Experientially based physics instruction

– using hands on experiments and computers

Final report from the *Council for Renewal of Higher Education* project 167/96

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Abstract

Developing a functional understanding of mechanics, in accordance with canonical physics, has proven to be one of the most difficult challenges faced by students. In this report the development and implementation of conceptual labs in mechanics will be described. It is shown that educational design combining appropriate use of interactive technologies, hands-on and carefully designed instructions can foster a functional understanding of the involved physics. It is also shown that the educational implementation is crucial and that the outcome is not determined by the use of a certain educational technology.

Introduction

Developing a functional understanding of mechanics, in accordance with canonical physics, has proven to be one of the most difficult challenges faced by students. Studies by many different researchers have shown that the misleading conceptions about the nature of force and motion, which many students have, are extremely hard to change. These strong beliefs and intuitions about common physical phenomena are constituted by previous personal experiences and affect students' interpretations of the material presented in a mechanics course and in later courses. Research has shown that traditional instruction does very little to influence students' "common-sense" beliefs [see for example McDermott, 1997, and references therein; Hake, 1997; Hestenes *et al*, 1992; McDermott & Redish, 1999 and references therein; Arons, 1997 and references therein].

Most papers on student learning problems in mechanics are written within a constructivist framework and very few successful attempts in designing learning environments which bring conceptual understanding of mechanics about is reported in the literature.
However RealTime Physics (Thornton, 1997a; Sokoloff et al, 1998; Thornton and Sokoloff, 1998), Tools for Scientific Thinking (Thornton, 1987, and 1989) and Workshop Physics (Laws, 1997a) are exceptions with reported remarkable learning results.
In the academic year of 1994/95 Microcomputer-Based Labs (MBL) were first introduced at the physics-teaching laboratory at Högskolan Dalarna in an electricity course. In subsequent years MBL were introduced in a more full-fledged fashion and labs were further developed.

The development of the labs using MBL-tools were inspired by, but not identical to, the pedagogical approaches applied in RealTime Physics and Tools for Scientific Thinking and inspired by research in Physics Education (see for example McDermott, 1997; Thornton, 1997a; Laws, 1997b). In this paper we will not go into any detailed analysis of the differences between our curricula and the ones mentioned above.

For some decades sensors attached to a computer have been used in most experimental physics research laboratories. An attachment of a sensor to a computer creates a very powerful system for collection, analysis and display of experimental data. Today several systems, specially developed for schools and undergraduate courses, are commercially available for different computer platforms. In a Microcomputer Based Laboratory (MBL-lab) students do *real* experiments, not simulated ones, using different sensors (force, motion, temperature, light, sound, EKG…) connected to a computer via an interface. One of the main educational advantages of using MBL is the real-time display of experimental results and graphs thus facilitating direct connection between the real experiment and the abstract representation. Because data are quickly taken and displayed, students can easily examine the consequences of a large number of changes in experimental conditions during a short period of time. The students spend a large portion of their laboratory time observing physical phenomena and interpreting, discussing and analysing data with their peers. The MBL context adds capacity and flexibility that, to be exploited requires the lab to be reconceptualised, giving students more opportunity to explore and learn through investigations (Tinker, 1996; Thornton, 1997).

This makes it possible to develop new types of lab experiments designed to facilitate better student learning and to use labs to address common preconceptions. *To take full advantage of MBL the educational implementation is important, not the technology! Active engagement is important!*

Implementation of MBL-labs and curriculum reform in Mechanics

The physics department at Högskolan Dalarna started using MBL in the 1994/95. Labs using MBL-technology have been introduced in most physics courses. In 1996/97 a curricular reform involving the mechanics courses in a civil engineering programme taught in co-operation with the Royal Institute of Technology (KTH) started. Before the reform the mechanics courses were identical to those given at the KTH. The courses were taught with lectures and recitation sessions and no labs were included. The mechanics course was split in two parts: An ”introductory” part (9 ECTS credits) and ”advanced” part (6 ECTS credits). Both courses had a theoretical and mathematical approach. The introductory course taught kinematics and dynamics of particles (including general 3-dim motion) and included an introduction to systems of particles. The advanced course concluded the teaching of systems of particles and also included non-inertial frames of reference and mechanics of rigid bodies (including general 3-dim motion and inertia tensors).

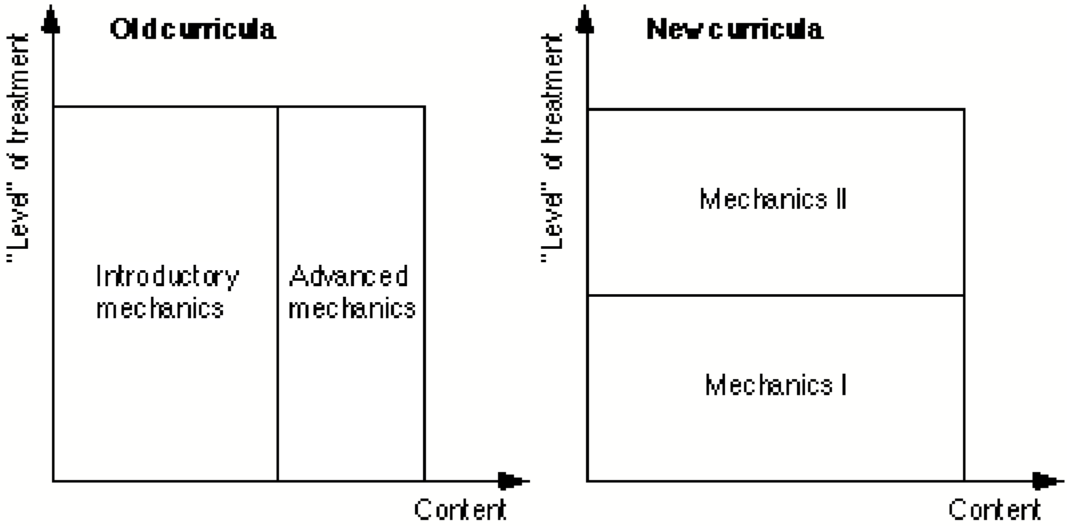

Fig 1. Sketch of the organisational differences between the old and the new curricula in mechanics

In the new curricula this structure was altered and the mechanics sequence was taught as two courses of equal length: Mechanics I (7,5 ECTS credits) and Mechanics II (7,5 ECTS credits). The content areas covered in the Mechanics I course was broader than the previous introductory course and included a treatment of systems of particles, rotary motion and rigid body mechanics, but the level of mathematical treatment was less sophisticated. The Mechanics II covered about the same content areas as Mechanics I but on a higher mathematical level and included for example general 3-dimensional motion and inertia tensors. In the new curricula was also an introduction to Lagrangian dynamics and an introduction chaotic motion included, which were not included in the old curricula. Labs were introduced in both courses. The new Mechanics I course was given the first time in the 1996/97 academic year and Mechanics II 1997/98.

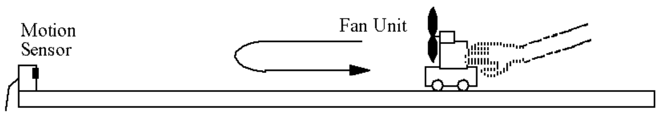

Fig 2. A typical setup at a MBL-experiment. A low-friction cart is pushed towards a motion sensor. A fan unit attached to the cart provides an approximately constant force in a direction opposite to the initial movement and the cart will thus change its direction of motion. The results are shown in figure 3. Note that the fan unit provides a *visible* force.

In the Mechanics I course all new concept are always introduced in lecture by a demonstration. Demonstrations are selected by their importance for conceptual introduction and development and not for their "entertainment" value. Some demonstrations use MBL-tools. Thus direct experience of a concept is given before the presentation of theory in lecturers (concepts first). More time was spent on kinematics than traditionally is done in Sweden in mechanics courses. As pointed out by Laws (1997b) it is essential that students understand kinematics before moving on to dynamics and research have shown that a physics lecturer cannot assume that all students have achieved a functional understanding of kinematics in the upper secondary school.

The theory is later applied in solving problems in recitation sessions. In 1996/97 they were quite traditional with the instructor solving selected end of chapter problems. However emphasis has been put on "thinking aloud" about the concepts applied and to discuss the context of a problem and the relevance of the answer thus modelling how physicists would think and act. In part of the recitations in 1997/98 were problems inspired by the Active Learning Problem Sheets (Heuvelen, 1991a and 1991b) introduced. These problems were solved in co-operative groups.

In the course laboratory the students again gain real-world experience. Most labs are of a discovery type and done co-operatively in groups of 2-3 students. The students are usually asked to start an experiment by discussing with their peers and make a prediction of the outcome of that experiment. Thus student's preconceptions relevant to the phenomenon being studied are elicited. Secondly they perform the experiment and are asked to compare outcome and prediction. If the outcome and prediction do not agree, they are asked to reflect on their observations. This challenges students' personal theories and helps them in their process of substituting their naive belief with a more "scientific" one. (Hewson, 1984) If outcome and prediction do agree this strengthens beliefs that are in agreement or close to the scientifically accepted ones. During a well-implemented MBL-lab students discuss physical concepts and the connections between different concepts instead of just verifying a formula. It is the students are also asked to write a report in their own word after each laboratory session. This services several processes: While describing a phenomenon in their own words, the students once more have to reflect on their own conceptions, and writing reports is also a good training for life after graduation.

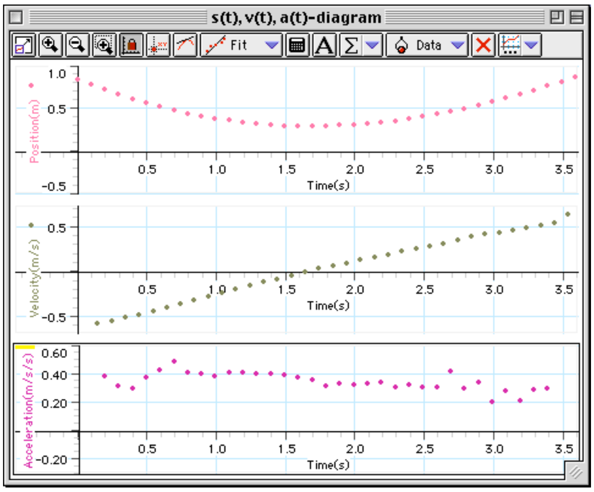

Fig 3. Results of the MBL-lab shown in fig 1. The position, velocity and acceleration as functions of time are displayed. A common misconception is that the cart has zero acceleration at the turning point and another common misconception is that the acceleration is in the direction of motion. By asking the students to make a prediction and sketch the s(t), v(t) and a(t) graphs *before* the experiment and by the rapid display of the experimental results these misconceptions can effectively be addressed.

The labs used in Mechanics I 1997/98 are described in table 1. The approach chosen have been influenced by RealTime Physics (Sokoloff *et al*, 1998; Thornton, 1997a; Thornton and Sokoloff, 1998) and Workshop Physics (Laws, 1997a). The labs are both using MBL-equipment and software from PASCO or Videopoint Videonalysis software. One lab uses the tutorial software Graphs and Tracks (Trowbridge). The most important education advantage of using MBL is the immediate response of such a system. Experimental data from real-world experiment are immediately presented on the computer screen in a graphical format and can immediately be analysed. This quick response is essential for challenging or strengthening students personal theories and makes it easier for students to connect a real-world phenomenon with its more abstract graphical representation. Brasell (1987) has shown that even a very short delay in the presentation of experimental data is detrimental for student comprehension.

- **Motion**

This lab introduces kinematics concepts using MBL and also uses the tutorial software Graphs and Tracks I & II.

- **Analysis of motion using Videopoint**

Introduces two dimensional kinematics using Videopoint.

- **Force and motion I**
- **Force and motion II**

The force and motions labs use MBL-equipment to study dynamics (Newton I and Newton II). Cases with friction and friction free cases are studied.

- **Ballistic pendulum**

A ballistic pendulum is used to determine the muzzle speed of a ball fired by a projectile launcher. This is an ”open” lab where the students are required to deduce necessary equations themselves.

- **Impulse and collisions**

This lab uses the new PASCO force sensor to measure forces during collisions (Newton III) and to experimentally study the impulse - momentum law

- **Moment of inertia**

This lab uses the rotary motion sensor to study rotary motion, moments of inertia and oscillatory motion (ideal and physical pendulums). To study physical pendulums and the parallel axis theorem (Steiner’s theorem) we used equipment, which were designed and manufactured at Högskolan Dalarna together with the rotary motion sensor.

Table 1. Labs (4 h) used in the Mechanics I course in 1997/98.

The approach chosen in the Mechanics II course is very similar to that in Mechanics I. When introducing MBL-labs in our Mechanics II course we wanted to use as much equipment familiar to students from the mechanics I course as possible, use tools (MBL using PASCO ScienceWorkshop and Video with VideoPoint software) familiar to students from the Mechanics I course. However the equipment and tools should be used for investigations at a "higher" level. By using almost the same equipment as in the introductory course kept costs limited and allowed us to have one lab set-up to each lab-group of 2 — 3 students. The labs used in Mechanics II are briefly described in table 2. Besides these labs, some demonstrations using MBL were performed during lectures, for example a gyroscope demonstration. The coupled harmonic oscillator lab is discussed in more detail in Bernhard (1998b).

Air resistance (1- and 2-dim motion)

This lab uses MBL and Videopoint to study motion with air resistance. Motion with air resistance is also modelled using MATLAB. The part analysing 1-dim motion is included as a refresher (this part could very well be included in an introductory mechanics or a high school course).

- **Linear and non-linear oscillations**

Linear and non-linear oscillations are studied using MBL and MATLAB. This lab also serves as a prelude to the chaos lab.

- **Chaos**

Chaotic systems are studied using MBL and an Excel-model.

- **Accelerated systems**

Different accelerated systems are studied using Videopoint and with modelling using Excel or MATLAB.

- **Moment of inertia** (advanced)

MBL are used to study rotary motion and moment of inertia. This lab is more advanced than the corresponding lab in Mechanics I.

- **Coupled harmonic oscillator**

Coupled harmonic oscillators with 2, 3 or 4 masses are studied using MBL and the fast Fourier transform (FFT) tool included in the MBL-software.

Table 2. Labs (4 h) used in the Mechanics II course in 1998/99.

Assessment

General

To investigate the functional understanding in mechanics achieved by the students the research based tests Force Concept Inventory (FCI, Hestenes *et al* 1992, Bernhard 1997) and Force and Motion Conceptual Evaluation (FMCE, Thornton and Sokoloff 1998, Bernhard 1998a) were used. Both tests use multiple-choice questions to assess student conceptual understanding of mechanics. The distractors (wrong answers) are carefully chosen and correspond to common common sense beliefs (misconceptions). The multiple-choice format of FCI or FMCE makes it feasible to do controlled large-scale educational studies. Both the FCI- and the FMCE have been shown by their developers to be reliable and valid measures of student conceptual understanding of basic Newtonian mechanics (Hestenes *et al* 1992, Thornton and Sokoloff 1998). Students response to the questions of FCI and FMCE in an open ended format correlates very well to their answers on the multiple-choice format. The FCI-test is the most commonly used mechanics conceptual evaluation test in the USA today.

In the 1996/97 academic year the FCI-test was used for pre- and post testing of students taking the new Mechanics I course. That year was also second year students post tested after the advanced mechanics course (old curricula). In the 1997/98 academic year both the FCI- and the FMCE-test were used for pre- and post testing. A summary of the FCI-results can be found in Table 3. To facilitate comparison between courses with different pre-test scores, it is meaningful to calculate a ”normalised gain” g (Hake 1997). The normalised gain is defined as gain/(maximum possible gain). R Hake (1997) has reported a survey of 62 introductory physics courses (6542 students) in USA assessed by FCI. According to Hake’s data the normalised gain is remarkably similar for courses using the same teaching strategies despite differences in the pre-test scores. The normalised gain has increased from 25% in 1996/97 to 45% in 1997/98. The post-test FCI-scores have increased from 72% to 75% for male students and from 54% to 68% for female students between 1996/97 and 1997/98. It should be pointed out that the FCI-data for 1997/98 are matched and the pre- and post-test averages only include those students who took both tests.

Freshman year	Protest Average	Post-test Average	Gain (G)	Normalised gain (g)
95/96		62%(*)		
96/97	52%	64%	12%	25%
97/98 (**)	51%	73%	22%	45%

Table 3. Results of pre- and post testing using Force Concept Inventory (FCI, Hestenes *et al* 1992) on students taking Mechanics I (7,5 ECTS credits) at Högskolan Dalarna. Gain (G) = post-test - pre-test. Normalised gain (g) = gain / (maximum possible gain). *Post-test done after the advanced mechanics course (Older curricula. These students had 15 ECTS credits in mechanics). **Matched sample.

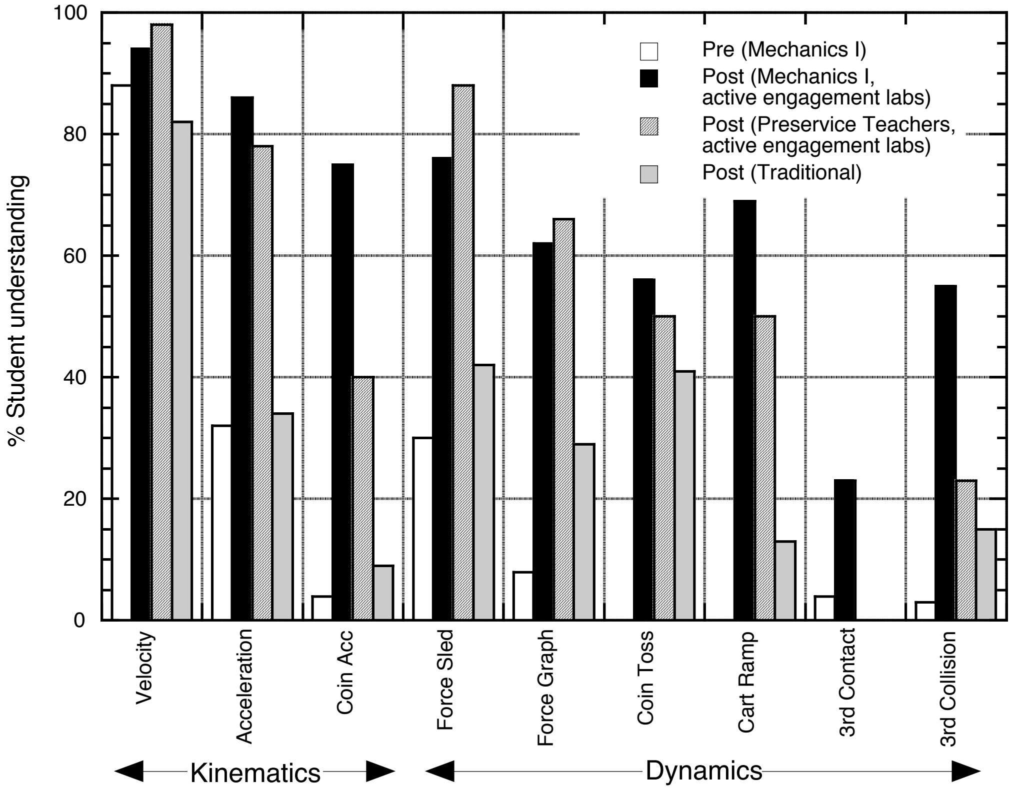

Figure 4. Results of pre- and post testing of student conceptual understanding of Mechanics using the Force and Motion Conceptual Evaluation (FMCE, Thornton and Sokoloff 1998). Data is included from the following groups:

Mechanics I: Students who took the Mechanics I course spring semester 1998.

Preservice Teachers: Test taken at the beginning of autumn semester 1998 by 7:th semester preservice teachers who studied physics spring semester 1996 in their second semester. These students took a subset of the labs (preliminary versions) used in Mechanics I.

Traditional: Test taken at the beginning of autumn semester 1998 at Högskolan Dalarna by students who have had taken different traditionally taught engineering mechanics courses.

In 1997/98 post testing with FCI was also supplemented with the FMCE-test. This test was used together with the FCI to facilitate a comparison between these tests and since some analysis tools have been developed in association with the FMCE-test. The results of pre- and post-tests are displayed in figure 4. The response on the FMCE-test have also been analysed using the conceptual dynamics model developed by R K Thornton (1995, 1997b). According to the pre-test approximately half of the students had a force-follow-velocity view when entering the course and a very low fraction had acquired a Newtonian view. It should be noted that all students had studied physics in either the upper secondary school (”gymnasium”) or in a prepatory year (”basår”). After the Mechanics I course approximately 60% of the students had a Newtonian view and less than 20% of the students had an Aristotelian force-follows-velocity view. According to Thornton most students do not hold a coherent Newtonian view before instruction and after traditional instruction and many students hold different views for increasing velocity, constant velocity and decreasing velocity. A detailed analysis is displayed in figure 5.

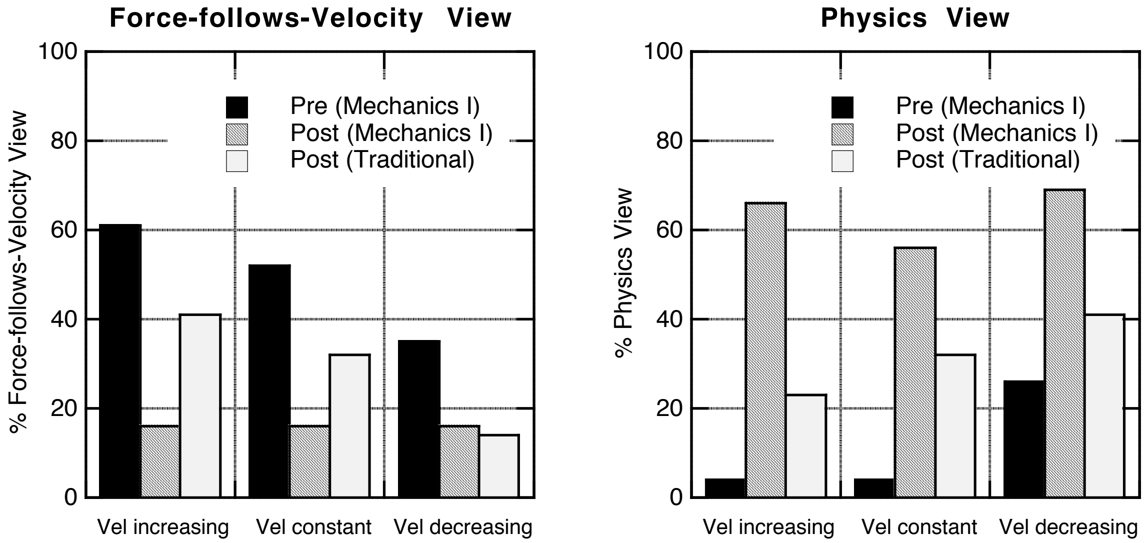

Figure 5. The left-most graph shows the percentage of students holding the ”Force-follow-Velocity” view and the right-most graph shows the percentage holding a ”Physics” view. Student’s views are assigned from FMCE-data using the conceptual dynamics method developed by R K Thornton (1995 and 1997b). Other students view than the ones displayed above account for a significant percentage of the total views.

Gender Differences

Female freshman students at Högskolan Dalarna have lower pre-test values on the FCI than male students as shown in table 4. No analysis of gender differences in FCI- or FMCE-scores have to our knowledge been published except as abstracts in the AAPT Announcer (Hake *et al* 1994, Blue and Heller 1994, Flood *et al* 1994, Blue and McCullough 1996). However according to these abstracts and unpublished data (McCullough 1998 and Crouch 1998) the situation seems to be similar in USA.

It should be noted that the normalised gains achieved in Mechanics I 1997/98 are almost identical (se table 4) for male and female students, which indicates that the teaching method used was equally effective for both sexes. In the year before there was a much larger difference in the post-test scores between male and female students and in 1996/97 the scores were 72% for males and 54% for females. Thus much of the success of the 1997/98 course can be attributed to a large increase in female FCI-gain. However, most of the FCI-data we know of report differences of normalised gains between the sexes with larger g for males. For

Gender	N	Pre-test Average	Post-test Average	Gain	Normalised gain
Male	18	54%	75%	21%	45%
Female	8	44%	68%	24%	43%
All	26	51%	73%	22%	45%

Table 4. Results of pre- and post testing using FCI on students taking Mechanics I 1997/98 split by gender. Matched sample (only students taking pre- and post-test are included). Post-test data 1996/97 were 72% for male students and 54% for female students.

example Laura McCullough (1998) reports a $g(FCI)_{male}$ = 41% and a $g(FCI)_{female}$ = 34% from the University of Minnesota and R R Hake (1998) reports a $g(FCI)_{male}$ = 66% and a $g(FCI)_{female}$ = 55% from Indiana University. Both universities used active engagement methods. Since female students usually have lower FCI pre-test scores, the gender differences increase during most university or college mechanics courses. However, since we have achieved an almost equal normalised gain for both sexes, and since Crouch (1998) report similar results from the last years at Harvard it should be possible to achieve gender fair instruction in mechanics. It should be noted that it is not necessary to have female instructors to achieve gender fair instruction. In 1997/98 all parts of the Mechanics I course were taught by two male teachers (both senior lecturers) and in 1996/97 the course were taught by two male teachers (one senior lecturer teaching lectures, one class section and one lab section and one instructor teaching one lab section) and one female teacher (lecturer teaching one class section and one lab section). It should be interesting to further investigate which factors in curriculum and instruction are important for the achievement of gender fair instruction.

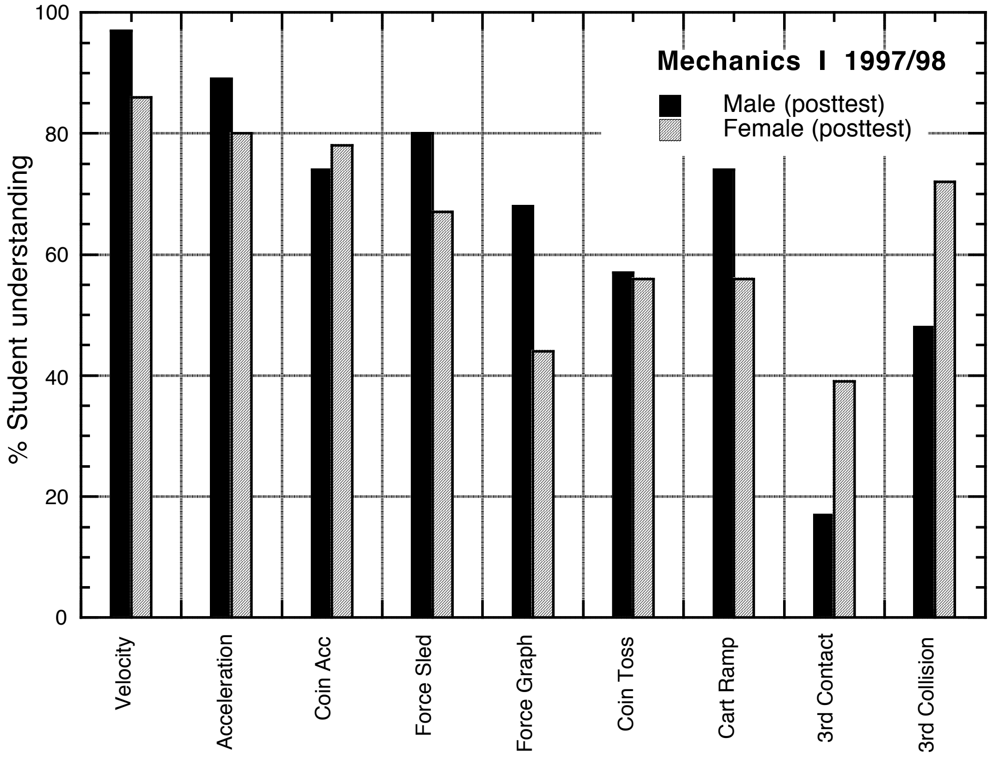

Figure 6. Post-test FMCE-data for Mechanics I 1997/98 split by gender. N_{male} = 23 and N_{female} = 9.

Comparison with different curricula

To facilitate comparison with different curricula the FCI- and FCME-test have also at the beginning of the autumn semester 1998 been administered as post-tests to pre-service science teachers studying in their 7:th semester and to different groups of engineering students who have attended traditionally taught engineering mechanics courses. The pre-service science teachers studied physics in their second semester the spring semester 1996. In the mechanics part of the course they took early versions of labs corresponding to the Motion lab and the Force and Motion labs. They also took a lab using `VideoGraph` video analysis software and one using `Interactive Physics`. The results of the FMCE-test for these groups are displayed in figure 4 together with pre- and post-test data for the Mechanics I course 1997/98. Participation for both the preservice teachers group and the ”traditional” group were voluntary and thus it can be supposed that the results for both groups are slightly better than a true average.

However the differences between on one side the Mechanics I group and the pre-service teachers group and on the other side the ”traditional” group are too large to be ignored. They are also consistent with results reported in the literature. The good results for the pre-service teachers 5 semesters after a mechanics course that used some active engagement elements suggest that active engagement methods induce a permanent conceptual shift. The weaknesses in results of the pre-service teachers compared with Mechanics I correlate very well to improvements and changes since 1996. It can thus be concluded that the active engagement methods we are using, or similar methods, are effective with Swedish students.

As mentioned above R R Hake (1997) has analysed FCI-data for traditional and active engagement physics classes. According to Hake’s study is $g_{\text{Traditional}}$ = 23% and $g_{\text{Active Engagement}}$ = 48% in average. However Hakes study is based on data from various instructors who had chosen to submit their data after testing was done. Saul and Redish (1998 a and b) have performed a controlled study with second implementations of some active engagement methods at colleges and universities in USA. They got a slightly lower average than Hake. The FCI-date from their study together with our data is shown in table 5 and the FMCE-data are shown in table 6. Our gains compares very well with the gains achieved by other classes.

Teaching Method	Normalised gain (FCI)	Reference
Workshop physics	41%	Saul and Redish 1998a
Tutorials in Introductory physics	35%	Saul and Redish 1998a
Group Problem Solving	34%	Saul and Redish 1998a
Mechanics I (1997/98)	45%	This study
Traditional	16%	Saul and Redish 1998a

Table 6. Comparison of normalised gains for different teaching methods using the FCI-test.

Teaching Method	Normalised gain (FMCE)	Reference
Workshop physics	65%	Saul and Redish 1998b
Mechanics I (1997/98)	61%	This study
Traditional	14%	Saul and Redish 1998b

Table 7. Comparison of normalised gains for different teaching methods using the FMCE-test.

Other implementations

In our project and in other projects very positive learning effects using MBL have been reported. The question thus arises: Is the reported good learning effects of MBL due to inherent properties of the MBL-technology or is the educational implementation crucial? The ideas behind this project and the technology used in the labs have been implemented in courses outside this project. However different instructors have different educational "views" which have led to different ways of implementing the MBL-labs. Below we will briefly discuss two implementations. These have been discussed in more detail elsewhere (Bernhard, 2003, 2005a and 2005b).

One implementation was in a course for Pre-service Teachers 98/99. The labs in this course were characterised by:

- MBL-technology was used in the labs.
- The original labs were transformed into formula verification labs with rewritten instructions.
- No POE-cycle was used.
- MBL was mainly used as a technological tool.

The result from the FMCE-test is displayed in fig. 7.

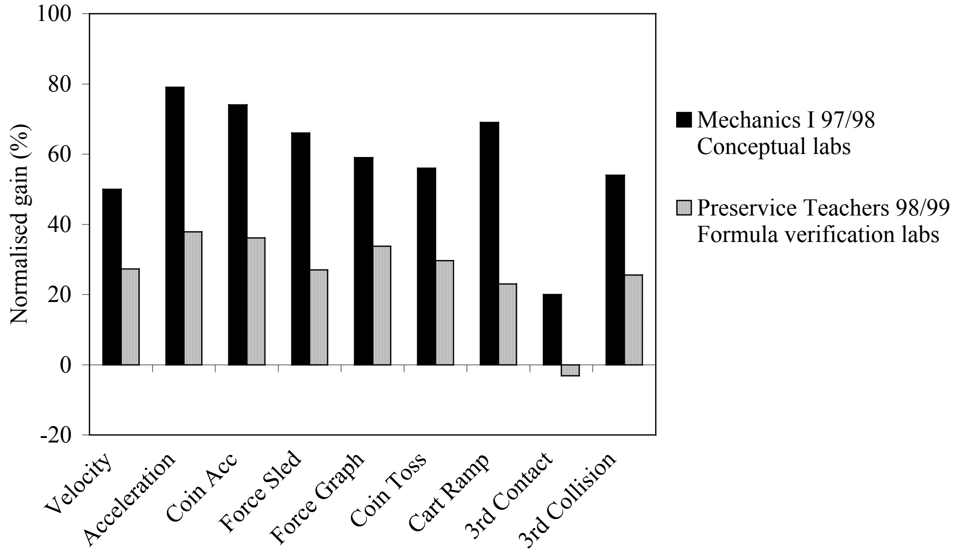

Fig. 7. Comparison of normalised gains (Hake 1997) of two courses using the same MBL-technology in labs but different educational approaches. Note the negative learning gain for Newton 3rd law contact forces.

Another implementation was done in an introductory physics course for engineering students. 25 students of a total of 125 students took an "alternative" lab course consisting of 4 MBL-labs of 4 h length. The labs were

- Motion
- Force and motion I
- Force and motion II
- Impulse and collisions

These labs were updated versions of similar labs used earlier in the Mechanics I course. The regular labs taken by the remaining 100 students was problem solving labs (Richardson labs).

Except for 16 h of labs the students had the same lectures and participated in the same problem solving classes. The result from the FMCE-test is displayed in fig. 8.

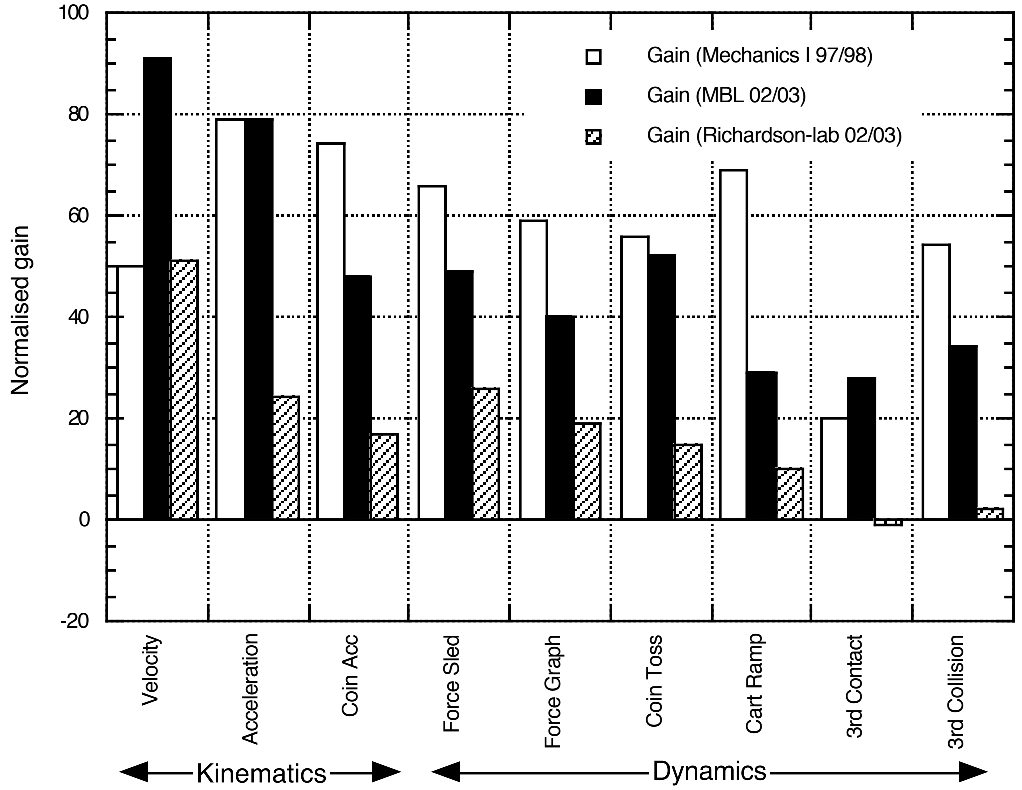

Fig 8. Normalised gains for different courses as measured by the FMCE-test.

Conclusions and discussion

In line with other reports from other curricula using MBL our assessment data show that our reformed Mechanics courses with associated labs has been quite successful in inducing better functional understanding of mechanics. It should be noted that as part of the curricular reform the number of lecture and recitation hours was reduced to keep the course within approximately the same budget when labs were introduced. The old curricula students who achieved a 62% average on FCI after the advanced mechanics course had received about 3 times as much ”theory” teaching than the new curricula students had after Mechanics I! Although it is difficult to compare achievements on examinations, it can be concluded that the 1997/98 course were better problem solvers since the students achieved significantly better than the students did previous year. This is also in agreement with Hestenes and Wells (1992). Also

The gains achieved by our students compare favourably when compared with implementations of some active engagement curricula (Saul and Redish, 1998a and 1998b). Still from some of our data and from results from courses where these labs were implemented in an improved versions it can be concluded there is room for further improvements in a continues process.

Euler and Müller (1999) have claimed that MBL is the only curricula using computers, which have been consistently successful in achieving good learning results. However the results presented in fig. 7 above and further discussed elsewhere (Bernhard, 2003, 2005b) indicates the importance of how the task is formulated by the teacher in the lab instructions. It should be stressed that the outcome is not determined by the use of a certain educational technology.

Tinker (1996, page 3) points out: "*It is not usually advantageous to simply replace a traditional lab with an equivalent one using MBL. This kind of 'substitution' policy is easiest for schools to implement, but the result of such a substitution is often a simple lab made more difficult and expensive by the inclusion of computers with no educational gain. The MBL context adds capacity and flexibility that, to be exploited requires the lab to be reconceptualized, giving students more opportunity to explore and learn through investigations. This, in turn, often requires a change in teaching style that takes time and institutional commitment*".

Thus one has to look in detail in the educational design. This project is taken further in a project supported by Swedish Research Council: *Educational conditions for meaningful learning in science and engineering with interactive technologies*. The idea in this project is to examine in detail the interaction taken place in labs using interactive technologies to gain an understanding in which details in the educational design are critical for insightful learning. The result from this project will be helpful in a process to further improve the labs developed by us and to extend the ideas to labs in other courses in science and engineering.

The success of this project have inspired (at least) two other projects supported by the Council for the Renewal of Higher Education namely *Activity based education in electricity and circuit theory* (project 035/99, concluded) and *Helping students to make sense of formal physics through interactive lecture demonstrations* (090/G03, ongoing). In the first project conceptual labs were implemented in an electric circuit theory course for engineering students. In the second project the ideas behind conceptual labs described in this project are implemented in a lecture setting.

To conclude this project have shown that it is possible to develop and implement conceptual labs in mechanics and that such labs can foster a functional understanding of physics.

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