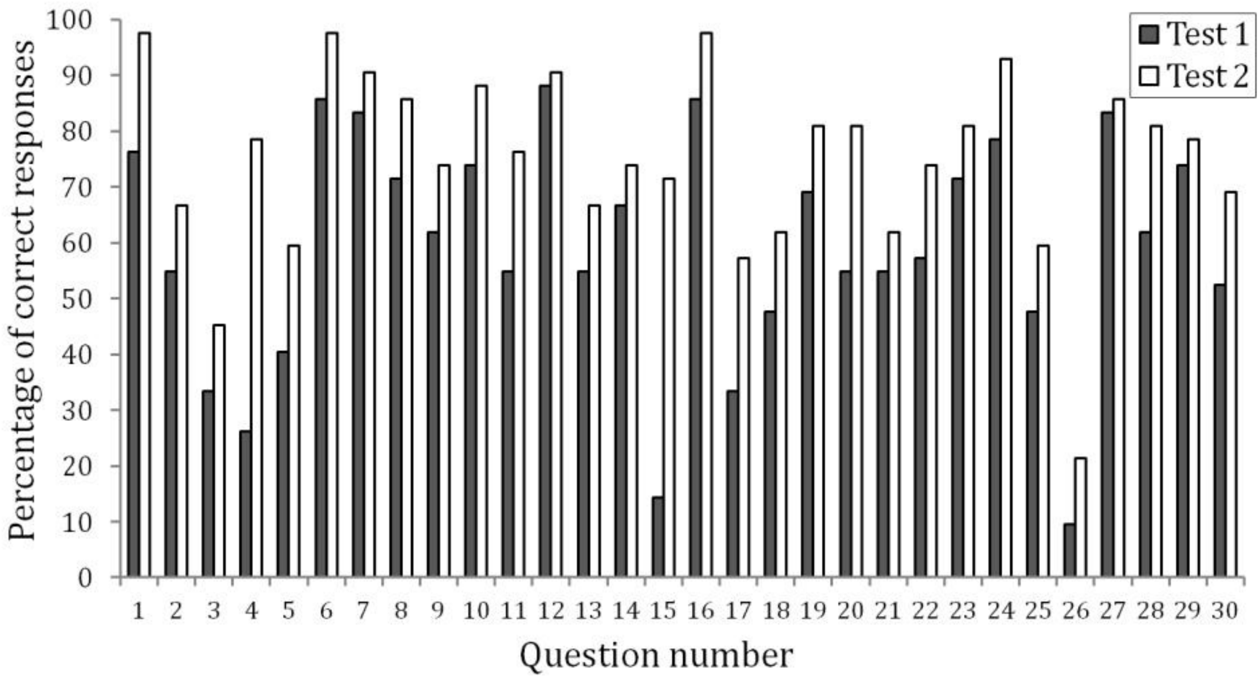

Figure 2: The percentage of correct responses for each question for both the pre-instruction FCI (test 1) and the post-instruction FCI (test 2) for N=42 matched pairs.

Discussion and conclusion

We have shown that a modelling approach to teaching mechanics leads to real conceptual gains as measured by the FCI. The modelling approach involves active participation in the process of constructing models both within and without the class. Model making emphasises discussion and the use of representations, such as diagrams, graphs, mathematical equations and verbal descriptions, both to understand the problem at hand as well as to construct the model. We have developed a protocol, ACME, for both teaching and assessing modelling.

Looking in more detail at the conceptual gains, it is clear that there has been a general improvement in performance across the whole FCI, but in particular in questions 4 and 15, which both test Newton's third law of motion. As we have described, previous testing had identified questions 15 and 26 as causing particular problems among incoming students so the gain on question 15 is especially encouraging. The mis-application of Newton's second law described earlier was addressed by constructing a model in class of a number of masses subject to acceleration and showing, through applying Newton's second law to each mass individually as well as the total mass, that as the acceleration of each mass is identical each mass acts as if opposed by a force exerted by the adjacent mass. Construction of free body diagrams for each of the masses then makes it clear that the action-reaction pairs do not act on the same body and that it is possible to have a net force while still having equal and opposite reactions. Question 26 presents a greater difficulty and requires further research, as the improvement in performance, whilst significant, is not as good as might be hoped for.

In addition to formal testing, the students' attitudes towards the modelling approach were recorded through interviews with selected students. One finding to emerge is that students found the emphasis on representations encouraging. Nersessian[13] has argued that the kind of spatial reasoning employed in constructing scientific concepts is not special to scientists, but is simply a developed form of a normal reasoning process. It is not surprising, therefore, to find that some students already used representations in their approach to problem solving. These students reported gaining confidence from the modelling approach. However, there were other students who reported a tendency to use equations as the principle method of solving a problem in mechanics and for them the emphasis on different kinds of representations was new. These students wanted feedback on whether their use of representations was correct or not. Glaser[17] has described a representation as a "*cognitive structure … constructed by a solver on the basis of domain-related knowledge and its organization*". There is no such thing, therefore, as a right or wrong representation as every modeler thinks differently and will construct their own representation. This could be a simple, well known form, such as a free-body diagram, or something else entirely. The key feature, however, is that it must be useful, so rather than asking whether the representation is correct or not it is more insightful to ask whether the representation could be used to explain some aspect of the problem to a third person. Future work will concentrate on developing confidence in the modelling method through practice in constructing representations and using the explanatory power, or otherwise, of the representations as feedback.

In summary, a modelling approach has been incorporated into a conventional lecture format with clear conceptual gains. Key to this method of instruction is to include as many opportunities as possible for interactive modelling and discussion and future work will attempt to expand this aspect of the modelling curriculum

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