

Helping students to make sense of formal physics through interactive lecture demonstrations

Final report from the *Council for Renewal of Higher Education* project 090/G03

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ABSTRACT

Educational research repeatedly shows that delivery mode instruction, such as “traditional” lectures, commonly does not help students to acquire sufficient functional understanding of physics: typically, students just achieve a 15-20% normalized gain on the *Force and Motion Conceptual Evaluation* (FMCE). Previously, we have successfully designed different “conceptual” labs in physics and in electrical engineering, where an average normalized gain of 61% on the FMCE has been achieved.

Inspired by our previous success with conceptual labs – and with a starting point in the ideas on so called *Interactive Lecture Demonstrations* as developed by David Sokoloff, Ron Thornton and co-workers – our aim with this project has been to a) test how interactive lecture demonstrations best are to be enacted in a Swedish lecture setting, and b) investigate the results of such lectures in terms of student understanding. As in the conceptual labs, interactive lecture demonstrations utilize computer-assisted data acquisition and analysis of data from a “real” experiment in real-time. In the lecture setting, however, only one experimental set up is used, and the students have to engage with the task by following the lecture, making predictions and answering questions on a worksheet.

In the project, we have designed and implemented the interactive lecture demonstration format with a starting point in previous experiences and research. We have also investigated the results of these lectures by means of quantitative and qualitative methods. The result of the quantitative tests shows a 37% normalized gain on the FMCE, indicating that the implementation of this approach is better than “traditional” lectures. However, the result is not as good as the results obtained from the conceptual labs, probably because the students here were not as engaged in the experiment as they had been in the lab setting. Still, one should take into consideration that interactive lecture demonstrations use fewer resources; for instance, only one set of equipment is needed. For this reason, we suggest that the use of interactive lecture demonstrations should be considered in cases where it is not possible to implement a full set of conceptual labs. It would also be interesting to explore the optimal combination of labs and lectures. In sum, the implementation of interactive lecture demonstrations show that it is possible to do reforms, and achieve active learning, in the framework of a lecture setting.

HELPING STUDENTS TO MAKE SENSE OF FORMAL PHYSICS THROUGH INTERACTIVE LECTURE DEMONSTRATIONS

The aim of this project have been to develop and implement “interactive lecture demonstrations” as a platform for helping students to acquire a functional understanding of physics. Interactive lecture demonstrations can be described as an “active engagement” learning environment in a lecture setting, where computer-assisted data acquisition and analysis tools are used together with demonstration equipment and carefully developed worksheets. In this project, the interactive lecture demonstrations have been implemented in an introductory physics course (mechanics, wave motion, optics and thermodynamics) taken by engineering students at Campus Norrköping, Linköping University.

BACKGROUND: CONCEPTUAL DIFFICULTIES IN MECHANICS

It is well known that “traditional” delivery mode instruction does not help most students in their understanding of formal physics. It has been shown that most students, even after having been enrolled in university level courses, adhere to everyday “common-sense” beliefs, which often are contradictory to the canonical physics they have been taught.

The problems with traditional education and some indications to what is needed is well stated in an consensus reached by Physics education researchers in USA [see McDermott (1997) or Thornton (1997)]:

- Facility in solving standard quantitative problems is not adequate criterion for functional understanding. Questions that require qualitative reasoning and verbal explanation are essential.
- A coherent conceptual framework is not typically an outcome of traditional instruction. Rote use of formulas is common. Students need to participate in the process of constructing qualitative models that can help them understand relationships and differences among concepts.
- Certain conceptual difficulties are not overcome by traditional instruction. Persistent conceptual difficulties must be explicitly addressed by multiple challenges in different context.
- Growth in reasoning ability does not usually result from traditional instruction. Scientific reasoning skills must be expressly cultivated.
- Connections among concepts, formal representations, and the real world are often lacking after traditional instruction. Students need repeated practice in interpreting physics formalism and relating it to the real world.
- Teaching by telling is an ineffective mode of instruction for most students. Students must be intellectually active to develop a functional understanding.

Studies (performed by us and by others) indicate that there is no significant difference between students in USA and Sweden.

INTERACTIVE LECTURE DEMONSTRATIONS

In order to address this problematic situation, several educational innovations have been developed and employed. We have earlier developed an innovative “learning environment” in mechanics at a smaller Swedish University (The Swedish Council for Renewal of Higher Education: Project 167/96, *Experientially based physics instruction – using hands on experiments and computers*) with conceptual labs utilising computer-assisted data acquisition and analysis – commonly referred to as *Microcomputer Based Laboratory* (MBL) – which has resulted in excellent learning gains on standardised conceptual tests such as FCI and FMCE (Bernhard, 1997, 2000, 2001, 2003, 2005). The obtained normalised gains (Hake, 1997) are presented in table 1. The result obtained from “traditional” teaching corresponds very well with the results obtained by for example Hake (1997) and Saul and Redish (1998). Our results from the reformed courses compares very well (in level with or better) with the results obtained by different “innovative” approaches in USA and Europe. In some subsequent refinements, even better results have been obtained.

Still, the use of MBL-labs is expensive, especially in large student groups. 100-150 students typically follow the introductory physics course for engineering students at Campus Norrköping, Linköping University. An implementation of MBL-labs in mechanics therefore requires large investments in computers, interfaces, sensors and other equipment. For the time being, and with the present economic situation at the department, this has been judged not to be feasible.

For this reason, the implementation of *Interactive Lecture Demonstrations* (ILD) has been considered. Interactive Lecture Demonstrations have many similarities with the MBL approaches briefly described above. Both MBL and ILD use computer-assisted data acquisition and analysis of “real” experiments in real-time. Both approaches are designed to engage students in inquiry through which they “discover” the intended content guided by the teacher, technology and materials (“guided discovery”). One common feature of both approaches is the use of the so called *predict – observe – explain* cycle. We have proposed (Bernhard & Lindwall, 2003) that the documented success of certain curricula using MBL, in many different settings, may be understood from the design of these curricula that frames the tasks in such a way that a focus on conceptual issues is almost a requirement for solving the tasks successfully.

One major difference between MBL and ILD is that MBL is performed in a lab setting and ILD are performed in lecture settings. In ILD, one set of equipment (computer + interface + appropriate sensors + other experimental equipment) is used and the experimental results are displayed through some large-screen display. In traditional lecture demonstrations, students often are passive recipients that want to be entertained or stay unfocused. The content of demonstrations in ILDs are not chosen for their “entertainment” value, but are directed towards areas with known problems of student understanding.

THE STRUCTURE OF THE LECTURE ACTIVITIES

The interactive lectures, in the implementation discussed in this report, consist of two main activities. First, there are occasions where the teacher uses the technology (see Figure 1) to carry out the interactive demonstration tasks together with the students. Secondly, there are activities that resemble traditional physics lessons where the teacher mostly uses the whiteboard to explain relevant concepts and theoretical assumptions regarding mechanics. Using this rough division, the interactive lectures can be seen as consisting of the two separate activities *interactive demonstrations* and *lectures*, where the technology is actively used only during the demonstrations, which is the part we focus on here.

To ensure students active engagement (“brains-on”) interactive lecture demonstrations are supposed, according to the original developers, to use this cycle:

- The lecturer describes the demonstration carried out and performing it without collecting data.
- Students are asked to make and write down their individual predictions on specially designed prediction sheets (~1 min).
- Students discuss their predictions with their neighbours and indicate their prediction consensus prediction on their prediction sheets (~2-3 min).
- The predictions are discussed in class and the various predictions are put on board.
- The demonstration is performed and data is collected and displayed in real-time. The students copy the result on result sheets.
- The lecturer leads a brief discussion reflecting on why the results obtained make sense and how it relates to other answers.

Our idea has been to take the ILDs developed by Thornton and Sokoloff as a starting point for further adaptation and development. The already developed ILDs have then been adapted (and tested on) to Swedish students. Also some new interactive lecture demonstrations for rotary motion and rotary dynamics have been developed.

A typical physical setup for interactive demonstrations in a lecture hall is shown in figure 1. Besides, off course, the lecturer and the students, there are some kind of equipment for a physical experiment (in this case a car with low-friction wheels, with a fan as a source of force, moving on a track), equipment for measurement, processing and display of experimental data in real-time (In this case a motion sensor, an interface, a computer with suitable software and a screen on which the results are displayed. Sometimes called probeware.) and specially designed student worksheet (See figure 2 and 3). The probeware as well as the worksheets are essential for the interactive lecture demonstrations.

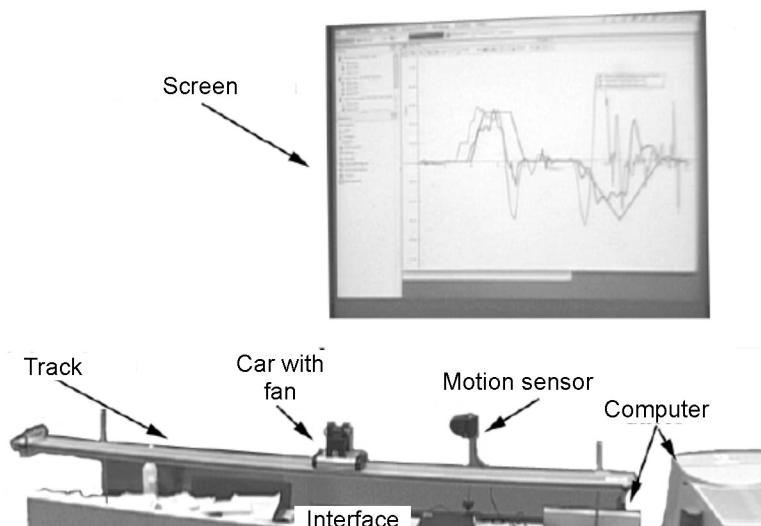


Figure 1. A typical setup in an interactive lecture demonstration.

According to a large body of research it is important that students establish a sound functional understanding of basic kinematics to be able to develop a sound understanding of dynamics. The first two sets of interactive lecture demonstrations are developed to meet this need. In figure 2 and 3 are displayed a lecture demonstration there a student volunteer is asked to try match the displayed velocity-time graph. Before this task a demonstration involving matching a position-time graph have been gone through.

This demonstration is somewhat different from most of the other interactive demonstration in so far that no prediction sheet is involved and that the student or the teacher performing the requested motion is the “experimental equipment”. In this case the actual motion performed has the role of prediction in other interactive demonstrations.

To solve this task successfully students have to make several important conceptual distinctions. For example they have to discern the differences between a position-time graph and a velocity-time graph. Further, they have to realise the *physical* meaning of constant velocity and of negative velocity and many other things.

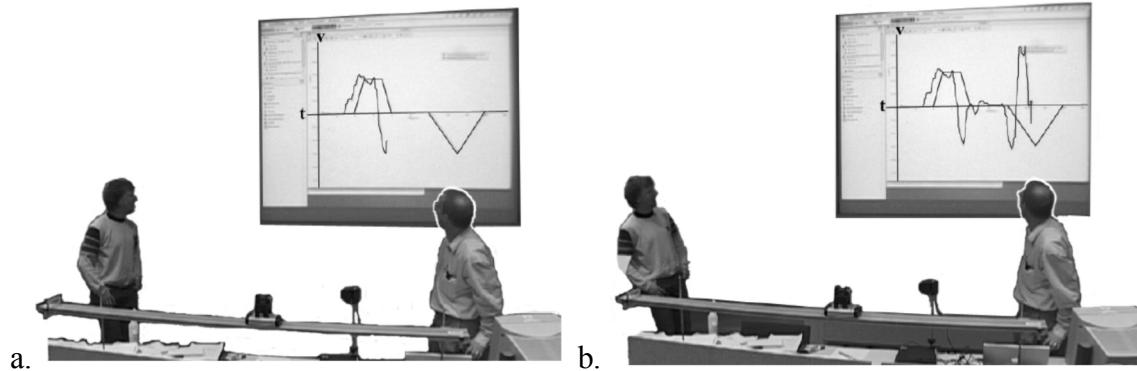


Figure 2. An evolving lecture demonstration. In front of the lecture hall a student volunteer is trying to walk a trajectory that would match a given $v(t)$ graph. In a) he has walked through the first part and in b) the later part of his motion is showed. The student as well as his peer and the lecturer can see the graph evolving in real-time at the same time as the actual walk.

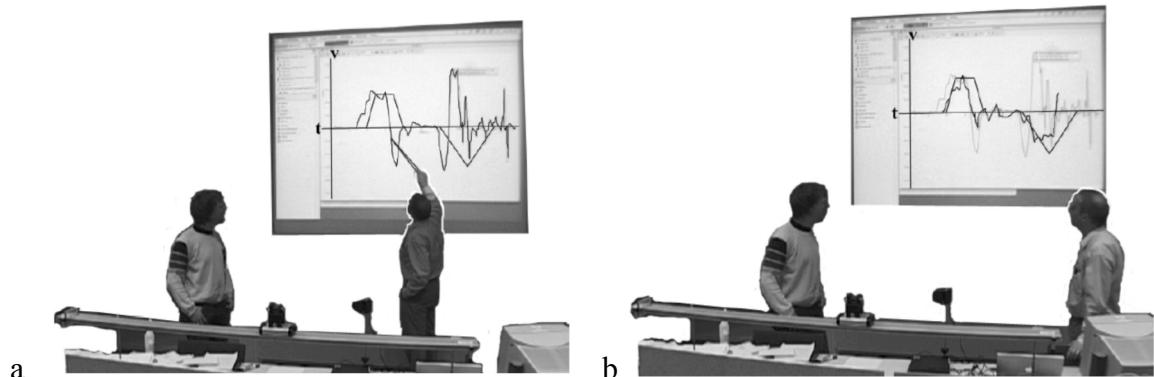
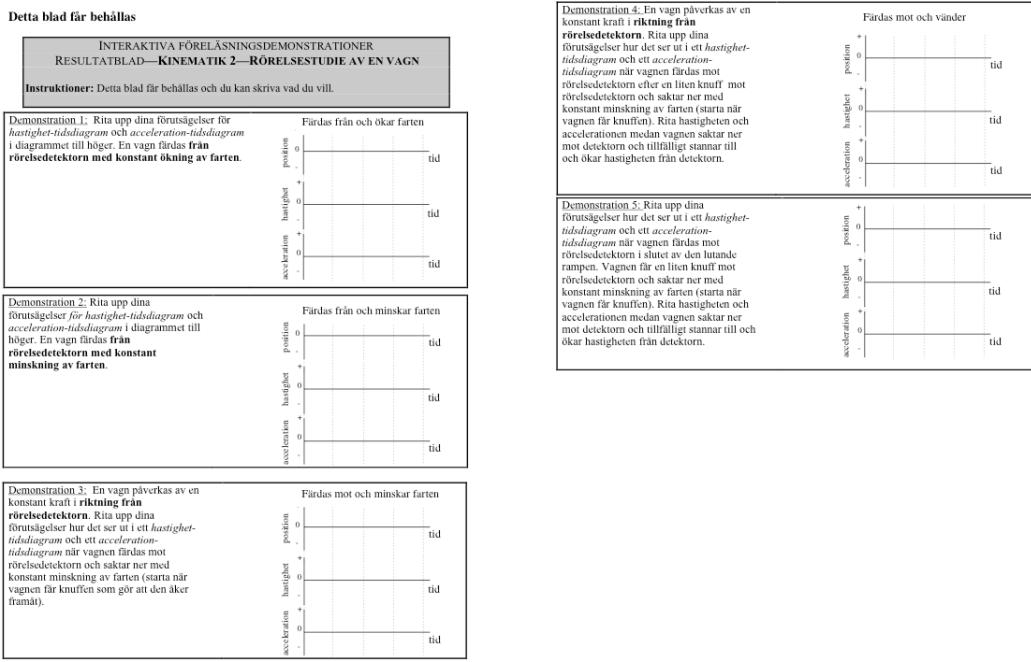


Figure 3. In a) the results are discussed by the lecturer, the student and the rest of the class and in b) is shown a second attempt with a resulting graph much more similar to the prescribed one.

Even when there is only one student at a time that can walk in front of the motion detector, students involvement in this demonstration are typically high. Below is now described another kinematics demonstration with excerpts from worksheets. In figure 4 is shown a worksheet.



Interaktiva föreläsningsdemonstrationer

1

Kinematik 2

Interaktiva föreläsningsdemonstrationer

2

Figure 4. Example of a student worksheet (In Swedish) used for making predictions and recording experimental outcomes. This worksheet is from one of demonstration series regarding kinematics.

The tasks in the interactive lecture demonstrations are chosen to focus on important conceptual issues. One example of this is negative velocity and that we can have non-zero acceleration even when the velocity is zero. In figure 5 is shown a demonstration where a car with low-friction wheels are given an initial velocity toward the motion detector. At the same time the fan mounted on the car provides a force in the opposite direction. Initially the car will move toward the motion detector, slow down until zero velocity is reached, the direction of motion will then change and the speed of the car will increase. The sequence described above is carried out, i.e. before the predictions and the discussion the demonstration is performed without making measurements.

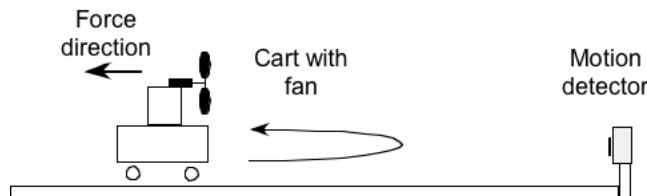


Figure 5. One of the demonstration tasks from the worksheet in figure 4. A low-friction cart is pushed towards a motion sensor. A fan unit attached to the cart provides an approximately constant force in a direction opposite to the initial movement and the cart will thus change its direction of motion. Example of a student's prediction and experimental results are shown in figure 6. Note that the fan unit provides a *visible* force.

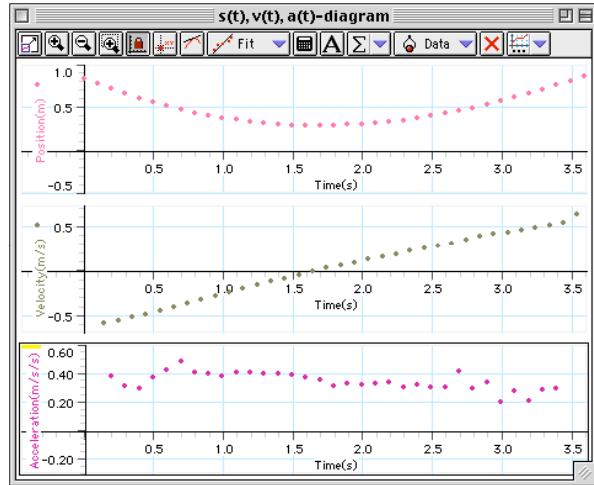
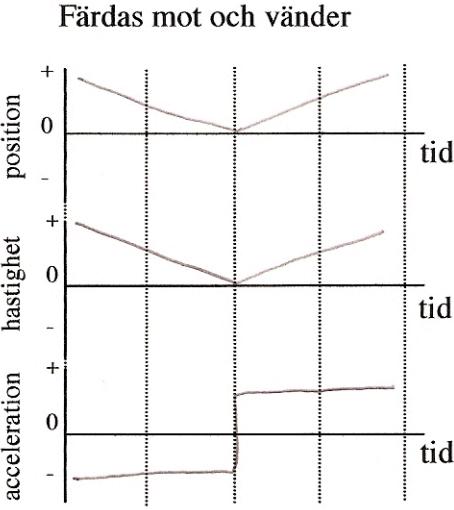


Figure 6. a) A prediction from a student regarding the motion described in the text and in figure 5 (Translation: hastighet = velocity, tid = time, färdas mot och vänder = moving toward then away). This student's conception of motion is not according to canonical physics. b) Experimental results showing, in this case, a discrepancy between student prediction and the actual results.

The task briefly described above and in figure 5-6 is designed to meet common learning difficulties in kinematics. In physics laboratory and in demonstrations it is common to use equipment with very low friction to show the “truth” of Newton’s laws. However our lifeworld are not free from friction, rather students’ should learn to consider friction within a Newtonian framework. If friction is excluded, it would typically lead to students not believing in Newton’s laws because absurd and counter-intuitive results. In the equipment used in the interactive lecture demonstrations it is possible vary friction and a frictionless world can be demonstrated as a limiting case.

In figure 7 is shown a demonstration involving friction. A cart with a friction attachment is given an initial push up an inclined plane. Students are asked to consider the forces involved and to sketch the resulting $v(t)$ and $a(t)$ -graphs. In figure 7b the results are shown.

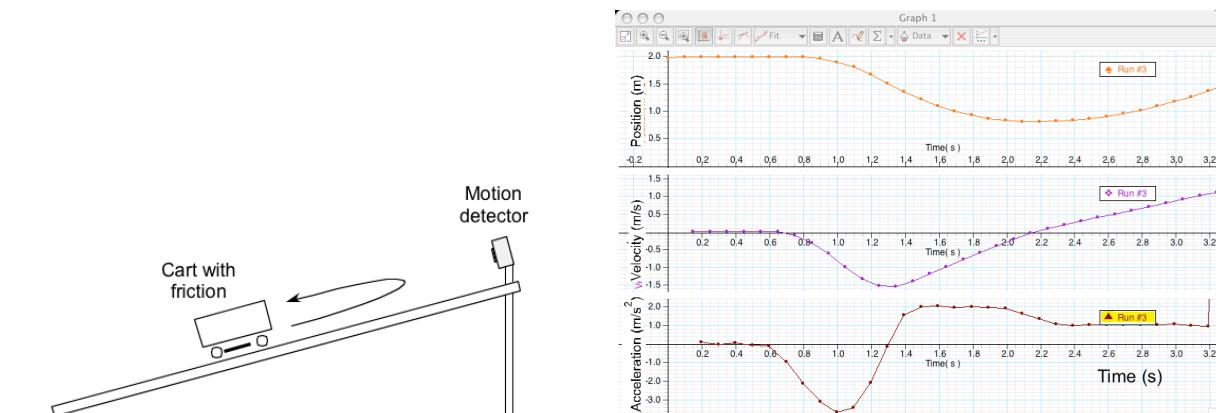


Figure 7. a) Demonstration involving a cart with friction given an initial velocity upwards along an inclined plane and b) the resulting experimental results.

The result in figure 7b displays the, maybe counter-intuitive, result that the acceleration is larger when the car is moving upwards than it is when moving downwards. This result is a good starting point for discussing the forces involved.

It is not possible in this report to discuss all demonstrations. The examples described should give some flavour of the technique of interactive lecture demonstrations.

RESULTS FROM CONCEPTUAL TESTS

To investigate the functional understanding in mechanics achieved by the students the research based conceptual test *Force and Motion Conceptual Evaluation* (FMCE, Thornton & Sokoloff, 1998) have been used. The test uses multiple-choice questions to assess student conceptual understanding of mechanics. The distractors (wrong answers) are carefully chosen and correspond to common sense beliefs (misconceptions) as shown in the research literature on misconceptions. The multiple-choice format of FMCE makes it feasible to do controlled large-scale educational studies. The FMCE have been shown by their developers to be reliable and valid measures of student conceptual understanding of basic Newtonian mechanics (Thornton & Sokoloff, 1998). Students response to the questions of FMCE in an open ended format correlates very well to their answers on the multiple-choice format.

The FMCE-test was given to the students on one of the first lectures as a pre-test (one lecture, 45 min, were set aside for this) and during one of the lectures after the mechanics part the test was administered as a post-test.

Students' achievements on the conceptual FMCE-test are presented in figure 8 and in table 1. In table 1 the calculated "normalised gain" is compared to "reformed" and more "traditional" mechanics curricula. According to the results presented in figure 8 our implementation of interactive lecture demonstrations have achieved better than more "traditionally" taught mechanics curricula, but not as good as in curricula using a fuller implementation of MBL-labs.

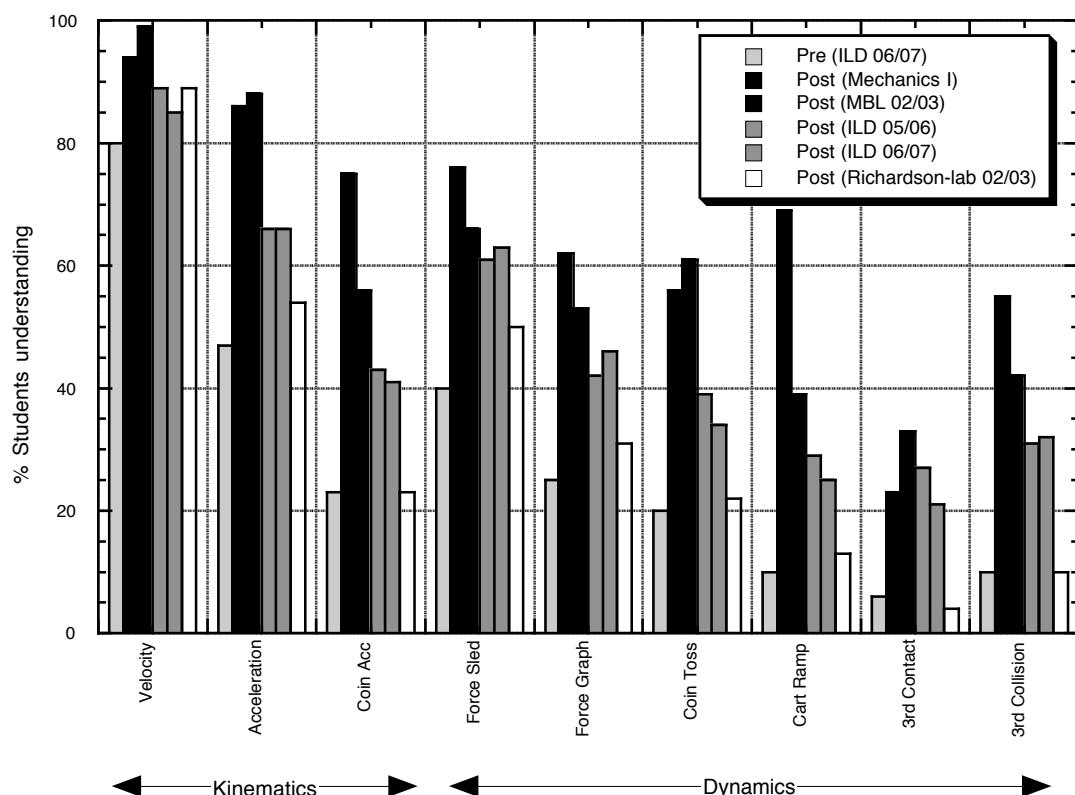


Figure 8. The results achieved, for different conceptual clusters, on the FMCE-test (Thornton & Sokoloff, 1998) by different courses in Sweden.

Teaching Method/Course	Norm. Gain (FMCE)	Reference
Traditional (USA)	16%	Saul and Redish (1998)
Traditional (Sweden)	18%	Bernhard (2005)
Workshop physics (USA)	65%	Saul and Redish (1998)
RealTime physics (secondary implementation, USA)	42%	Wittman (2002)
ILD (example of secondary implementation, USA)	26%	Redish (2003)
MBL 1997/98 (Sweden)	61%	Bernhard (2005)
Physics 02/03 (Sweden) MBL-labs	48%	Bernhard (2005)
ILD 05/06 (Sweden)	37%	This study

Table 1. Learning gains for different courses (Redish, 2003; Saul & Redish, 1998; Wittman, 2002) as measured by the FMCE-test (Thornton & Sokoloff, 1998).

Also table 1 display a similar picture as figure 8. Our implementation of interactive lecture demonstrations lead to better results on the FMCE-test than traditionally taught mechanics courses. However our implementations of MBL (MBL 1997/98 and Physics 02/03), which were inspired by RealTime physics, have lead to much better results. But as discussed above and will be briefly discussed below a full implementation of MBL demands more resources.

GOOD RESULTS, BUT COULD THEY BE IMPROVED?

As a conclusion an obvious question to ask is if the project have been successful and if we could recommend an institution to try to implement interactive lecture demonstrations. This question do not have a simple answer, rather it depends on the resources available.

If it is possible to implement a full set of MBL-labs such a curricula would probably lead to higher learning gains (However, see for example Bernhard (2003) and Sassi (2001) for implementation problems in MBL). If the resources are more limited interactive lecture demonstrations is way to go. Interactive lecture demonstration requires only one set of experimental equipment, one set of probeware, one computer and can be utilised in a lecture section. MBL requires a lab with several sets of experimental equipment, several sets of probeware, several computers and must be taught in several lab sections requiring more staff. However it should be remembered that interactive lecture demonstrations requires some (limited) time to setup before each lecture.

Another question to ask is if our results could be improved. The original developers of interactive lecture demonstrations Ron Thornton (Tufts university) and David Sokoloff (Oregon) have reported spectacular results with this approach (FMCE post-test 70-90% with pre-test ~20%) on the increase of student functional understanding of mechanics (Redish, 2003). However it's also reported from secondary users of ILD (see for example Johnston & Millar, 2000; Wittmann, 2002; and Redish, 2003) that it could be difficult to implement. In

our experience with interactive lecture demonstrations we have found it difficult to initiate whole-class discussions in a lecture setting. It might be that US students are more used to express them verbally in a classroom setting. However secondary implementations of ILD in the US have not got as good achievements as we have in this project. Still we suggest that the quality of classroom discussion might be critical factor (cf. Redish, 2003) and special training or extensive experience is crucial if the extremely high gains reported should be reached.

Therefore it is very important to be observant for crucial details and therefore we plan to continue assess this project with different methods. As mentioned above we have used conceptual tests. To identify crucial details (and also identify implementation problems), but also for documentation, we have videotaped most of the interactive lecture demonstrations (Figure 1-3 are from these videotapes). These videotapes have yet only been partially analysed. A cross-cultural comparison involving implementation of interactive lecture demonstrations at different institutions (with different outcomes on conceptual tests) in different countries would give valuable information for further development and for the understanding of crucial details. Also, in some cases, a combination of MBL-labs and interactive lecture demonstrations might lead to improved learning.

To conclude, we suggest that the use of interactive lecture demonstrations should be considered in cases where it is not possible to implement a full set of conceptual labs. The implementation of interactive lecture demonstrations show that it is possible to do reforms, and achieve active learning, in the framework of a lecture setting.

REFERENCES

- Bernhard, J. (1997). Experientially based Physics Instruction using hands on Experiments and Computers. Proceedings of PTEE 1997, Copenhagen.
- Bernhard, J. (2000). Teaching engineering mechanics courses using active engagement methods. Proceedings of PTEE 2000, Budapest.
- Bernhard, J. (2001). Does active engagement curricula give long-lived conceptual understanding? In R. Pinto & S. Surinach (Eds.), Physics Teacher Education Beyond 2000 (pp. 749-752). Paris: Elsevier.
- Bernhard, J. (2003). Physics learning and microcomputer based laboratory (MBL): Learning effects of using MBL as a technological and as a cognitive tool. In D. Psillos & K. P. & V. Tsifles & E. Hatzikraniotis & G. Fassoulopoulos & M. Kallery (Eds.), Science Education Research in the Knowledge Based Society (pp. 313-321). Dordrecht: Kluwer.
- Bernhard, J. (2005). Experientially based physics instruction - using hands on experiments and computers: Final report of project 167/96. Stockholm: Council for Renewal of Higher Education.
- Bernhard, J., & Lindwall, O. (2003). Approaching Discovery Learning. Proceedings of ESERA2003, Nordwijkerhout.
- Hake, R. R. (1997). Interactive-engagement vs traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. American Journal of Physics, 66, 64-74.
- Johnston, I., & Millar, R. (2000). Is There a Right Way to Teach Physics? CAL-laborate, 5.
- McDermott, L. C. (1997). How Research Can Guide Us In Improving the Introductory Course. In J. Wilson (Ed.), Conference on the Introductory Physics Course: On the Occasion of the Retirement of Robert Resnick (pp. 33-46). New York: John Wiley & Sons.
- Redish, E. F. (2003). Teaching Physics with the Physics Suite. New York: John Wiley.
- Sassi, E. (2001). Lab-work in physics education and informatic tools: Advantages and problems. In R. Pinto & S. Surinach (Eds.), Physics Teacher education Beyond 2000 (pp. 57-64). Paris: Elsevier.
- Saul, J. M., & Redish, E. F. (1998). An Evaluation of the Workshop Physics Dissemination Project. College Park: Dep. of Physics, University of Maryland.
- Thornton, R. K. (1997). Learning Physics Concepts in the Introductory Course: Microcomputer-based Labs and Interactive Lecture Demonstrations. In J. Wilson (Ed.), Proceedings Conference on Introductory Physics Course (pp. 69-86). New York: Wiley.
- Thornton, R. K., & Sokoloff, D. R. (1998). Assessing student learning of Newton's laws: The Force and Motion Conceptual Evaluation and the Evaluation of Active Learning Laboratory and Lecture Curricula. American Journal of Physics, 66(4), 338-352.
- Wittman, M. (2002). On the dissemination of proven curriculum materials: RealTime Physics and Interactive Lecture Demonstrations. Orono: Dep. of Physics and Astronomy, University of Maine.