Research paper

Improving engineering students’ learning through the use of a variation approach: Examples from a research-based learning environment in mechanics

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Abstract

In this paper I describe a study where 25 students of a total of 111 taking a physics course for engineering students participated in 16 hours of alternative, conceptual, labs instead of 16 hours of regular, non-conceptual, labs. All students participated in the same set of lectures and the same problem-solving sessions. A feature of the conceptual labs is the use of technology as a tool to aid students’ inquiry. In addition, systematic variation, based on the theory of variation, has been introduced into the design of the assigned tasks. Results from a “Force and Motion Conceptual test (FMCE)” show a marked difference in achievement, with normalised gain of 48% for the students participating in the conceptual labs and 18% for the students participating in the non-conceptual labs. Some data from video-recordings of student courses of action in the conceptual labs are also presented.

Keywords: Engineering education research, design-based research, lab-work, learning environment, variation theory, conceptual learning.

1. Background, aims and framework

“It’s good that you are bored” says grandmother to her son and grandson in the Swedish storybook Happy Alfie Atkins [Lycklige Alfons Åberg] [1]. Father and son are bored and unhappy because Christmas holidays are about to end, and Alfie’s best friend has mumps so can’t come and play. They start to fantasize that it should be either Christmas or a birthday every day. However, grandmother brings them back to reality by telling them “it’s good that you are bored” since “otherwise you wouldn’t appreciate having fun”.

This storybook captures very well the essence of Variation theory developed by Ference Marton and co-workers [15]. According to this theory, the experience of difference (variation), rather than the recognition of similarity, is most important for learning. For Alfie and his father to even be able to experience “fun” and “happiness” they need to experience “boredom” and “sadness”, as the wise grandmother points out. Similarly, according to Variation theory, to be able to discern concepts such as weight we need to experience both heavy and light objects. In contrast, it is widely believed that learning requires confirmation and the recognition of similarities, in accordance with the Latin phrase “Repetitio est mater studiorum” (“the mother of all learning is repetition”). However, as pointed out by Marton and Trigwell [14], “repetition” is not necessarily restricted to mechanical repetition of precisely the same thing again and again. The optimal kind of repetition could be doing similar, but slightly varied, things

One important aim in engineering education is that students should not only learn to understand theories and models and their relation to objects and events, but also learn to use and apply these models and theories. Especially during lab-work, students are expected to link observed data to theoretical models and to the objects and events they are exploring [18, 27]. However, according to a large body of research, establishing relevant connections between concepts, representations, theories/models and observable objects and events is a very difficult task for students [16, 30]. Further, although it has been well-known for some time that acquiring a conceptual understanding of mechanics is one of the most difficult challenges faced by students very few successful attempts to
bring conceptual learning about are described in the literature. On the contrary, research has shown that most students participating in an university level course had not acquired a Newtonian understanding of mechanics at the end of the course [e.g. 3, 5, 12, 16, 17, 23].

For students’ learning it is important that the learning environment enables them to focus on the object of learning and discern its critical features. Recently, I described 10 years of experiences of designing and using conceptual labs in engineering education that have successfully fostered insightful learning [5]. A conceptual lab is described as “one that helps students to develop fruitful ways of linking concepts and models to objects and events [3]. Furthermore, it is a place of inquiry, where students’ ‘ways of seeing or experiencing … the world [are developed]’; i.e. the lab is an arena for further learning and not simply for the confirmation of theories and formulas that have already been taught in lectures” [5]. A common feature of these labs is that they make use of a technology called probe-ware or Microcomputer-Based Labs (MBL).

Probe-ware systems were introduced into physics teaching almost three decades ago and are good examples of the use of interactive technology in physics education [28]. They consist of a sensor or probe connected to a computer, which analyses data collected by the probe, and transforms experimental data directly into a graph on the computer screen. When using probe-ware, students can perform experiments using a range of different sensors to gather data on variables such as force, motion, temperature, light or sound. The simultaneous collection, analysis and display of experimental data is sometimes referred to as real-time graphing. The immediacy of this technology allows the design of labs that foster a functional understanding of physics most effectively [9, 22, 23, 28]. It has been proposed [19, 24] that the following characteristics of learning environments using probe-ware are primarily responsible for the learning achievements reported: “1. Students focus on the physical world. 2. Immediate feedback is available. 3. Collaboration is encouraged. 4. Powerful tools reduce unnecessary drudgery. 5. Students understand the specific and familiar before moving to the more general and abstract. 6. Students are actively engaged in exploring and constructing their own understanding.”

However in an earlier paper [3] I have demonstrated that not all labs using probe-ware lead to high post-course achievements in mechanics conceptual tests. Lindwall [13] has analysed different learning environments and argues that many other environments fulfil conditions 1-6 described above, but without achieving good results in conceptual tests. In this paper I present an analysis of task structure and students’ courses of action in mechanics conceptual labs, using variation theory as an analytical tool. I also report that a change of only 16 hours of labs, with the rest of the course unchanged, led to clearly significant improvements in students’ conceptual understanding of mechanics.

2. Methodology and object of study

2.1 Methodology for evaluating labs

The research-based conceptual test Force and Motion Conceptual Evaluation (FMCE) has been used to investigate the functional understanding of mechanics attained by the students. The test presents multiple-choice questions to assess students’ conceptual understanding of mechanics. The distractors (wrong answers) are carefully chosen to correspond with common-sense beliefs (misconceptions) as shown in the research literature on misconceptions. The multiple-choice format of FMCE makes it feasible to conduct controlled, large-scale educational studies. The FMCE has been shown, by its developers, to provide reliable and valid measures of students’ conceptual understanding of basic Newtonian mechanics [25]. The FMCE-test was taken by the students both during one of the first lectures, as a pre-test, and after the course as a post-test. In Figure 1a pre-test data are presented as ‘absolute’ values for different conceptual clusters, while in Figure 1b the data are presented using a measure called normalised gain [9], defined as $g = \text{Gain}/\text{Gain(max possible)}$ where Gain is the difference between pre- and post-test values. Normalised gain provides a measure that can be used to compare courses in terms of their enhancement of test achievements, by comparing normalised pre- and post-test values.
Results of my earlier studies show that the students achieve better results (using the FMCE-test as a measure of success) if we create lab-instructions that apply teaching strategies in line with variation theory than if the teacher adopts a non-conceptual approach [3, 5]. This led to the following questions: i) Which aspects of the learning environment direct the students towards the intended object of learning? ii) How can we further develop these aspects?

To help answer these questions students’ courses of action in labs have been recorded using digital camcorders. The data have been used to detect typical interaction patterns and find evidence supporting, or refuting, hypotheses regarding the generality of these patterns [11]. In the analysis I have focused on central characteristics of learning environments to explore what the students do and the resources they use, see [See, 13, for a review and more details] for a review and more details.

2.2 Setting and object of study

As part of a larger study [5], the students taking the mechanics part of an introductory physics course for engineering students were offered, in the academic year 2002 – 2003, the option to take an alternative “conceptual” lab-course (details of the labs are described below). The alternative “conceptual” lab-course as well as the regular “non-conceptual” lab-course consisted of four 4-hour lab-sessions, i.e. a total of 16 hours of labs. However, it should be noted that all students followed the same set of 20 hours lectures (with all students in a lecture hall) in mechanics and participated in similar sets of 12 hours problem-solving sessions (with groups of approximately 30 students led by a doctoral student). Thus the only difference between the groups, in terms of teaching, was the 16 hours of labs. The features of the alternatives are summarised in table 1.

![Table 1. Organisation of the mechanics part of the physics course for engineering students.](image)

The students participating in the alternative conceptual labs were volunteers since for formal reasons students could not be randomly assigned to groups. As can bee seen in figure 1a, the pre-course conceptual understanding of mechanics of the two groups was very similar, with close to negligible differences.

The labs in the alternative conceptual lab course were a subset (4×4 h) of conceptual labs used in an earlier conceptual lab-course (7×4 h) utilising probe-ware technology and instructions in line with active learning [e.g. 2, 4].

Motion: This lab introduces kinematics concepts, using probe-ware, and the tutorial software Graphs and Tracks I & II.
Force and motion I: The aim of this lab is to give a conceptual understanding of the relationship between position, velocity, acceleration and force with “friction-less” motion using probe-ware technology.
Force and motion II: This lab continues the study of dynamics (Newton’s first and second laws). Cases with friction are also studied.
Impulse and collisions: This lab uses force sensors to measure forces during collisions (Newton’s third law) and to experimentally study the impulse - momentum law.
The regular labs were so-called Richards’ labs [20] in which students explore the relationship between different physical variables for a given physical set-up, e.g. a bifilar pendulum. These labs are not typical “cookbook labs” and students are free to choose their own procedures, hence the labs could be categorised as inquiry type labs. According to, for example, Trumper [29, p. 658] a common attribute of successful physics laboratory activities “is that they are learner-centered. They induce students to become active participants in a scientific process in which they explore the physical world, analyze the data [and] draw conclusions”. Hence it could be expected on theoretical grounds that the regular Richards’ labs in this course should be successful in bringing conceptual learning about.

3. Results

3.1 Results from Force and Motion Conceptual Evaluation (FMCE)

The FMCE pre-test results are presented in Figure 1a. Although students could not be randomly assigned to the groups, the between-group differences in pre-course conceptual understanding of mechanics were very small, almost negligible. The difference between the groups’ pre-test average values is not statistically significant (t = 0.58, p = 0.36). In Table 2 the normalised gains of the students taking each of the lab-courses are summarised (and compared with those taking other courses) and in Figure 1b the data are presented for different conceptual domains.

![Figure 1a](image1.png)
![Figure 1b](image2.png)

Figure 1. a) Absolute pre- and post-course FMCE-test results for students participating in the conceptual and non-conceptual lab-courses. b) Comparison of the achievements of the two groups of students, using normalised gain.

The differences in results between the regular (non-conceptual) and the alternative (conceptual) labs are striking. The students participating in the conceptual labs achieved a normalised gain of 48%, compared to just 18% for the students participating in the non-conceptual labs. This difference is strongly statistically significant (t = 2.93, p = 0.0003). In Figure 1b it can be seen that there is a large difference in normalised gain for all conceptual clusters in the FMCE-test, especially for the element related to Newton’s 3rd law (contact forces and forces in collisions).

3.2 Analysis of task structure and results from analysis of video recordings

Space does not permit the presentation of multiple examples and extensive transcripts. However one example will be discussed in some detail below, accompanied by an analysis of the task structure and some transcripts from students’ courses of action.

**Acceleration with zero velocity.** In this activity students monitor the motion of a cart propelled by a fan that provides almost constant acceleration (see Figure 2a). The students give the cart an initial push in the opposite direction to that in which the force of the fan is acting, so that the cart will slow down and reverse its direction of motion. They do this after studying the motion of the
cart without reversing its direction, but with acceleration in different directions. Students are first asked to observe the motion of the cart (without measuring it) and then to sketch their predictions of how the motion will be represented by position-time, velocity-time and acceleration-time graphs. After they have made their predictions the motion of the cart is once more observed and this time the probe-ware equipment is used to measure the motion, and simultaneously display it as a graph (a typical graph is shown in Figure 2b). To make accurate predictions, not only do the differences between position, velocity and acceleration have to be discerned, but also the relationships between these concepts. Velocity and position vary, but students have to recognise that the acceleration is constant, and that a zero velocity does not imply that the acceleration is zero - as is commonly believed. Asking the students to make predictions before the experiment is performed facilitates comparisons between their thinking and reality, i.e. a variation in the space of thinking models. Students thus have the opportunity to discriminate between different “models” and see which is the most powerful. In excerpt 1, below, students discuss what the acceleration should be when the velocity is zero at the cart’s turning point, and what the acceleration-time graph should look like around this point.

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Excerpt 1

1. Beata here I don’t think the acceleration will be constant
2. Cecilia no for it will only [increase then
3. Beata [it will
4. Cecilia =stop then
   ((a few turns are missing here due to a change of tape))
5. Beata something like that increases
   ((makes a sketch))
6. Cecilia then it becomes zero
7. Beata =for a little while when it turns

The students suggest that the acceleration “becomes zero for a little while when it turns”. However, after performing the actual experiment Cecilia finds that “the acceleration turns out strange”; contrary to their prediction it is not zero, as shown in Figure 2b. After discovering that their prediction was not correct, and the acceleration was not in fact zero, the students discuss the results for a long time and finally in excerpt 2 they decide to ask the instructor.

Excerpt 2

1. Beata it is so [strange
2. Cecilia [acceleration in this case
3. Cecilia the acceleration can’t be constant (.) since it stops and when it starts again
4. Cecilia can it be constant?
5. JONTE yes
6. Cecilia for it feels [weird

After some discussion between the students’ and instructor the issue is resolved in excerpt 3.
Excerpt 3
1. JONTE there you have zero (.) but if you look at delta v:: even at this point
2. Cecilia =you mean that the velocity doesn’t change much
3. JONTE no but you [have you
4. Beata [no
5. JONTE the whole time a constant [change in velocity
6. Cecilia [okay
7. JONTE =per unit of time
8. Cecilia yes
9. Beata if you have a straight line (.) you will have the same slope on it (.)
   then you will have the same acceleration the whole way (3.7)
10. Cecilia *mi:*!
11. Beata because acceleration is
12. Cecilia [it’s because
13. Beata [=the derivative of velocity

As can be seen in the excerpt above, it took several turns before the students realised in the final
turns why acceleration is not zero when the velocity is zero at the turning point.

As a general finding, analysis of video recordings from the conceptual labs showed that students’
courses of action are framed by encounters with the instructions, the technology, the teacher, and
other students, as can be seen in the excerpts above. When using the technology, students receive
immediate feedback. In the process of constructing graphs they can see when they make mistakes.
Students intertwine different interpretative resources as well as different experiential domains,
such as graphical shapes, with narrative accounts of past actions. Learners must focus on the
central aspect of the graph and, in order to complete the assignments, they have to make certain
conceptual distinctions. The instructions for the task specify the process and both the variance and
invariance in the learning space. In order to solve the tasks successfully, the students have to deal
with certain concepts in certain ways. Teachers not only design the learning environment, choose
the technology and write the instructions, but also support students’ activities in the lab, including
encouraging students to shift their attention to central features of the graph while down-playing
less important aspects. Students have a common perspective of the graph and negotiate their
different interpretations of the graphical representation, experiment, and subject matter.
Discussions are made an important component of the process of solving the task. It should be
noted that the technology is present in all encounters.

4. Discussion, conclusion and implications

As pointed out in the introduction, a necessary condition for learning is that students are able to
focus on the object of learning and discern its critical features. A way to establish this, according
to the theory of variation developed by Marton and co-workers, is through the experience of
difference (variation), rather than through the recognition of similarity [15]. In a lab, an
experiential human–instrument–world relationship is established [10]. The technology used
places some aspects of reality in the foreground, others in the background, and makes certain
aspects visible that would otherwise be invisible. In labs, this can be used to bring critical features
of the object of learning into the focal awareness of students and to afford variation.

To solve the tasks in the labs students have to make conceptual distinctions between different
concepts of motion such as position, velocity and acceleration, i.e. develop from an
undifferentiated notion of “motion” to a differentiated conceptual understanding, such as that
presented in the acceleration example, when the cart’s velocity (but not acceleration) is
momentarily zero. One may be surprised that students did not learn this in high-school physics
courses. However, a large body of research shows that the data presented in Figure 1 are not
atypical for either high-school or university level students [e.g. 3, 5, 12, 16, 17, 23]. In the
example, the students would probably not have discovered the falsity of their belief that zero
velocity implies that acceleration is also zero, or that acceleration is in the direction of motion
without the combined guidance of probe-ware technology and instructions. In other tasks the
velocity is put in the foreground by the probe-ware technology and the instructions, so students
are more or less forced to realise the differences between constant position and constant non-zero
velocity, and between negative and positive velocity. In still other tasks the masses of colliding
cars are varied and students’ are led to the conclusion that the force sensors on the carts show the same forces, regardless of the mass and speed of the different carts. The task presented in the example, and the tasks in some labs, could seem to be almost too simple for a university level course. However, as pointed out by Laws [12], a thorough understanding of kinematics is essential for the understanding of dynamics.

<table>
<thead>
<tr>
<th>Teaching Method/Course</th>
<th>Norm. Gain (FMCE)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics 02/03 (Sweden) Conceptual labs</td>
<td>48%</td>
<td>This study</td>
</tr>
<tr>
<td>Physics 02/03 (Sweden) Non-conceptual labs</td>
<td>18%</td>
<td>This study</td>
</tr>
<tr>
<td>Traditional (USA)</td>
<td>16%</td>
<td>Saul and Redish [21]</td>
</tr>
<tr>
<td>Workshop physics (USA)</td>
<td>65%</td>
<td>Saul and Redish [21]</td>
</tr>
<tr>
<td>RealTime physics (secondary implementation, USA)</td>
<td>42%</td>
<td>Wittman [31]</td>
</tr>
<tr>
<td>Conceptual labs 1997/98 (Sweden)</td>
<td>61%</td>
<td>Bernhard [4]</td>
</tr>
</tbody>
</table>

Table 2. Learning gains for different courses in mechanics as measured by the FMCE-test [25].

As displayed in table 2, the learning gains are much higher for the conceptual labs than for the regular courses, and much higher than for traditionally taught courses. The course compares very well with secondary implementations of RealTime Physics. However, the normalised gain from the conceptual lab-course considered here is slightly lower than the gain obtained from an earlier conceptual lab-course (1997/98), since it included fewer lab sessions.

Probe-ware technology is not, in itself, sufficient for the effective learning of mechanics. In a previous study [3], I showed that labs using probe-ware can be effective for learning mechanics, but that this technology can also be implemented in ways that lead to low achievements. However, the normalised gain from the conceptual labs considered here is slightly lower than the gain obtained from an earlier conceptual course (1997/98), since it included fewer lab session. According to my analysis, the necessary patterns of variation were not included in the design.

The design of instructions, and hence task structure, seems to be important for student learning according to variation theory. In other studies I have shown that this theory can be used to design learning environments for interactive lecture demonstrations and learning electric circuit theory [5-7]. Hence, I argue that my results corroborate variation theory and show that this theory can be used as a ‘tool’ for designing labs to promote conceptual understanding [cf. 8, 26].

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References