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Using the Force Concept Inventory to monitor student learning and to plan teaching

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Abstract
This is the second of two papers focusing on the Force Concept Inventory, a multiple-choice test designed to monitor students' understanding of force and related kinematics. In this paper we outline how the FCI was used to evaluate student learning following a newly developed approach to teaching mechanics in a Finnish upper secondary school. We believe that this case offers a compelling example of the benefits (in terms of enhanced student learning) that can follow from research- or evidence-based approaches to teaching.

Keywords: M; Mech, TLA

Introduction
This paper provides an account of the development of a new approach to teaching mechanics in a Finnish upper secondary school and demonstrates how the Force Concept Inventory (FCI) (see the preceding paper: Savinainen and Scott 2002) was used both to evaluate this new teaching approach and to analyse the student learning. The teaching was carried out by one of the authors (AS) of this paper, as part of his normal day-to-day physics teaching with a group of 16-year-old students.

At present, in the UK and elsewhere, the question is being raised about the extent to which ‘Evidence-based practice in education’ (Desforges 2001) can lead to the enhancement of gains in student learning. We believe that the work described here can contribute to this debate by demonstrating how insights into research on teaching and learning in mechanics have been drawn upon to revise instructional approaches and to thereby improve student learning.

Teaching approach: Interactive Conceptual Instruction (ICI)
The teaching approach (which we refer to as Interactive Conceptual Instruction, ICI) was developed to promote conceptual understanding of the force concept and was based on the premise that developing an understanding of mechanics requires an interactive process in which there is opportunity for ideas to be talked through, and thought through, between teacher and students. In other words, the process should be consequent upon ongoing teaching and learning dialogues.

Interactive Conceptual Instruction entails four features or components, which overlap with each other to some extent:
- Conceptual focus
- Classroom interactions
- Research-based materials
- Use of texts

The first feature involves focusing on the development of conceptual understanding. In
ICI conceptual focus is achieved by utilizing the principle of ‘concepts first’ (Van Heuvelen 1991), where new ideas are first developed at a conceptual level with little or no mathematics. This contrasts with traditional approaches where definitions are usually introduced, and expressed, in mathematical form. In ICI, the teaching often starts with demonstrations of phenomena, which act as a focus for observation and discussion, leading to an introduction by the teacher of the relevant physics concepts. Only after the students have a good grasp of the concepts is quantitative problem solving introduced. For example, in teaching about acceleration, conceptual understanding might first be addressed through simple demonstrations of changing velocities, involving change in magnitude and/or direction of velocity. The students observe the demonstrations and then discuss in pairs about whether or not there is a change in velocity. Graphical and diagrammatic representations are used to describe the demonstrated motions and the students are encouraged to talk through, and move between, these different representations as they develop their understandings. These qualitative treatments are followed by an introduction to the mathematical definition of average acceleration and an empirical measurement of the acceleration of a falling object.

The second feature of the ICI teaching approach involves promoting different forms of classroom interactions and is based on the premise that meaning making is a dialogic process where students benefit from talking through their developing ideas (see Scott 1998). In particular, Peer Instruction, as developed by Mazur at Harvard University, is used to actively engage the students in the learning process.

Mazur (1997) describes the method thus:

The basic goals of Peer Instruction are to exploit student interaction during lectures and focus students’ attention on underlying concepts. Instead of presenting the level of detail covered in the textbook or lecture notes, lectures consist of a number of short presentations on key points, each followed by a ConceptTest—short conceptual questions on the subject being discussed. The students are first given time to formulate answers and then asked to discuss their answers with each other. This process (a) forces the students to think through the arguments being developed, and (b) provides them (as well as the teacher) with a way to assess their understanding of the concept.

Mazur has used the FCI at Harvard University to evaluate the successfulness of Peer Instruction (Crouch and Mazur 2001) and the FCI gains achieved have been amongst the best ever reported.

In ICI, the students discuss conceptual exercises in pairs in the way described by Mazur. It is very important that after pair discussion students compare their explanations with the explanation provided by the teacher. Points arising from demonstrations and laboratory experiments are used as a basis for oral conceptual exercises, which can be flexibly tailored to match the teaching situation at hand.

The third feature of the ICI teaching approach involves use of research-based materials. Question-and-answer conceptual exercises designed by the teacher are used in the early stages of meaning making. These exercises enable constant feedback on developing student understanding as advocated by Mazur. Research-based exercises serve as diagnostic tools, which allow for more reliable formative assessment (Black and William 1998) of student understanding as the teaching sequence progresses. The Ranking Task Exercises (O’Kuma et al 2000), for instance, are very useful for this purpose. Research-based exercises can reveal difficulties that students may still have and inform further teaching on the topic.

The fourth feature of ICI involves the ways in which texts are used to promote understanding. The students do not take ordinary notes; instead they make additions, remarks and underlinings in the textbook. Here the focus is on interacting with, and coming to an understanding of, the text, rather than on copying out words from one page to another. In addition, the students are often asked to read the relevant section of the textbook prior to the lesson, thereby releasing time for active discussion. Concept maps, which are constructed by the teacher, are also used as a means for summarizing sections of work. The concept maps allow the students to see ‘the big picture’ and the relations of key ideas in a concise form (Novak and Gowin 1984). In addition, students
are encouraged to write their own summaries of work completed.

The ICI approach described above shares similar features with the interactive-engagement method defined by Hake (1998). Hence it might be expected that the ICI approach would offer the potential to promote enhanced learning gains in conceptual understanding of mechanics.

Collection and analysis of the FCI data
The focus group for this study consisted of Finnish students (age 16, $n = 24$) following a preparatory International Baccalaureate (IB) programme. The students had encountered mechanics in their lower secondary school studies. For this particular sequence of lessons (total duration approximately 30 hours), the students were exposed to Interactive Conceptual Instruction (ICI) and had available to them an American algebra- and trigonometry-based physics textbook (Giancoli 1998). All teaching took place in English.

A Finnish translation of the 1995 version of the Force Concept Inventory was used (Halloun et al 1995, Koponen et al 2000) and was administered prior to, and on completion of, the teaching programme. The Finnish translation of the FCI was used because the students’ competence in English would not have been sufficiently good at the beginning of the programme.

How successful was the teaching?
As outlined in the preceding paper (Savinainen and Scott 2002), Hake’s normalized gain provides a way to evaluate successfulness of a mechanics course. Hake’s normalized gain is defined as (Hake 1998)

$$
\langle g \rangle = \frac{\langle S_{\text{post}} \rangle - \langle S_{\text{pre}} \rangle}{100\% - \langle S_{\text{pre}} \rangle}
$$

(1)

where $\langle S_{\text{post}} \rangle$ and $\langle S_{\text{pre}} \rangle$ are the final (post) and initial (pre) class averages.

All the traditional teaching programmes in Hake’s large survey yielded gains lower than 0.3 regardless of teachers’ experience or academic background (Hake 1998). Viiri (1996) compared FCI scores achieved by Finnish and American students and concluded that the results were very similar. This suggests that physics students have the same kinds of difficulties in the USA and Finland in learning the concept of force, and Viiri’s finding therefore provides some justification for making comparisons between American and Finnish students in terms of FCI gains.

For this particular study only the ‘matched’ results—i.e. for those students who took both the pre- and post-test—are reported. The results are as follows ($n = 22$; two students did not take the pre-test):

- Pre-test average: $\langle S_{\text{pre}} \rangle = 28\%$ (s.d. 14%)
- Post-test average: $\langle S_{\text{post}} \rangle = 69\%$ (s.d. 17%)
- Hake’s normalized gain: $\langle g \rangle = 0.57$
- Effect size (Cohen’s $d$): $d = 2.6$.

The probability of guessing correct answers for the FCI questions is 20%. It can therefore be concluded that the students’ initial knowledge and understanding of mechanics was very poor. This was by no means a surprise because the students had received only limited instruction in mechanics in lower secondary school.

Hake’s normalized gain value (0.57) for the class falls into the medium-$g$ region and is above the average (0.48) of American interactive-engagement high school, college and university introductory physics courses reported in Hake’s survey (Hake 1998). ‘Effect size’ is a family of indices that measures the magnitude of impact of a particular treatment. It is the standard metric in educational research and a value of 0.8 is considered to be high (Cohen 1988).

Both the values of average normalized gain and effect size reported here suggest that the Interactive Conceptual Instruction approach was very successful in promoting learning. Although the research design adopted does not permit direct comparisons in learning gains between matched control and experimental classes subjected to ‘new’ and ‘traditional’ teaching, we believe that comparisons with FCI data gathered in research studies internationally allow us to claim relative success for the ICI teaching approach. Furthermore, we are aware of the difference between the learning gains achieved through ICI and those achieved through earlier more traditional approaches to teaching by author AS (Savinainen 2001).

Although Hake’s normalized gain and the effect size point to the overall success of the teaching, these data do not provide information about specific learning difficulties that students may have encountered in coming to an understanding of the force concept. This issue is addressed in the next section.
Evaluation of learning

The first set of data presented here (figure 1) provide information about the distribution of pre- and post-test scores for the focus class. It is clear that the distributions of scores are very different for pre- and post-tests.

In the post-test, 77% of the students (17 out of 22) exceeded the ‘entry threshold’ (60%) to the Newtonian world and 18% (4 out of 22) exceeded the ‘mastery threshold’ (85%). These thresholds were defined by Halloun and Hestenes (1995).

The pre- and post-test scores for individual items are presented in figure 2.

It is useful to calculate the average gains for individual test items (for example, using Hake’s formula, the average gain calculated for item 7 is 0.83). These confirm quantitatively what can be observed from figure 1. Post-test scores are much higher than pre-test scores in many questions but there are three questions in which the post-test scores are actually lower than the pre-test scores (questions 9, 21 and 23). This implies that the teaching has had a negative effect in relation to students’ responses to these questions!

To gain a more detailed idea about how student responses changed after instruction, the results are presented in figure 3 along the six conceptual dimensions (see Savinainen and Scott 2002) of the force concept probed in the FCI.

These results indicate that the teaching was quite ineffective in relation to Newton’s Second Law: Hake’s average gain was only 0.14. All of the questions in this dimension were consistently answered at a poor level, and in particular the students had great difficulties with two-dimensional motion (questions 14, 21 and 23). The students had not studied vectors in mathematics before the mechanics course and this may partially explain their difficulties with these questions. This hypothesis gains support from the very low success rate with answers to question 9, which addresses vector addition of velocities.

In addition, only slight overall improvement is identified in the kinematics dimension (average
This is partially explained by the fact that the same poorly answered questions relate both to Newton’s Second Law and to kinematics categories. At the same time there were some kinematics questions which were very well answered (questions 19 and 20). These questions address differentiation between kinematics concepts. Students made substantial gains along all the other dimensions, with improvements in performance relating to the dimensions of ‘superposition principle’ and ‘kinds of forces’ being particularly impressive.

It is interesting to compare the students’ responses to two FCI questions, which focus on the contact force between two cars where a smaller car is pushing a larger car. In question 15 the two cars are accelerating and in question 16 they move with constant velocity. Almost all the students (20/22) answered the latter question correctly, but many fewer (10/22) answered the former question correctly. This suggests that many students had difficulties in generalizing from Newton’s Third Law to cover both the accelerated and uniform velocity cases, with many students believing that Newton’s Third Law does not hold in a dynamic situation. Other instruments used to probe conceptual understanding (for example, open questions from Huffman 1997) in the study confirmed this supposition. This particular misconception, which has been referred to as the ‘dominance principle’, has also been found to present a major obstacle to learning by Hestenes et al (1992).

Bao and Redish (2001) have developed a statistical method (Concentration Analysis), which enables identification of those multiple-choice responses that are based upon the most common correct or incorrect modes of students’ thinking. By applying this technique of Concentration Analysis to the FCI responses from the focus class, and by examining the distribution of responses to individual items, it was found that the most common specific misconceptions after teaching were:

- ‘last force to act determines motion’
- ‘velocity proportional to applied force’
- ‘greater mass implies greater force’

The misconceptions, as listed here, relate to the taxonomy developed by Hestenes et al (1992), which was presented in the preceding article (Savinainen and Scott 2002). The analysis reveals that the first and second misconceptions were actually amplified by the teaching. Most of the students in the focus group will, however, continue studying physics in the International Baccalaureate programme and there will be the opportunity to address the difficulties revealed by the FCI.

**Discussion**

In this paper we have demonstrated how insights and evidence from physics education research can be drawn upon, in day-to-day secondary school teaching, to enhance the learning gains of students in the conceptual domain of mechanics. The effect on learning gains compares very favourably with the outcomes of more traditional teaching approaches, as reported in the international science education research literature.

We believe that the increased learning gains can be linked to three aspects of the associated pedagogy:
• the use of interactive approaches where an ongoing dialogue between teacher and students focuses on development of conceptual understandings and where the students have time and opportunity to talk through their developing understandings, with the support of the teacher.

• the use of research-based instruments, such as the FCI, which enable quick and detailed formative assessment of students’ learning to be made.

• the development of a detailed knowledge and understanding of the conceptual terrain of the subject area, by the teacher, including the canonical physics knowledge, student misconceptions and representations in between.

Furthermore we believe that the use of an instrument such as the FCI can offer a very helpful introductory focus, and springboard, for the teacher in developing these aspects of pedagogy.

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Antti Savinainen has a BEd degree and an MPhil in Physics. He has been a Marie Curie Fellow at the University of Leeds, where he worked closely with Dr Philip Scott. He teaches in a secondary school in Kuopio, Finland, and aims to complete his PhD in Physics Education in the near future.