# [O22] Learning classical mechanics through visual modelling

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## Abstract

It is widely recognised that, compared with a generation ago, the entry level knowledge of physics undergraduates has declined markedly due to changes in the teaching of both physics and maths in schools. Many students now lack in-depth knowledge of either differential calculus or Newtonian mechanics. In response to these difficulties we have designed our first year classical mechanics course from January 2009 around a series of computer-based modelling exercises in VPython, the 3-D visual extension to the Python language. Students construct computer models to solve kinematic and dynamic problems by numerically integrating over small forward time-steps to calculate displacements and velocities from known accelerations. In effect, these are computer-based experiments in which, instead of building experimental apparatus, students build models by first identifying and articulating the forces and components of the system, encoding these into a computer model, testing whether the model works, and finally using the working model to investigate physical laws. Concepts in mechanics can therefore be learnt and applied without recourse to differential calculus. Starting with uniform linear motion, and working through constant acceleration and variable forces, the complexity of the models steadily increases until at the end of the course we finish with forced, damped harmonic motion. Pre- and post-course testing using the Force Concept Inventory has been used to evaluate students' learning.

## Introduction

It is a common experience that, increasingly, students entering higher education in the UK are less able in mathematics. This affects student learning in physics in three identifiable ways. First, confidence in mathematics is low and very difficult to build up, so a high level of mathematical skills might never be acquired; second, lectures on topics which draw heavily on mathematical principles, such as electricity and magnetism or mechanics, are hard to follow and hard to grasp; and third; even if mathematical knowledge and skills are acquired, it is difficult for many students to transfer this knowledge from the mathematical domain to the physical context.

This leaves physics educators with something of a dilemma; should maths be taught alongside the physics, given the difficulties described above, or should time be spent developing mathematical skills before physics, at the risk of turning off students? Possibly there is a third way, which is to concentrate on physics concepts themselves through the construction of models. This is the approach we have taken at the University of Hull based on the work of David Hestenes (Hestenes, 1987), emeritus Research Professor at Arizona State University, who is one of the pioneers of modelling in physics education, as well as that of Ruth Chabay and Bruce Sherwood (Chabay and Sherwood, 2008). Not surprisingly, Hestenes is a strong advocate of the power of modelling to improve student learning as he was primarily responsible for identifying the naive views that physics students often hold about the world and which are tested by the FCI, or Force Concept Inventory (Hestenes, 1992). In a workshop in modelling at the 2006 GIREP conference[1] Professor

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[1] The importance of model-based learning in undergraduate physics education can be seen from a snapshot of recent activity in the field. The state of computation in physics courses in the US was covered in a recent issue of Computing in Science & Engineering (Computing in Science & Engineering 8 (5) 2006, special issue) and within Europe there are two notable software developments: Modellus, developed in Portugal by Vitor Teodoro (http://phoenix.sce.fct.unl.pt/modellus/), and Coach, developed in at the Amstel Institute, Universiteit van Amsterdam, where the 2006 GIREP (Groupe International de Recherche sur l'Enseignement de la Physique) conference devoted to modelling in physics was held. This week-long conference (Modelling in Physics and Physics Education, 20 - 25 August 2006, AMSTEL institute, Faculty of Science, University of Amsterdam, Netherlands) played host to some 400 academics from 40 different countries.

Hestenes described his own experiences of using the FCI to develop effective teaching in physics through modelling (Hestenes, 1987 and 1992).

The FCI was developed as an instrument for quantifying student learning of Newtonian concepts. In fact, physics education research really started with its development because it showed for the first time in a quantitatively meaningful way that traditional, lecture-based learning does not necessarily lead to the ability to apply knowledge. Hestenes has shown that FCI scores correlate with functional understanding of complicated Newtonian concepts and testing of thousands of students post-learning reveals that traditional, lecture-based learning yields the lowest scores (Halloun and Hestenes, 1985). Reformed teaching, which means teaching reformed according to the findings of physics education research, comes second and model-based learning comes out on top. Thus the FCI has revealed that though students taught traditionally might well be able to declare knowledge of concepts they are unable to apply those concepts to solve physical problems. Students taught using model-based learning, on the other hand, can use the concepts to solve physics problems.

Traditional teaching is based on what Hestenes calls the “transmissionist” theory; that is, instructors try to transmit their knowledge to students who are, in the main, passive spectators whose own hidden beliefs, preconceptions, and conceptual filtering impede their learning. In my own researches into cognitive models of learning (Sands, 2007) communication in a conventional lecture was investigated to try to identify what it is that students concentrate on and remember most immediately after the lecture. Students were presented with a simple questionnaire based on Biggs’ model of the Structure of Observed Learning Outcomes (SOLO) in which he proposed five levels of learning outcome based on a complex interconnection between the encoding of material and the thinking about it that takes place before the outcomes are demonstrated (Biggs, 2003). Of these five hierarchical levels, the middle three, unistructural, multi-structural, and relational, are the most important for these purposes as, these terms mean that students will demonstrate learning on, respectively, a single concept or idea, a number of unrelated concepts, or a number of concepts that the student has related to each other in some way. My aim was to see which of these is most common; do students concentrate on just a few facts or ideas or, as might be hoped, do they relate concepts delivered in the lecture to existing knowledge?

The results, presented at the GIREP-EPEC conference in 2007[2], were surprising; rarely, if ever, did students relate concepts to each other or to existing knowledge and more often than not students could only remember a single concept. Different students recalled different concepts unless the lecture was so constructed as to emphasize just one new concept which was approached from a number of perspectives by way of reinforcement. What came across very clearly is that just stressing the importance of a particular idea throughout a lecture did not act as a cue to students to remember it and even among a small class of around 10 students responses as to the single most important or memorable concept varied. Although the reasons why particular concepts stood out were not investigated, there were occasions when it was clear that the most memorable concept related to ideas with which the students were pre-occupied and which was therefore relevant and timely from their perspective. The rest of the information delivered in the lecture was simply filtered out and seemingly discarded. For Hestenes this is only part of the problem; not only is information filtered out, but what remains is distorted by naïve beliefs about the world (Halloun and Hestenes, 1985) which do not accord with the scientific view. These beliefs are very difficult to change, especially within a conventional lecture where the information necessary to change these beliefs is simply filtered out or distorted to fit the existing, but naïve world view.

Model-based learning offers a potentially powerful way to overcome these difficulties because it is based on the constructivist view that students construct their own knowledge through discourse, active engagement, articulation, evaluation and participation. A successful modelling cycle has two stages; construction followed by application, in which the model is taken out of its immediate context and applied to other situations. Moreover, modelling does not need to be mathematical. The approach described here follows Chabay and Sherwood (2008) and is based on VPython,

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[2] Frontiers of Physics Education, GIREP_EPEC Conference, 26-31 August, 2007, Optija, Croatia.

which is so constructed that it takes a single line of code to place an object such as a sphere with a specified radius and colour on the screen at a given point in a 3-D Cartesian coordinate system. This sphere can represent a massive body, such as a planet, or a particle, such as an atom or an electron and can be made to move by assigning to it a velocity and updating its position after a small time step. This whole process takes no more than a few lines of code. Interactions between particles and with forces can be represented in a similar way. It takes perhaps no more than ten to 15 lines of code to represent a mass visually, move it, and have it bounce off a wall. Therefore the emphasis is not on computer programming, though inevitably some basics must be learned, but on understanding and encoding the correct physics. The visual representation, which is rotatable in all dimensions to give an accurate 3-D depiction, provides instant feedback by allowing the student to see instantly whether the physics is sensible and corresponds to experience. If a ball doesn't bounce, passes through a wall, or gains too much kinetic energy it is immediately obvious. Visual representation of complex 3-D interactions together with the capacity for instant feedback provides a very powerful tool for promoting understanding.

## Methodology

A course of twenty "lectures" was delivered to 51 students in their first year of an English bachelor's degree. By way of background, the opportunity to deliver this course using the modelling approach arose through the retirement of the member of academic staff who had previously delivered a conventional 20-lecture, mathematically based course on classical, linear mechanics. The syllabus, exam structure and total contact time were all constrained by the existing programme specification, but there was complete flexibility in the mode of delivery. A 20-hour course was developed which consisted of a mixture of demonstrations using VPython models, walk-through exercises, modelling sessions, and PowerPoint presentations to deliver some of the more formal ideas. All four techniques were fully integrated in the delivery of a class. By way of assessment, students had to construct two models as well as sit a conventional exam in which one of the questions tested their knowledge of mechanics rather than Python programming.

As discussed by Chabay and Sherwood (2008), the choice of models is not obvious. The syllabus had to include simple harmonic motion and basic wave phenomena as well as kinematic and dynamic concepts based on Newton's laws of motion. Therefore a number of models were constructed which demonstrated;

- Motion under constant velocity
- Motion under constant acceleration, such as ballistic trajectories
- Position dependent forces, such as electrostatic or gravitational attraction
- SHM, including damping and forced harmonic motion
- Basic wave motion, as shown by a linear chain of oscillators

In addition, students had to construct a number of models in class and two models by way of assignment. These last two comprised exercises on ballistic motion, specifically maximising the horizontal distance travelled by a golf ball launched with fixed energy off a cliff, and electrostatic forces, namely scattering of a light ion off another, heavier ion under simplifying assumptions.

The power of numerical computational modelling is demonstrated in these last two exercises. The problems admit of analytical solutions, but they are not simple. However, by constructing a simple computer model in which the positions, velocities, forces, and accelerations are updated students can see the behaviour and use the model to explore aspects of the physics. In using VPython to demonstrate SHM, however, the issue is slightly different. The mathematics of free oscillations, that is oscillations that are unforced and undamped, is not difficult, but in order to extend the analysis to the case of damped motion it is necessary to introduce the difficult concept of the complex exponential, which is best understood in the context of uniform circular motion. As is well known, SHM is simply the projection in one dimension of this uniform motion in two dimensions, but this is difficult to visualise mentally and difficult to grasp. VPython is an excellent vehicle for demonstrating these ideas, as shown in figures 1&2, which are taken from screen shots of a Python programme. In figure 1 the velocity of the ball moving vertically in a line is seen to be given by the vertical component of the velocity of a sphere rotating at constant speed. Figure 2 makes the same point about the acceleration. Thus VPython was used both as a tool for demonstrating concepts as well as vehicle for students to construct their own models.

**Figure 1.** Part of a screen shot showing the velocity vector of a rotating body directed along the tangent to the circle. Its vertical component is identical to the vertical velocity of a body executing SHM along the diameter of the circle.

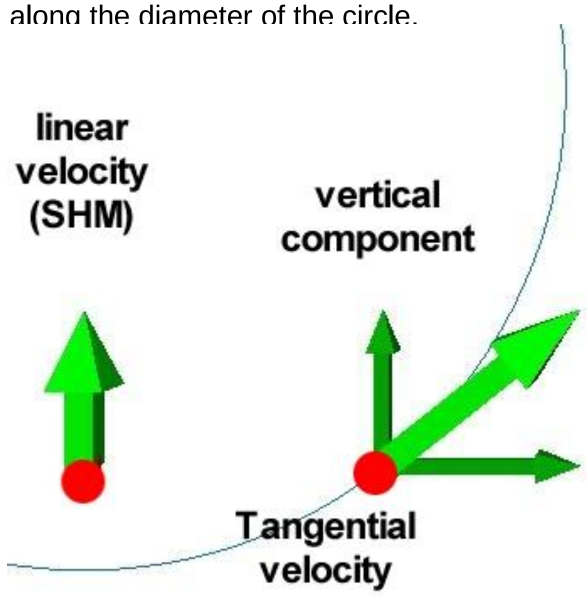
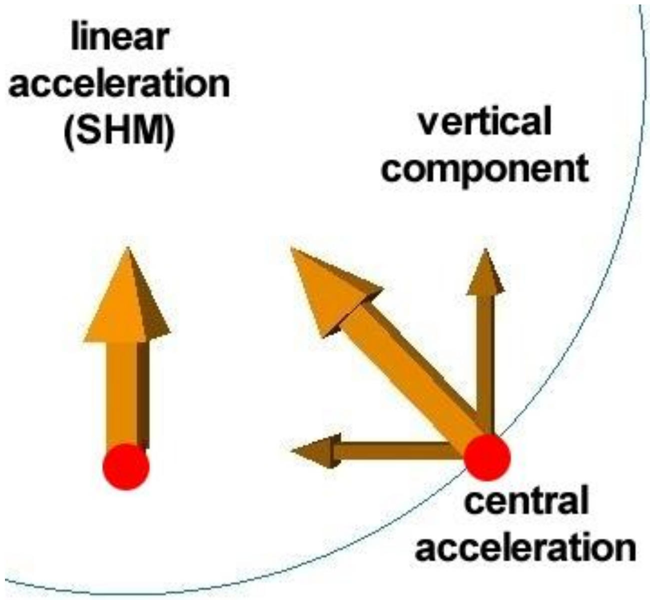


**Figure 2.** Part of a screen shot of the same programme showing the rotating body's acceleration vector directed toward the centre. Its vertical component is identical to the acceleration of a body executing SHM along the vertical diameter of the circle.

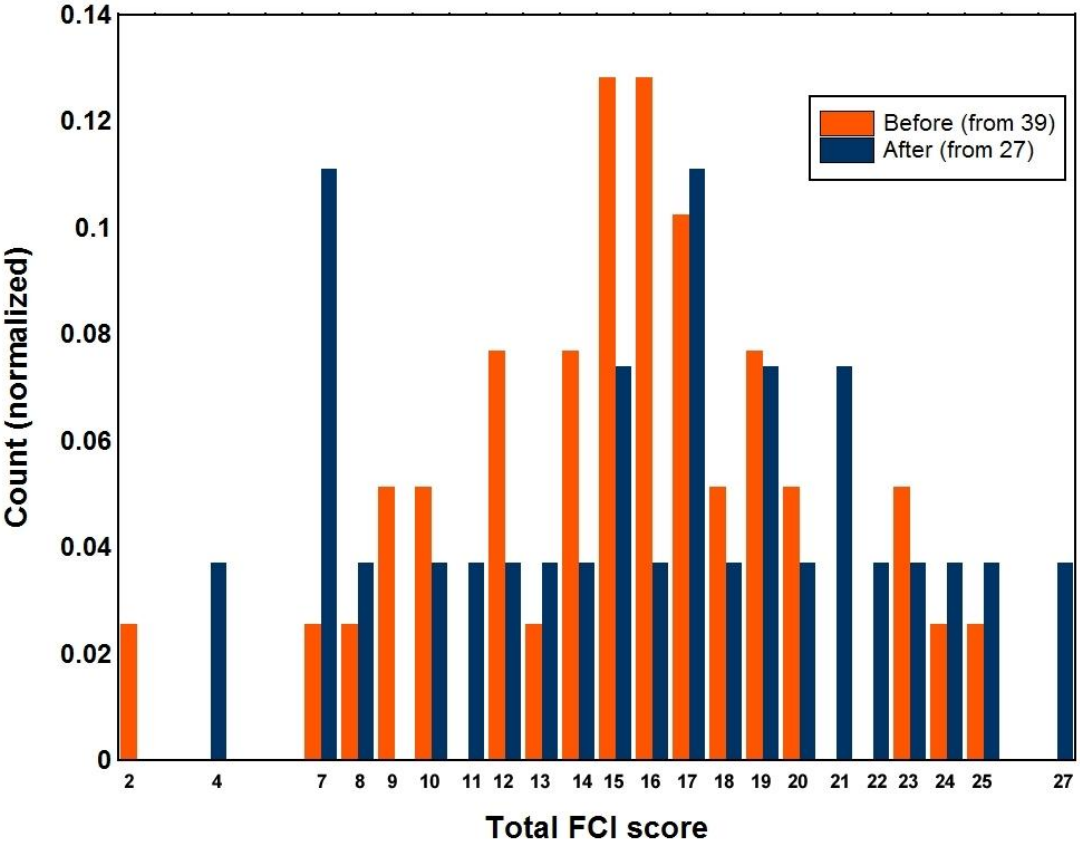


As with any innovation in teaching, evaluation is important. Aside from the normal methods of module feedback, such as a questionnaire, which provides information on the students' perceptions of the course, the FCI has been used both before and after instruction to try to measure conceptual gains resulting from this method of instruction.

## 3. Outcome

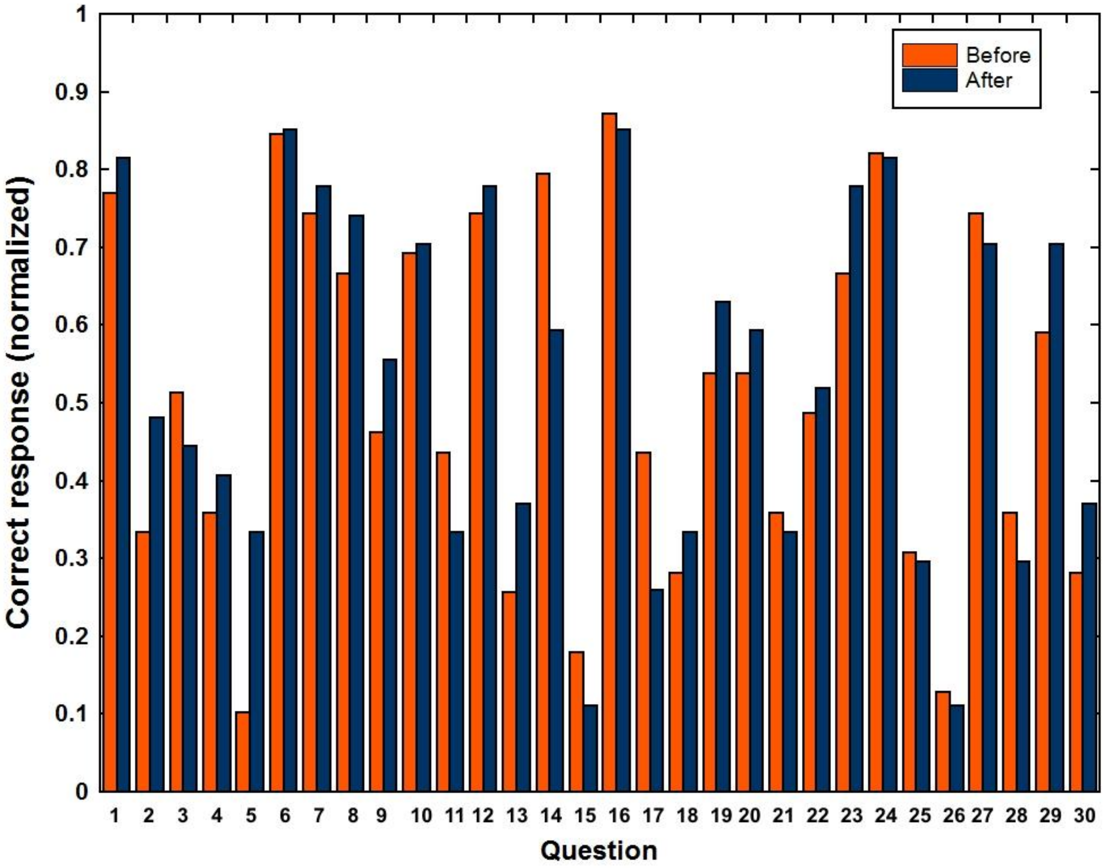
Figure 3 shows the distribution of FCI scores both pre- and post-instruction.

**Figure 3.** The normalised distribution of FCI scores.



The difference between the two distributions is not large, but if anything the post-instruction distribution indicates a slight improvement in scores. It is clear that, like Chabay and Sherwood, the full educational potential of modelling has not been achieved and further analysis reveals a complex set of factors that prevent detailed conclusions about student learning being drawn from this data. For example, figure 4 shows the breakdown of FCI scores by question. Both the pre-instruction and post-instruction curves are remarkably similar and there are only a few questions where large differences are observed.

**Figure 4.** The percentages of correct answers broken down by question in both pre- and post-instruction FCI tests.

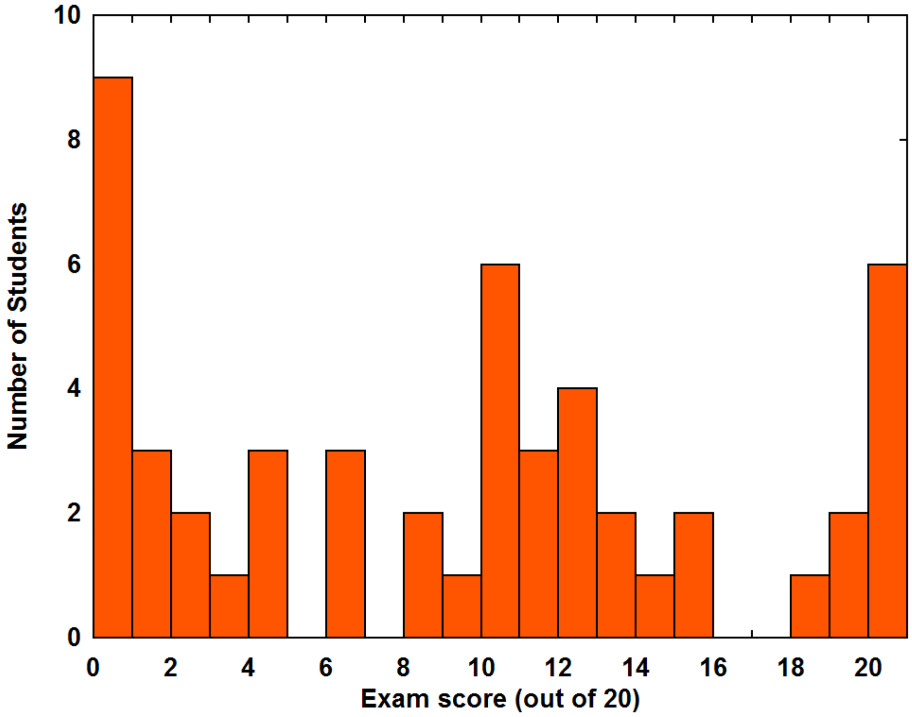


There are gains on a number of questions, for example 2, 5, 8, 9, 13, and 23 as well as others, and there are also some instances, as in questions 14 and 17, where students have altered their choice to an incorrect response. There are also several questions where there is very little change. What is perhaps a little surprising is that, pre-instruction, at least half of the respondents, and in some cases many more, gave the correct response in about half of the questions. The change in FCI scores in figure 3 reflects these trends; that there is little room for improvement in some questions, and that gains are offset by some losses. The total FCI scores do not tell the whole story, therefore, and the breakdown by question provides a better basis for understanding what is happening among the class.  Detailed analysis of the breakdown of the distribution of responses to each question, for example the number of students choosing A, B, C, etc., yields further information which can be used to modify the instruction next year. There are three questions that stand out as having very low-pre-instruction scores; questions 5, 15 and 26. The first of these involves identifying the forces involved in circular motion and the last two involve Newton's third law. Analysis of some of the other questions indicates that some students believe in the idea that a force is associated with the motion itself.

In retrospect it is perhaps not so surprising that Newton's third law should cause difficulties. Although this topic was addressed in the course it was done in the context of electrostatics forces where students have to realise that the force exerted by one charge, say A, on another, B, is exactly the same as the force exerted by B on A. In questions 15 and 26, however, the forces are reactive; they arise from the contact of one body pushing on another. As such they are not active forces in as much as they do not affect the motion. It is very difficult, therefore, to model such forces and it is entirely reasonable that students who did not understand this aspect of the third law before instruction will not have altered their view after instruction. This suggests that additional activities need to be introduced to complement the modelling. One possibility is small group discussion around a set of scenarios which require students to distinguish between Newton's second and third laws, as for example in questions 15 and 16. Over 80% of respondent correctly identified the forces in question 16, which differs from question 15 only in that it involves identifying the forces acting when one body is pushing another at constant speed whereas in question 15 the bodies are accelerating. Quite possibly, then, students are interpreting these two questions in terms of Newton's second law rather than the third so that if the bodies are accelerating a net force must exist. It would be easy, though wrong, to conclude from this that the reactive force must be smaller than the thrust, whereas the two must be equal and opposite if the bodies are moving with constant speed. If this is the case then this is not so much a problem of modelling as failing to recognise which law is relevant. Hence the need for other activities to help students clarify their thinking on forces.

Finally, consider the range of FCI scores both before and after instruction. It is evident from figure 3 that there is a very wide range in prior understanding of mechanics concepts at the start of the course and nearly as wide a range after the course. The end-of-year exam results are similar (figure 5).

**Figure 5.** The range and end of year exam score in mechanics. Students have to answer one question from two and can gain a maximum of 20 marks.



A similar spread of marks has been observed in other modules taken by these students as well as in the cumulative end-of-year mark, suggesting that the spread in knowledge and understanding on entry reflects a wide range in abilities as much as preparation in mechanics. Within the class this manifested itself in two ways. First, as pointed out by Chabay and Sherwood (2008), not all students take to programming and though Python is an easy language some students struggled. Second, some students' attendance record was poor, with the result that the spread of attainments is as illustrated in figures 3 and 5. As figure 3 shows, there were some significant gains in the FCI after instruction, but the spread in the FCI scores indicates that some students didn't make much progress at all. This might be due to difficulties with Python, but the verbal feedback indicates that in general students enjoyed this aspect of the modelling and most of those who struggled initially eventually made sense of it. It would seem, then, that the biggest factor affecting the FCI scores is the range of abilities within the class. In the short term there is little prospect of this changing and for the future a slight change of emphasis may be required to help the weaker students get to grips with modelling in VPython.

## Conclusion

A first year course in mechanics based on modelling in VPython has been developed in which students construct models of mechanical systems within the class as well as outside as part of an assignment. In addition VPython models are used within the class to illustrate specific concepts. Pre- and post-course testing using the FCI indicates gains by some students, but not the overall gains that might have been expected on pedagogical grounds. A number of factors have been identified, the most significant of which appears to be the mixture of abilities within the class. More detailed analysis has indicated difficulties with Newton's third law as well as some of the persistent naive views that are often discussed in the literature on the FCI. It is clear that the full educational potential of modelling has not been realised in the present course and the evidence suggest that complementary activities are needed to help students identify the correct forces. In addition, a slight change in emphasis early on in the course should help with the early stages of Python programming.

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