Learning in the laboratory through technology and variation: A microanalysis of instructions and engineering students’ practical achievement

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ABSTRACT
Mechanics, first experienced by engineering students in introductory physics courses, encompasses an important set of foundational concepts for success in engineering. However, 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 engender conceptual learning have been described in the literature. On the contrary, research has shown that most students participating in university level courses had not acquired a Newtonian understanding of mechanics at the end of their respective courses.

Recently I have described more than 10 years of experiences of designing and using conceptual labs in engineering education that have successfully fostered insightful learning. In the framework of the larger project I have developed labs applying variation theory in the design of task structure and using sensor-computer-technology (“probe-ware”) for collecting and displaying experimental data in real-time. In previous studies, I have shown that these labs using probe-ware can be effective in learning mechanics with normalised gains in the g≈50-60% range and with effect sizes d≈1.1, but that this technology also can be implemented in ways that lead to low achievements.

One 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. In a lab, an experiential human–instrument–world relationship is established. 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.

In this study, I will account for how the design of task structure according to variation theory, as well as the probe-ware technology, make the laws of force and motion visible and learnable and, especially, in the lab studied make Newton’s third law visible and learnable. I will also, as a comparison, include data from a mechanics lab that use the same probe-ware technology and deal with the same topics in mechanics, but uses a differently designed task structure. I will argue that the lower achievements on the FMCE-test in this latter case can be attributed to these differences in task structure in the lab instructions. According to my analysis, the necessary pattern of variation is not included in the design.

I will also present a microanalysis of 15 hours collected from engineering students’ activities in a lab about impulse and collisions based on video recordings of student’s activities in a lab about impulse and collisions. The important object of learning in this lab is the development of an understanding of Newton’s third law. The approach analysing students interaction using video data is inspired by ethnmethodology and conversation analysis, i.e. I will focus on students practical, contingent and embodied inquiry in the setting of the lab.

I argue that my result corroborates variation theory and show this theory can be used as a ‘tool’ for designing labs as well as for analysing labs and lab instructions. Thus my results have implications outside the domain of this study and have implications for understanding critical features for student learning in labs.

Keywords
Lab-work, conceptual change, variation theory, tool-mediated learning.

1. INTRODUCTION
“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 [2]. 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 “Repetito est mater studiorum” (“the mother of all learning is repetition”). However, as pointed out by Marton and Trigwell [3], “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 [4, 5]. 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 [6, 7]. 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. 7, 8-12]. As is demonstrated in figure 1 obtaining a conceptual understanding of Newton’s 3rd law is especially difficult for most students and only 5-10% of university level students could correctly answer the the 3rd law questions in the FMCE-test [13] after studying introductory mechanics with conventional instruction.

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 [12]. A conceptual lab is described as “one that helps students to develop fruitful ways of linking concepts and models to objects and events [11]. 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” [12].

In recent decades there have been many attempts to create learning environments that are not only exploratory, but also direct students’ attention towards relevant concepts and phenomena in a process known as guided discovery [14, 15] or interactive-engagement [16]. Labs adopting these processes foster an inquiry-driven learning environment in which students are guided in their inquiry by carefully designed instructions, technology, and teacher support. Examples include curricular projects such as Workshop Physics [9, 17], RealTime Physics [18, 19], and Tools for Scientific Thinking [20]. A common feature of these projects 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 [21]. 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 [8, 16, 21, 22]. It has been proposed [23, 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 [11] I have demonstrated that not all labs using probe-ware lead to high post-course achievements in mechanics conceptual tests. Lindwall [25] has analysed different learning environments and argues that many other environments fulfill 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.

Figure 1. Student’s understanding of some different conceptual clusters in mechanics after High-school (pre) and after non-conceptual university level courses (post) based on results on the FMCE-test [13].
2. THEORETICAL FRAMEWORK

2.1 Variation theory
As described briefly in the introduction, most students do not change their conceptions of mechanics concepts, i.e. they do not change their ways of seeing the world using force and motion concepts from a naive to Newtonian understanding, even after one or more university level course(s) in mechanics. Hence, teaching and learning in mechanics need to be developed to engender “conceptual change” in order to heighten students’ “ways of seeing” (and understanding) physical phenomena. Learning is seen as developing students’ ways of experiencing the world to develop capabilities to handle novel situations in powerful ways [26, 27]. My view is close to the view about conceptual change described by F. Marton and M.-F. Pang [28]: “Perception is seen as discernment (and not construction, for instance), and our concern is primarily the differences between different ‘ways of seeing’ Above all, our answer to the question ‘What changes in conceptual change?’ is different from the answers suggested by other theorists. In our view it is the world, the world seen, the world lived that changes. (p. 542)”

Variation theory, developed by Marton and co-workers [2, 29-34], provides an explanatory framework describing the conditions required for learning. Central to this theory is the notion that we learn through experiencing differences, rather than recognizing similarities. Central concepts in variation theory are discernment, simultaneity and variation. Learning is seen as the process of developing certain capabilities and values that enable the learner to handle novel situations effectively. Powerful ways of acting emerge from powerful ways of seeing. Thus, aspects that can be discerned by the observer determine how something is seen in a particular way. People discern certain aspects of their environment by experiencing variation. When one aspect of a phenomenon or an event varies, while one or more aspects remain the same, the one that changes is the one that will be discerned. One of the main themes of variation theory is that the pattern of variation inherent in the learning situation is fundamental to the development of certain capabilities. It should be noted that ‘discerning’ is not the same as being ‘being told’.

Experiencing variation amounts to experiencing different instances simultaneously. This simultaneity can be either diachronic (experiencing, at the same time, instances that we have encountered at different points in time) or synchronous (experiencing different co-existing aspects of the same thing at the same time.

2.2 Mediating tools
According to variation theory an important condition for learning is that students are able to focus on the object of learning and discern its critical features. An essential part of a lab is the use of appropriate kinds of instrumentation to study an experimental set-up or natural phenomenon. Thus, a human experience in the laboratory is a mediated experience [35-37] and the relationship can schematically be expressed as [38, 39]:

Human ⇔ Instrument ⇔ World.

In science, instruments do not merely “mirror reality”, but mutually constitute the reality investigated. This technology can be used to place some aspects of reality in the foreground, others in the background, and to make certain aspects readily visible that would otherwise be invisible or difficult to perceive [38-40]. Technology can thus be used in conceptual labs to frame our experience or give shape to the figure-background relationship [37, 41, 42] and hence bring critical features into the focal awareness of students and highlight any relevant variation.

3. METHODOLOGY AND OBJECT OF STUDY

3.1 Setting and object of study
This study is part of a series of projects [12] that were focused on the design and implementation of “conceptual labs” inspired by the success of the curricula such as RealTime Physics.

In this paper the focus will be on a lab entitled impulse and collisions. In four cases (I, III-V) a similar design using probe-ware and utilising a task structure in line with the recommendations of variation theory (“conceptual labs”). In case II [11] an instructor used probe-ware but transformed the original task structure into a formula-verification structure (“non-conceptual labs”). Finally cases V-VI are part of the same general physics courses where students as volunteers could chose, as part of an experiment, to participate in the conceptual lab-course (case V) instead of the regular lab-course (case VI) [43].

Table 1. Overview of the different cases discussed in this paper.

<table>
<thead>
<tr>
<th>Case</th>
<th>Lab</th>
<th>Year</th>
<th>number of students</th>
<th>Main student body</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Probe-ware conceptual</td>
<td>97/98</td>
<td>40</td>
<td>Engineering</td>
</tr>
<tr>
<td>II</td>
<td>Probe-ware non-conceptual</td>
<td>98/99</td>
<td>31</td>
<td>Student-teachers</td>
</tr>
<tr>
<td>III</td>
<td>Probe-ware conceptual</td>
<td>99/00</td>
<td>25</td>
<td>Student-teachers</td>
</tr>
<tr>
<td>IV</td>
<td>Probe-ware conceptual</td>
<td>00/01</td>
<td>20</td>
<td>Student-teachers</td>
</tr>
<tr>
<td>V</td>
<td>Probe-ware conceptual</td>
<td>02/03</td>
<td>25</td>
<td>Engineering</td>
</tr>
<tr>
<td>VI</td>
<td>non-conceptual</td>
<td>02/03</td>
<td>86</td>
<td>Engineering</td>
</tr>
</tbody>
</table>

3.2 Task-structure
In this section I examine examples of tasks in labs used in the different cases and focus on an analysis of the tasks in terms of discernment, simultaneity and variation.

In table 2 is summarised the structure of tasks related to Newton’s 3rd law in the probe-ware labs in cases I and III-V. Two carts are placed on a track and on each cart a force-sensor is mounted and connected to a computer through an interface. Two motion sensors in each end of the track measure the motion of the carts. One or both of the carts are set in motion and collides. During the experiment the forces and the acceleration are measured and displayed in real-time on the computer screen. A predict-observe-explain cycle is used and before each
In an experiment with a single cart running toward a stop. In this case a force-sensor is mounted on the cart and the velocity is measured and the students are asked to verify the impulse-momentum law.

In terms of variation of the motion and masses of the colliding carts the task structure is similar in the conceptual (case I and III-V) and non-conceptual (case II) labs. However there are critical differences in terms of discernment and simultaneity. In the conceptual labs forces and accelerations are measured and displayed in graphical form in real-time during the experiments. Students are also instructed to do predictions of accelerations and forces before each experiment. On the other hand in case II no measurement of force is made; instead velocity is measured, and students are not asked to do any prediction of forces. Students are asked to verify Newton’s 3rd law after the measurements are done, but to do so requires a two-step calculation. Hence the term non-conceptual is used for the lab in case II since the forces are not discerned simultaneously with the experiment.

Table 2. Overview of task structure used in the impulse and collisions lab in cases I and III-V (probe-ware conceptual).

<table>
<thead>
<tr>
<th>Task</th>
<th>Cart 1 Motion</th>
<th>Cart 2 Motion</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>still</td>
<td>moving</td>
<td>$a_1, a_2, F_1, F_2$</td>
</tr>
<tr>
<td>2</td>
<td>moving</td>
<td>moving</td>
<td>$a_1, a_2, F_1, F_2$</td>
</tr>
<tr>
<td>3</td>
<td>still</td>
<td>moving</td>
<td>$a_1, a_2, F_1, F_2$</td>
</tr>
<tr>
<td>4</td>
<td>moving</td>
<td>moving</td>
<td>$a_1, a_2, F_1, F_2$</td>
</tr>
<tr>
<td>5</td>
<td>The light cart (“car”) is pushing the heavy cart (“truck”)</td>
<td></td>
<td>$F_1, F_2$</td>
</tr>
</tbody>
</table>

In table 2 is summarised the structure of tasks related to Newton’s 3rd law in the probe-ware labs in cases I and III-V. Two carts are placed on a track and on each cart a force-sensor is mounted and connected to a computer through an interface. The motion of the carts was measured by two motion sensors in each end of the track. One or both of the carts is given a push towards the other cart and collides in an elastic collision (due to magnetic bumpers). During the experiment the forces and the acceleration are measured and displayed in real-time on the computer screen. A predict-observe-explain cycle is used and before each experiment the students are instructed to predict the accelerations and forces for the two carts.

To address the common (mis-)conception that only a moving object exerts a force when colliding with an object that stands still experiments are made with one of the carts in rest and one set in motion (task 1, 3 and 4) and with both carts set in motion (task 2). In tasks 3 and 4 extra mass is put on one of the carts to address the conception that an heavier object exerts a larger force than a lighter object. Finally in task 5 the conception that only the cart pushing another object exerts a force is addressed.

Table 3. Overview of task structure used in the impulse and collisions lab in case II (probe-ware non-conceptual).

<table>
<thead>
<tr>
<th>Task</th>
<th>Cart 1 Motion</th>
<th>Cart 2 Motion</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>still</td>
<td>moving</td>
<td>$v_1, v_2$</td>
</tr>
<tr>
<td>2</td>
<td>moving</td>
<td>moving</td>
<td>$v_1, v_2$</td>
</tr>
<tr>
<td>3</td>
<td>still</td>
<td>moving</td>
<td>$v_1, v_2$</td>
</tr>
<tr>
<td>4</td>
<td>moving</td>
<td>still</td>
<td>$v_1, v_2$</td>
</tr>
</tbody>
</table>

The task structure in the case II impulse and collision lab is summarised in table 3. On a first look it looks very similar to the task structure used in cases I and III-V. However there are important differences. In case II force is never measured during the collisions but only the velocities. Students are asked to predict the velocity graphs but are not asked to predict forces. The students are instructed from the measurement of the velocities $v_1$ and $v_2$ calculate the momentum ($p=mv$) and the kinetic energy ($K=\frac{1}{2}mv^2$). In a second step they are asked to verify that Newton’s 3rd is valid (This can be done by taking the time derivative of the momentum $F=dp/dt$). As a forerunner to the collision experiment the students in case II are asked to do an experiment with a single cart running toward a stop. In this

3.3 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 [13]. The FMCE-test was taken by the students during one of the first lectures, as a pre-test, and after the course as a post-test. In Figure 1 and 2 pre- and post-test data are presented as ‘absolute’ values for

![Figure 2](image-url)  

Figure 2. Student’s understanding of some different conceptual clusters in mechanics after High-school (pre) and after conceptual university level courses (post) based on results on the FMCE-test [13].

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different conceptual clusters, while in Figure 3 and table 4 the data are presented using a measure called normalised gain [16], defined as \( g = \frac{\text{Gain}}{\text{Gain(max possible)}} \) 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. In all six cases I-VI the FMCE was administered as a pre- and as a post-test.

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 [11, 12]. 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 in case V, and in some labs in case VI, have been recorded using digital camcorders. The data have been used to detect and record students’ words and actions. The approach analysing students interaction using video data is inspired by ethnomethodology [45, 46] and conversation analysis [47], i.e. I will focus on students practical, contingent and embodied inquiry in the setting of the lab. 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, 25, for a review and more details] for a review and more details.

Table 4. Learning gains for different courses in mechanics as measured by the FMCE-test [13].

<table>
<thead>
<tr>
<th>Teaching Method/Course</th>
<th>Norm. Gain (FMCE)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workshop physics (USA)</td>
<td>65%</td>
<td>Saul and Redish [48]</td>
</tr>
<tr>
<td>Traditional (USA)</td>
<td>16%</td>
<td>Saul and Redish [48]</td>
</tr>
<tr>
<td>RealTime physics (secondary implementation, USA)</td>
<td>42%</td>
<td>Wittman [49]</td>
</tr>
<tr>
<td>Conceptual labs 1997/98 (Case I) (Sweden)</td>
<td>61%</td>
<td>Bernhard [50]</td>
</tr>
<tr>
<td>Physics 02/03 (Sweden) Conceptual labs (Case V)</td>
<td>48%</td>
<td>This study</td>
</tr>
<tr>
<td>Physics 98/99 (Sweden) Non-conceptual labs (Case II)</td>
<td>30%</td>
<td>This study</td>
</tr>
<tr>
<td>Physics 02/03 (Sweden) Non-conceptual labs (Case VI)</td>
<td>18%</td>
<td>This study</td>
</tr>
</tbody>
</table>

4. RESULTS

In figure 1 the overall results on the FMCE concept test is presented for some non-conceptual courses including case VI. As discussed previously mechanics concepts are difficult for students to learn and understand. However as in shown in figure 2 and table 4 students understanding of mechanics (as measured by FMCE) can be drastically improved by properly designed and implemented conceptual labs. In table 4 the results from some innovative curricula in the US is included as a comparison. As can be seen results in the same range as the US results has been achieved. Still in figure 2 it can be seen that to properly understand Newton’s 3rd law is a difficult task. In the analysis of video-recordings some reasons for this will be presented.

As is demonstrated in figure 3 student participation in conceptual labs (cases I, III-V) seem to lead to considerably better results on the FMCE-test compared to the non-conceptual labs (cases II and VI). However for case II (probeware non-conceptual 98/99) there are a difference between the results on 3rd law contact and 3rd law collision. As is described in section 3.2 no tasks addressing contact forces were included in the design of labs in case II. The design related to collision forces, however, involved varying the mass of the carts but forces were calculated after the experiment and not measured in real-time as in cases I and III-V. Thus the impulse and collisions lab in case II could be seen as “semi”-conceptual in relation to collision forces (including some variation in line with variation theory but not sufficient focus on forces) and non-conceptual in relation to contact forces.

As mentioned in section 3.3 student courses of action were recorded by video in cases V and VI. A general finding, analysis of video recordings from the conceptual labs (case V) showed that students’ courses of action are framed by encounters with the instructions, the technology, the teacher, and other students. 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. In a forthcoming paper transcripts from students’ courses of action will be presented together with a detailed analysis.

5. DISCUSSION AND CONCLUSION

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 [2]. In a lab, an experiential human–instrument–world relationship is established [39]. 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.

In this paper it has been demonstrated through the analysis of task-structure and student’s courses of action in labs that the results on concept tests correlate to how well the lab is designed in line with variation theory [See also 11].

This study is part of a series of projects [12] in which courses in mechanics and electric circuit theory, introductory as well as advanced, have been developed and studied. The projects have been put into practice at two different Swedish universities, with different teachers, and with different groups of students (engineering and trainee teachers). The conceptual labs have been organised in different ways: as labs, as problem-solving labs (integrating problem-solving and lab sessions), and as interactive lecture demonstrations (the labs taken to the lecture hall). In all cases, except for the case when labs using probe-ware were implemented as formula verification labs [11], good learning results have been achieved [See also 51, for long-time learning effects].

As mentioned previously, the development of conceptual labs was originally inspired by the approaches taken in RealTime Physics (RTP) [18, 19]. RTP has had great success in improving student learning at its primary development sites in the USA, but this and other research-based curricula have often been less successful following transfer to secondary implementation sites, although still far better than traditionally taught courses [49, see Table 1]. Many tasks in my design of conceptual labs for introductory mechanics courses are similar to those developed for RTP. However, I have not simply transferred a Swedish translation of RTP. Instead, some tasks from RTP have been selected, adopted and adjusted to suit a different course structure and different culture. In addition, for some courses in advanced mechanics and engineering electric circuit theory there were no similar tasks in RTP - so tasks were designed “from scratch”. Table 4 shows that my co-workers results as well as my own compare very well with different implementations of research-based curricula. I claim that one reason for our success is that our designs and re-designs are not ad hoc, but based on a theory of learning: variation theory. This work, however, offers a slightly different explanation for the success of RTP (and similar curricula) than offered in the literature.

Recently, other work in science and engineering based on variation theory has begun to appear. In several papers by, for example, Duncan Fraser, Cedric Linder and co-workers [52-54] examples are provided from chemical engineering, process dynamics and physics. Thuné and Eckerdal [55] have used the notion of variation to design learning activities in computer programming. The examples in these papers, together with our results, provide evidence of successful designs in engineering education using variation theory.

The findings show, through examples from many different courses, that properly designed labs, or lab-like learning environments, can provide a good environment for insightful learning. I conclude that all these results support the notion that variation theory is valuable in such a development.

6. ACKNOWLEDGEMENTS

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