Abstract
Students come to our courses with a personal theory of physics. Most students do not change their personal theories during a traditionally taught physics course. In this paper I will give some reasons for this and also highlight some successful active-engagement curricula who help students to modify their personal theories of physics and thus help them acquiring a good functional understanding of physics.

Invited paper presented at
Physics Teaching in Engineering Education (PTEE 2000),
Abstract

Students come to our courses with a personal theory of physics. Most students do not change their personal theories during a traditionally taught physics course. In this paper I will give some reasons for this and also highlight some successful active-engagement curricula who help students to modify their personal theories of physics and thus help them acquiring a good functional understanding of physics.

KEYWORDS: Physics Education Research.

Introduction

Some years ago I started to include some “simple” conceptual questions in the exams of the physics courses I taught. These questions could be answered by qualitative reasoning and no or very simple calculations were needed. The results were first quite surprising: Most students performed very poorly on the conceptual questions which most physics would consider as to be almost ‘to easy’, while they sometimes solved ‘difficult’ multiple-step quantitative problems better than expected. Some of the ‘top’ students with high scores on the quantitative problems had very low scores on the conceptual part.

Question: Does the lamp glow?

Answer: Many students argued that the lamp would not glow, since the electrons went to the earth instead. Some argued that it depended on whether it was plus or minus which were connected to the earth.

Question: A 24 V Direct Current source is connected to a transformer with 100 turns on the primary side and 50 turns on the secondary side. On the secondary side is a 12 Ω load connected. Calculate the voltage $V_2$ on the secondary side and the current $I_2$ through the load. The transformer can be treated as an ideal transformer.

Answer: Most students used $V_2 = N_2/N_1 V_1$ uncritically got $V_2 = 12$ V and $I_2 = 1$ A as an answer instead of $V_2 = 0$ V and $I_2 = 0$ A. They overlooked the necessity of having an alternating current to have a varying magnetic field and to obtain induction.

Fig 1. Examples of some of the ‘simple’ ‘conceptual’ questions I started to ask students on my exams some years ago. These turned out to be the most difficult questions on my exams. The question to the left is from Epstein: Thinking Physics [1].
My ‘discovery’ is in good agreement with the results of recent Physics education research: Most students, even at the university level, do not learn basic concepts as a result of standard instruction and often graduates with unaltered misconceptions and may have deep misunderstandings. The facility to solve standard ‘end of chapter’ or exam problems are not an good indicator of functional understanding!

Space and time does not allow this paper to be a review, instead I have chosen to highlight some findings of physics education research with focus on results with implications for physics teaching on the university level. I will also describe some reformed physics curricula, which are based on findings of modern learning theory. Good introduction to the findings of physics (science) education research can be found in conference proceedings, in a recent paper by McDermott and Redish and a paper by Redish and Steinberg and in some books. A good general introduction to teaching and learning at the university level can be found in the book by Ramsden and in a recent book by Bowden and Marton. A good general introduction to teaching and learning at the university level can be found in the book by Ramsden and in a recent book by Bowden and Marton.

**Student learning in Physics**

*What is the problem?*

As mentioned above my findings agrees very well with the results of physics education research and it has been shown that a majority of students entering and leaving basic undergraduate physics

- do not understand the meaning of velocity and acceleration
- have difficulties in distinguishing force, momentum and energy
- fail to distinguish heat from temperature
- have inappropriate understanding of the relation between voltage and current and believe that current is used up in a circuit
- fail to distinguish mathematics from physics and
- fail to distinguish a hypothesis from an experiment.
- all bodies of students have problems with defiances in functional understanding, even at highly selective schools or among graduate students. However the proportion of people exhibiting problems with conceptual understanding decreases as the ‘level’ of the students becomes more advanced, but does not drop to zero even among physics professors!

One way of assessing student learning is the use of well-designed conceptual tests. In mechanics the Force Concept Inventory (FCI) and the Force and Motion Conceptual Evaluation (FMCE) are widely used. These tests are both multiple-choice, however they were developed on the basis of a large body of responses in interviews. The distractors (wrong answers) thus corresponds to most common answers. The multiple-choice format makes investigations of student understanding and learning in large student bodies feasible. In figure 2 are two questions from the FCI-test shown together with some results obtained before their first university level course, but after studying physics in upper secondary school.

---

1. It should be noted that the German/Swedish/Danish/Norwegian/Dutch/French … word “didaktik” (or similar word) does not has the same meaning as the word “didactics” in English. The closest term in English is “education research”, for example Physics education research, Engineering education research … The word “didactics” in English have the meaning of a teaching which is for example overburdened with details and explanations and therefore is boring.
1. Two metal balls are the same size but one weighs twice as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. The time it takes the balls to reach the ground below will be:
   A. about half as long for the heavier ball as for the lighter one. 9%
   B. about half as long for the lighter ball as for the heavier one. 7%
   C. about the same for both balls. 72%
   D. considerably less for the heavier ball, but not necessarily half as long. 11%
   E. considerably less for the lighter ball, but not necessarily half as long. 1%

2. The two metal balls of the previous problem roll off a horizontal table with the same speed. In this situation:
   A. both balls hit the floor at approximately the same horizontal distance from the base of the table. 25%
   B. the heavier ball hits the floor at about half the horizontal distance from the base of the table than does the lighter ball. 22%
   C. the lighter ball hits the floor at about half the horizontal distance from the base of the table than does the heavier ball. 2%
   D. the heavier ball hits the floor considerably closer to the base of the table than the lighter ball, but not necessarily at half the horizontal distance. 43%
   E. the lighter ball hits the floor considerably closer to the base of the table than the heavier ball, but not necessarily at half the horizontal distance. 8%

(Bernhard 1997)

Fig 2. Two questions from the FCI-test together with the distribution of answers for a group of freshman students tested before their first university level physics course. A physicist would regard this two questions as similar. But, as is revealed in the answers, students does not see that the questions are similar. These differences do exist even after a university level course. Typical results after a course is 80-90% correct responses for question 1 and 40-50% for question 2.

Fig 3. Proportion of two different groups of engineering students from two different universities in Sweden holding “force-follows-velocity view” and “physics’ view” (Newtons 2nd law) after a traditionally taught university-level physics or mechanics course. Note that almost the same proportion of students believe in Aristoteles or in mpetus theories as in Newtonian physics! The proportions of students holding different intermediate views are not shown. Student views are assigned from FMCE-data using a method developed by R Thornton [19].

As seen in figure 3 about one third of the students after a traditionally taught physics or mechanics course at university level in Sweden still hold the medieval view that motion always requires a force and only about one third hold a complete Physicist’
view of Newton’s 2nd law. Note that student can believe in Newton for increasing velocity but not, for example, for decreasing velocity. As displayed in figure 4 students have a very poor understanding of dynamics but also a very poor understanding of some areas of kinematics after a university level course. Very few students could correctly describe the acceleration of, or the forces acting on, a coin tossed up in the air. Probably could almost all students recite Newton’s 3rd law correctly, but very few students displayed any understanding of the law. These results agree very well with results obtained by other researchers. The results discussed here are from the domain of mechanics, but if I had chosen a different physics domain the results would have been similar as displayed in my introductory example.

— I have taught the dog
— I can’t hear him whistle!
— I said that I had taught him
to whistle.
— not that he had learnt it!

Fig 5. What is taught is not necessarily learned!
**Why?**

One important question thus arises: Why do not most students learn to understand physics?

One explanation for this can be found in learning theories that focus on changes in the ‘mental apparatus’ of students [13, 16-18] and it is proposed that people tend to organise their experiences and observations into mental models. The students come to us with approximately 20 years of real-world experience and this experience has formed strong mental models called preconceptions (ideas held before instruction). These preconceptions may be incomplete and contain contradictory elements and also be misconceptions. This means that our students are not blank slates to be filled with teacher wisdom and that a physics course must take the into consideration the knowledge and the personal theories which students have prior to instruction. Unfortunately cognitive studies and science education research have shown that it is very difficult to change an established model substantially [20]. The perspective sketched above can be seen as an individual perspective on learning and has its origins in works by Piaget.

Another view is offered by sociocultural perspectives and has its origin in works by Vygotsky [21]. In this view learning and meaning-making is the result of social interactions with others or with interaction with cultural products such as books and other sources of culture. Learning is viewed as being socially and culturally situated and can be seen as an enculturation. In this perspective the most powerful mediator of learning is language.

![Diagram of Teacher and Learner Perspectives](image)

**Fig 6.** Teacher and each learner has his or her own perspectives on the five elements operating in an educative event. The challenge is to reach a shared perspective on each element. From [22].

Learning physics in the individual perspective could thus be seen as ‘learning to think as a physicist’ while in the sociocultural perspective learning could be seen as ‘learning to act and talk like a physicist’. There have been considerable debate on which of these perspectives mentioned above is the most fruitful one. However I would argue, in agreement with for example Leach and Scott [17] and Cobb [24], that both perspectives offer important insights. For us as physicists this is not problematic: We are trained, depending on the context, to for example view the electron or the photon either as a particle or a wave. We know that it is not fruitful to view the electron only as a particle. A joined perspective would thus see physics learning as ‘learning to think, act and talk like a physicist’ in the relevant contexts.
Both perspectives stress the crucial importance of the learners’ activity. Knowledge can not simple be transferred from the teacher to the learner. The learner uses his prior experiences and understanding in the process of constructing new meaning and thus learning is influenced by their existing knowledge about what is taught. One important implication is that teaching must take into account what the learner already know and that the learner can conceive what is taught different from the intentions of the instructor. Even ‘facts’ and ‘arguments’ presented by the teacher to refute a misconception, could be interpreted by a student as a support for their own personal theory. An useful notion to use in this context is the ‘learning demand’ which is the difference between the everyday and scientific modes of thinking in different domains [17].

At a meeting at Tufts University, USA, the participating physics education researchers reached an agreement on the following points [26-27]:

- Facility in solving standard quantitative problems is not an 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.*

**Some effective instructional models in Physics Teaching based on Physics Education research**

Over past few years a number of active engagement curricula based on the constructivist model of student thinking and learning have been developed in USA. The common denominator of these curricula is that they encourage active learning and peer co-operation and that they address student misconception in a constructivist mode (developmental or apprenticeship [28]). These curricula have obtained good results in conceptual tests [29]. Active engagement classes can be divided into different types according to their organisation [30] as is displayed in table 2.

<table>
<thead>
<tr>
<th>Research Based Instruction “Constructivism”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Developmental</strong></td>
</tr>
<tr>
<td>Based on</td>
</tr>
<tr>
<td>Conceptual understanding research</td>
</tr>
<tr>
<td>Techniques</td>
</tr>
<tr>
<td>Arrange Context to Illustrate Specific</td>
</tr>
<tr>
<td>Concept</td>
</tr>
<tr>
<td>• Challenge “Misconceptions”</td>
</tr>
<tr>
<td>• Guided Discovery</td>
</tr>
<tr>
<td>• Apply New Knowledge</td>
</tr>
</tbody>
</table>

*Students come to a course with a personal theory of physics. Course gets them to modify it*

| Table 1. Division of research based instruction based on its’ roots in educational theory. |

In classes using ‘*traditional format*’ the traditional division between lectures, recitations and labs are kept. However these components are revised.

- **Laboratory-based** models replace the traditional laboratory by a discovery type active learning laboratory.
- **Recitation-based** (problem-solving) models replace the recitation in which an instructor solves problems for 1-2 hours by active learning activities guided by carefully designed worksheets such as a mini-lab in which the students carry out shorter guided discovery experiments and learn reasoning in groups.
- **Lecture-based** models retain scheduling of the lectures and are carried out in a lecture hall, but modify the activities carried out by the students.

In the **full studio** classes, the teacher lectures only for short periods during the class. Instead most of student time is spent doing experimental activities in groups in designed experiments. The distinction between lecture, problem-solving and
laboratory vanish in full studio classes. These classes are often more expensive since more teacher time, space, and/or experimental equipment is needed compared to traditional lectures.

<table>
<thead>
<tr>
<th>Curricula</th>
<th>Developer</th>
<th>Selected References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Traditional format</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discovery Labs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Tools for Scientific Thinking</td>
<td>R. Thornton, Tufts; D. Sokoloff, U. Of Oregon</td>
<td>[31-32]</td>
</tr>
<tr>
<td>• RealTime Physics</td>
<td>R. Thornton, Tufts; D. Sokoloff, U. Of Oregon and P. Laws, Dickinson College</td>
<td>[27, 33]</td>
</tr>
<tr>
<td>• Socratic Dialogue Inducing (SDI) labs</td>
<td>R. Hake, Indiana University</td>
<td>[34]</td>
</tr>
<tr>
<td><strong>Lecture Based Models</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Active Learning Physics System</td>
<td>Alan van Heuvelen, Ohio State University</td>
<td>[25]</td>
</tr>
<tr>
<td>• Peer Instruction/ConcepTests</td>
<td>Eric Mazur, Harvard University</td>
<td>[35-36]</td>
</tr>
<tr>
<td>• Interactive Lecture Demos (ILD)</td>
<td>R. Thornton, Tufts; D. Sokoloff, U. Of Oregon</td>
<td>[27, 37]</td>
</tr>
<tr>
<td><strong>Recitation Based Models</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Co-operative Problem Solving</td>
<td>Ken and Pat Heller, University of Minnesota</td>
<td>[38-40]</td>
</tr>
<tr>
<td>• Tutorials in Introductory Physics</td>
<td>Lillian McDermott, et al., University of Washington</td>
<td>[41-42]</td>
</tr>
<tr>
<td>• Mathematical Tutorials</td>
<td>E. Redish et al., University of Maryland</td>
<td>[43-44]</td>
</tr>
<tr>
<td><strong>Full Studio Models</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Physics by Inquiry</td>
<td>Lillian McDermott et al, University of Washington</td>
<td>[45-46]</td>
</tr>
<tr>
<td>• Workshop Physics</td>
<td>Priscilla Laws, Dickinson College</td>
<td>[47-49]</td>
</tr>
<tr>
<td>• The Physics Studio</td>
<td>Jack Wilson, Rensselaer Polytechnic Institution</td>
<td>[50-51]</td>
</tr>
<tr>
<td>• Scale-Up</td>
<td>Beicner et al, North Carolina State University</td>
<td><a href="http://www.ncsu.edu/ncsu/pams/Physics_Ed/SCALE-UP">www.ncsu.edu/ncsu/pams/Physics_Ed/SCALE-UP</a></td>
</tr>
</tbody>
</table>

Table 2. Summary of some active engagement methods used in introductory physics courses

**Lab-based**

Labs are usually a common element in physics instruction and students are expected to be active during a lab session. However labs are often of “cook-book” nature with very explicit instructions or without instructions there students are expected to discover facts and scientific laws by themselves. Arons [7] have summarised the problems with the different types of labs as: “It has long been clear that tightly structured and directed laboratory experiments are dull and demoralizing for the students and generate little in the way of concept development or physical understanding. It is also clear that the other extreme of completely unstructured situations, in which students are supposed to conduct their own observations, inquiry, and final syntheses are also ineffective.”

Tightly structured labs and completely unstructured labs are not the only two possibilities of managing lab-work however. During the last decades there have been many attempts to create exploratory learning environments that also direct students’
attention towards relevant concepts and phenomena, so called guided discovery [52, 53] or interactive-engagement labs [29]. Thus, the labs are inquiry driven, but the students are guided in their inquiry by carefully designed instructions, technology, and teacher support. Among these attempts, we can find curricular projects such as *Socratic Dialogue Inducing Labs, RealTime Physics, and Tools for Scientific Thinking.*

Common for *RealTime Physics* (RTP) [27, 33] and *Tools for Scientific Thinking* (TST) [31-32] is that they make use of a certain technology called Microcomputer-Based Labs (MBL) or computerized data logging. MBL consists of a computer connected a sensor or a probe and is used in the collection, analysis, and display of experimental data by transforming the sensor’s signal to a graph on the computer screen. These curricula focus on concept building and are designed to address common student misconceptions and learning difficulties by using cognitive conflict, peer interaction and real-time graphing. TST was originally designed for use in non-calculus based physics courses and covers mechanics and thermodynamics while RTP is designed for use in calculus based physics courses and covers other branches of physics such as electricity and optics. The *Experientially based physics instruction* [54] project in Sweden was inspired by RTP.

*Socratic Dialog-Inducing Labs* (SDI) developed by Richard Hake [34] is an example of “guided construction” labs featuring hands-and-heads-on interactive experiments in introductory mechanics using simple equipment. SDI-labs are designed to enhance students’ conceptual understanding of Newtonian mechanics. This is done by using conceptual conflict; extensive analysis of concrete experiments in Newtonian mechanics using verbal, written, pictorial, diagrammatic, graphical as well as mathematical analysis; peer discussion; and Socratic dialogue with lab-instructors. SDI does not use MBL-equipment as in *Tools for Scientific Thinking* and in *RealTime Physics* but many features are otherwise, such as conceptual conflict, are similar. SDI require an instructor skilled in Socratic dialogues.

*Lecture Based Models*

In lecture based models part of the traditional lecture has been replaced by specially designed active-engagement activities.

*Interactive Lecture Demos* (ILD) [27, 37] is an adaptation of the ideas behind RTP-labs into the lecture format. Short experiments are performed in the front of class in a lecture hall using MBL-equipment for measurement and the display of experimental results in graphical form in real-time on a screen visible to all students. These experiments are quite similar to those performed by students in RTP and TST and the experiments are designed according to results from educational research and are not as typical lecture demonstrations chosen for their “entertainment” value but for their “educational” value. Student are also required to fill out worksheets during the ILDs with their predictions, discuss with their peers, and finally compare the final results with their predictions to get them actively engaged.

At Harvard University Eric Mazur has modified his lectures into an approach termed *Peer Instruction* [35-36]. After 10-15 minutes of lecturing the lecturer present one challenging multiple choice question to the students. The questions asked are concept oriented and the different alternatives presented correspond to common student
conceptions as shown by educational research. Initially the student’s vote on the alternative they think is correct and usually, because of the choice of different alternatives for answer, the students are divided into what is thought to be the right answer. The students are then instructed to discuss the problem with a neighbour and after 2-3 minutes of discussion the students answer again. Usually the discussion has led to a substantial improvement in correct answers. If not, the lecturer does not proceed with a new topic but instead present additional material on the problematic topic. This procedure will be repeated several times during a lecture.

*Active Learning Physics System* (ALPS) [25] is a series of worksheets developed by Alan van Heuvelen for use in lectures. Short period of lecturing are intertwined with individual student activities and peer discussion using the worksheets. Thus it has similarities with ILD and *Peer Instruction*, but ALPS do not rely on expensive technologies.

*Recitation-Based Models*

In recitation-based models recitations (recitation is the US English term for problem-solving sessions) are transformed into active-learning environments. Traditionally in recitations the instructor (professor, lecturer or a doctoral student) demonstrates problem-solving on the blackboard while the students watch passively and copy the solution in their notebooks.

![Figure 9](image.png)

*Figure 9.* Interactive computer-based tutorial on force and motion from Univ of Maryland. Students are up and around and actively participating in this classroom lesson where a motion sensor is used to provide real time graphs of position and velocity.

In *Tutorials in Introductory Physics* [41-42] Lilian McDermott and co-workers at University of Washington have developed carefully designed worksheets developed applying results from physics education research. These worksheets emphasize concept formation and qualitative reasoning and make use of cognitive conflict. Simple materials are used, for example bulbs and batteries. A further development of these tutorials is *Mathematical Tutorials* [43-44] developed at University of Maryland by Joe Redish and co-workers for use in calculus based physics courses. Hence these tutorials focus more on mathematical concepts than the original tutorials developed by McDermott and co-workers. In the *Mathematical Tutorials* MBL data acquisition equipment (see figure 9) is used as in TST, RTP, ILD and in *Workshop Physics*. In both versions of tutorials well-known student conceptual difficulties are addressed.

At the University of Minnesota Pat and Ken Heller have developed an approach called *Co-operative Problem Solving* [38-40]. They have developed a set of problems that require that students to work in groups since the problems are too difficult for students to solve individually. These problems involve realistic situations, that is they are context-rich, may contain incomplete data, may require the students to make
estimates or informed guesses and the student may even have to formulate part of the problem by themselves as in real-life. The composition of groups are carefully made in this approach.

Full Studio Models

Both the Workshop Physics [47-49] class developed at Dickinson College by Priscilla Laws, and the Physics Studio developed at Rensselaer Polytechnic Institute by Jack Wilson, make strong use of computer equipment to give the student a more quantitative view of the world. Studio physics [50-51] uses newly constructed "studios" in which classes with approximately 50 – 60 students are taught in a novel setting that incorporates lecture, recitation and laboratory in one class. Workshop Physics is an activity-based approach to teaching introductory physics without formal lecture. Students enrolled in Workshop Physics work in small groups to predict, observe, discuss phenomena, derive equations and perform quantitative experiments using MBL-computer interface and equipment, spreadsheets, modelling and digital video analyses. The Scale-Up project at NCSU is an attempt to use an integrated ‘studio’ setting in courses with larger enrolment because of the costs involved in running curricula like Workshop Physics. Workshop Physics is designed for classes of up to 24 students with 1 faculty and 1-2 teaching assistants. At presently Scale-Up work with groups of approximately 60 students, but an extension up approximately 100 students is planned.

Figure 10. Photos from Workshop Physics at Dickinson College. To the left a short introduction by assistant professor Hans Pfister and to the right the students at work.

Figure 11. The Workshop Physics classroom at Dickinson College. All “teaching” in Workshop Physics is conducted in this integrated classroom.
Are active-engagement curricula effective?
It is natural question to ask: Do these methods work? Hake [29] have collected assessment data using the FCI-test from more 6000 students participating in active engagement and "traditional" physics classes. According to Hake’s analysis all classes using some active engagement method had better gains than physics classes using "traditional" teaching methods. Even the worst-performing active engagement class performed better than traditionally taught classes. In a study of the learning effects of second-implementations of some of the curricula mentioned above Saul and Redish [55] got significant differences in understanding between traditional and reformed courses. These results are shown below in fig 12. I have got similar results when developing and implementing a curricula in Sweden which have similarities with RealTime Physics [54].

Fig 12. To the left are results obtained by Hake [29] using the FCI-test and to the right results obtained by Saul and Redish [55]. The results by Saul and Redish are interpreted using normalised gain $h = \frac{\text{gain}}{\text{maximum possible gain}}$ [29]. This makes comparision possible between groups with different pretest values.

From the studies of Hake [29] and Redish and Saul [55] together with the data published by many of the developers presented in table 2 one can thus conclude that active engagement curricula, as those mentioned above, are effective in helping students developing a good functional understanding of physics. It should be noted that many different curricula are effective, and thus is it always possible to find something which is possible to implement regard-less of different constrains and educational traditions.

Acknowledgements
This work is supported by the Swedish National Agency for Higher Education, Council for Renewal of Higher Education
References
9. Tiberghien, Jossem, and Barojas, eds. Connecting Research in Physics Education with Teacher Education. 1998, ICPE.


54. Bernhard, J., Teaching engineering mechanics courses using active engagement methods, these proceedings