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Secondary and university students' understandings of physical and technical phenomena: informing pedagogy and practice

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Introduction

This paper presents some findings from the piloting phase of our research on students' thinking about physical processes imbedded in a number of technical and natural phenomena. We mean by "thinking physics" how students use language of physics, i.e. appropriate terminology, concepts and modelling tools. This is an ongoing project at the department of mathematics and natural sciences, teacher education, Umeå University. The study is situated within a constructivist epistemology in which learning is construed as the creation of meaning from experience. This meaningful learning involves linking new ideas with pre-existing ideas (Driver and Erickson, 1983, Duit, et al, 1992). Students bring into science classes beliefs and ideas about the causes and mechanisms of natural phenomena, which they have developed, based on their socio-cultural environment and previous educational experiences. Some of these ideas are simply incorrect or over simplistic from a scientific point of view, others are quite near to if not essentially correct. The core activity of constructivism is to determine, clarify and ameliorate learners' erroneous conceptions of natural phenomena (Driver, et al., 1994). This constructivist approach to learning is considered as an important tool in the pedagogy of science teacher educators (Tiberghien, et al, 1998, Chang, 1999).

Furthermore, to organise effective physics teaching we need, on the one hand, an adequate understanding of the thought processes leading to the desired students' performance and, on the other hand, knowledge about what skills to "think physics" students coming to instruction already possess. Reif (1995) identifies following basic cognitive abilities vital for productive physics learning: "to interpret properly scientific concepts and principles, to describe knowledge effectively, and to organise it effectively." From this perspective an understanding and pedagogical use of semantics of physics is especially important. Semantics deals with meanings of words and linguistic expressions and their relations with the objects in the world to which they refer or which it is their function to describe (Bullock, et al., 1990). This field is gaining recently attention among science educators (Williams, 1999; Harrington, 1999; Prophet and Towse, 1999). Osborne (1996) maintains that learning ideas and concepts of physics is "more akin to the learning of a foreign language than it is to the learning of historical facts".

Physics uses a large technical vocabulary that often involves words that in everyday life have less precise or even contradictory meaning. Thus one needs ability to discriminate between uses of these words in different contexts. Moreover, we often use in different branches of physics terms and symbols that change their meanings with context. This makes it very difficult even for good students to decipher physics terminology and eventually learn to use it properly in scientific discourse.

Borges and Gilbert (1998) claim that "humans understand any phenomena or state of affairs by constructing a 'working model' of it and reason by manipulating such a model." They explain that in the process of mental model construction one simplifies a phenomenon or system selecting only some parts of the entity and relation between them for representation. In our discussions with students during the course work, we found that many of them felt uncomfortable with model-based thinking for approaching a study of natural world. "Why we have to simplify and idealise so much all the processes, they will not be like in the reality" was a common comment. We assume that ability to interpret, draw and use models is of great importance for physics teaching.

On a metacognitive plane, Redish (1994) talks about student's mental ecology. In this concept he includes different mental models for physical phenomena as well as different mental models for learning that students have prior physics courses. He encourages us to study purposefully these mental ecologies, through listening to students, observing them and discussing with them. As experience shows, different students can have different reasons for giving the same answer for a question. Thus, we can draw only limited inferences from the analysis of the questionnaire. We have to let students "think aloud" to get deeper insight into their reasoning processes. Therefore, an interview method will be actively used in the forthcoming main part of the study.

The ultimate purpose of this research is to provide a basis for further development of physics courses and teaching materials in our department. We hope that these courses would help more students to acquire confidence in using scientific tools of thinking for interpretation of natural and technical phenomena. Constructivist approach to learning emphasises the importance of building on prior experiences of learners. The first aim of the study was, therefore, to identify students' personal experiences with physics and existing understanding of selected natural and technical phenomena prior the physics courses at university.

Method

Physics knowledge and reasoning strategies can commonly be described with help of three types of symbolic representations: words, pictures and mathematical symbols. In this study, we deliberately decided to avoid any explicit reference to formulas and numbers, which are strongly associated for students with high school physics and have on many of them "brain paralysing effect". "Physics questionnaire – oh no!! I don't remember anything from my school physics course." We found that this reaction was in the first place connected with operation of mathematical symbols for problem solving, which is one of the main activities in the high school physics classes.

The data collection was based on a questionnaire consisting of seven open-ended "draw and write" items. We tried to give students the opportunity to explain what they are thinking about the matter of each item in words and pictures. Visualisation is very important in description and interpretation of physics information and problem solving. Therefore, each item contained a drawing task.

The level of knowledge demanded by the set up questions corresponds basically to grade nine standards in the Swedish science curriculum. We have tried in the formulation of questions to avoid similarity with typical formats for examinations and to encourage students to fully express their understanding of and thinking about the phenomena. Questions included in the instrument are related to the following physics areas: electromagnetism, light and sound and energy transformations. They present phenomena well known from the everyday life. The selection of content was based on our individual experience about students' difficulties in understanding these questions.

The questionnaire was evaluated by two colleagues from our department. They were asked to check whether any factors could be identified likely to negatively influence the validity of the replies given. A piloting of the instrument was conducted with a group of other, similar student teachers. The aim was to establish whether any problems might be experienced in understanding the instructions or the questions, and to find out how long it would take to administer the questionnaire.

Students had 40-45 minutes to answer the questions. This was relatively short time to allow "deep memory search" rather they had to demonstrate how efficient their ability to interpret concepts and phenomena was.

Data analysis was approached through an iterative process of information analysis. First, one researcher went through all of the responses on the questionnaire. The items of information from the drawings and texts in each question were grouped through identification of similarities and differences between them. Qualitatively distinct categories of description thus emerged. These categories were consequently crosschecked and refined by two other researchers and later used for codification. Statistical analysis of the responses was carried out with help of SPSS program.

Sample

Three groups of students participated in the study, one group from each three levels: the last year in secondary school science programme (gy), a university bridging science course (bc) and primary science student teachers (pst).

These groups can be also distinguished by students' prior educational background and attitudes towards science education. The *gy*-group is represented by students whose future plans are connected to some form of science studies. Therefore they were generally motivated to learn physics in school. The *bc*-group is constituted by students who for various reasons did not choose the science stream in secondary school but instead opted for the social studies stream. However, they changed their mind later and attended bridging science course to get necessary credits to enter primary science teacher preparation programme at university. The *pst*-group included students with the most diverse educational background. They completed either science or technical programmes in school, or attended adult education or bridging science course at university.

The questionnaire was administered to students present in class during a lecture session. The sample totalled 84 persons (gy-29, bc-20, pst –35). There was uneven gender distribution within the groups. In the secondary school group (gy) 55% of students were female, while in the other two groups young women represented more than 80% of the sample. Even if an analysis by gender would have been desirable this makes it difficult for us to compare the results by gender. Instead we will limit our analysis to study what is also our primary interest, namely differences in performance between the respective three groups.

Some findings and brief discussions of the results

General comments

The respondents' understanding of the various concepts ranged from intuitive or common sense notions to valid scientific viewpoints. In terms of areas of physics, the respondents showed some evidence of better understanding of energy transformation processes rather than of other issues. However, they displayed inconsistent and disparate understandings of almost all aspects of the questionnaire. Many of them held alternative interpretation of all the selected phenomena.

We could conclude from the analysis of the responses that considerable number of students had problems as regards the *interpretation of the questions*. They often misread the question or interpret it differently than it was written. We were quite confident for instance that a question with two tasks would not provide any difficulties for the students. However, the results revealed that about one third of the respondents did not answered (could not find out answer, forgot about or neglected) the second task in the question. We suggest that this was often result of the superficial reading/interpretation of the question. This issue will discussed further at relevant places bellow.

Presentation of results by items

Personal experience of physics

The answers on this question mainly included descriptions of the experience of formal physics learning at primary and high school, adult education or in a bridging course at university. This means that students could identify themselves only in relation to physics as a school subject but not in relation to physics as part of general human scientific culture and an important area of social discourse. Nobody mentioned for example their experience with physics as presented through different media or in public debate on nuclear power stations or environmental issues. Only one student related physics with his experience during military service in radio communication troops.

The strongest factor influencing personal experience with physics subject was a teacher. Most of the students commented on how the teacher influenced their attitudes and interest in the physics studies.

As the evaluation of the results show, some female students also express their experience of physics as still strongly male dominated subject, which is unattractive for girls. They wanted to work for changing this situation.

Q1. *torch*

With respect to this question, we expected that students would "think circuits", i.e. be able to identify the concept of electric circuit in this particular instance and thus show its understanding. High school students (gy-group) performed better than other two groups. 45% of *gy* students were able to make a complete drawing of the circuit in the torch. Four of them used schematic presentation of batteries '-11-' as they used to do in physics classes. Of the students in the sample, a total of 39% were not able to draw a circuit in the torch. Table below summarises students' replies to this question.

	Bc (%)	**Pst (%)**	**Gy (%)**	**Total**
Complete circuit & current	10,5	23,5	44,8	28,0
Circuit without lamp	42,1	20,6	24,1	26,8
No batteries but circuit	15,8		6,9	6,1
No circuit	31,6	55,9	24,1	39,0

The analysis of the questionnaire shows that students could have nominal knowledge about electric circuit, for example, some of them even draw a schematic presentation of the circuit next to our model-drawing of a torch. However, they experienced difficulty in interpreting this concept in the more practice-connected situation, i.e. they could not draw a circuit in the schematic presentation of the torch.

There was confusion among many respondents about a place of a current in the torch. An analysis of the drawings suggested that four categories of responses could be identified: 1) electric current circulates within each battery, 2) it goes on the surface of batteries, 3) it runs through the middle of the batteries into the bulb (and back), and 4) it goes passing through the batteries, bulb filament and a wire forming a circuit.

Q2. *magnet*

Students were asked in this question to account for the attraction between a magnet and a metal pin. In describing "magnet's functioning", many students displayed confusion between electricity and magnetism.[1] About half of the students in total and almost three quarters in *bc*-group explained that magnet's capacity attract metal pins is caused by electrical forces. A typical responses were that "positive magnet pole attracts negative electrons in the metal", "plus pole attracts negatively charged needles and vice versa". They have used a common rule that like charges repel and unlike charges attract each other.

More than 20% of the respondents drew or named, for example, "plus" and "minus" (or positive and negative) poles instead of "north" and "south." They assumed that magnetic polarity arises from an excess of electrical charges at one of the poles and a lack of charges at the other. When we asked where from comes up such a description of the magnet poles they thought that they heard and used it all the way from the primary school. Many students express their conviction that plus - minus (or positive and negative) and north – south poles are just synonymies in the description of a magnet.

Some students who used "magnetic force field model" to describe the phenomenon had also problems with illustration of magnetic field lines. We identified at least three different forms of presenting a shape of the magnetic field surrounding a bar magnet.

It is obvious that if a student teacher will carry own confusion about these terms into the school classroom this can produce profound confusion among the pupils. However, we observed such careless use of physics terminology as a quite common phenomenon during students' group-work in teacher education courses. The analysis of the questionnaire allow us conclude that students' confusions with terminology reflect their deep-rooted misunderstandings of magnetism phenomena.

Q3. *light and sound*

The students were asked to account for differences and similarities between light and sound. All of them were able to name one or two differences and similarities between these phenomena. We have found that roughly half of the students (55%) remembered about *differences in speed* of light and sound. This was the most representative answer. As to *similarity,* 91% of the students indicated that these phenomena have a *wave* character. However, nobody pointed out that these represent two different types of waves – mechanic and electromagnetic with corresponding properties. Students' responses demonstrate mosaic of miscellaneous bits of knowledge about wave properties (frequencies, reflection, amplitudes, interference, polarisation), which were named but unrelated to the more general and fundamental concepts. We assume that many students have a lack of understanding of the nature of light as an electromagnetic wave.

About 10% of the students indicated that light are rays, and about the same number suggested that light are particles while sound has always been characterised as waves. Previous research has shown that students at all educational levels have fundamental difficulties with interpretation of concepts related to light, sound and wave physics in general.[2]

Q4. *ray's way*

The geometrical optics question was difficult for many students. An analysis of their drawings of the ray's way when the ray hits an aquarium straight from the side produced four categories. In the table below we present the percentage distribution of the results.

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[1] Similar findings have also been reported in the interview-study of Borges and Gilbert (1998) conducted in Brazil. We could in principle identify that all mental models of magnetism (as pulling, a cloud, electricity, electric polarization and field model) described in their research report were in some form possessed by our students. However, we found that most common was understanding of magnetism as attraction among electrified bodies.

[2] See review of research on the learning and teaching physics prepared by McDermott and Redish (1999).

ray’s way	Bc (%)	Pst (%)	Gy (%)	Total (%)
Right line	15,0	5,7	37,0	18,3
Consequent refraction	15,0	22,9	48,1	29,3
Dispersion in water	50,0	62,9	11,1	42,7
Inconsequent refraction	20,0	8,6	3,7	9,8

Most of the students could recognise a case of the refraction problem here. This was quite a familiar task from the optics studies. The refraction tasks usually associated with bending of the ray’s way at the boarder between two mediums. Hence many students applied the familiar algorithmic procedure for drawing the ray’s way following their intuitive ideas about lows of reflection and refraction. The respondents were just not sure if the ray should bend up or down. These two alternatives were rather equally presented in the statistics of responses. It was difficult for the respondents to identify a special and simplest case when the ray hits the boarder at the right angle. Teachers usually consider the latter case as a trivial and often overlook it in the optics lessons.

Many students could not also find a balance in their reasoning between a model situation of the prototypical refraction problem (when any dispersion is neglected) and intuitive everyday idea about light spreading in the water. More than 40% of the respondents draw a picture of total dispersion in the water. This example shows that even simple diagrammatic representations of the geometrical optics can be difficult to relate with the real world situation.

Only 69% of the students commented on the speed of light through air, glass and water. More than half of them gave the correct interpretation that the speed of light is highest in air but only 17% indicated that it is slowest through the glass. We assume that 31% of the students who did not responded this item had not read the question statement carefully or had forgotten about the second part after struggling with the first part of the question.

Q5. *phases of matter*

In this question the students were asked to *draw a model* of a molecular structure illustrating the three phases of water. To be able to make correct model presentation they needed a prerequisite knowledge about the special property of water in a solid form, i.e. that ice has less density than water. This is well known fact from the daily experience. More than 40% of the *pst*-group could do this, but from the other two groups only one student could indicate this property. Success of the *pst* students could eventually be explained by the fact that they went through chemistry course just before they faced this pre-course questionnaire in physics.

In total, 42% of the students drew a picture showing the distance grows almost linearly between particles in transition from ice to water and then vapour.

Molecular arrangement	Bc (%)	Pst (%)	Gy (%)	Total (%)
Ice is more sparsely packed	5,0	42,9		19,3
Ice has tightest arrangement	40,0	8,6	25,0	21,7
Distance grows almost linearly	55,0	31,4	46,4	42,2
Distance almost the same		17,1	28,6	16,9

As these data indicate, it was not a simple task to make correct structural description of a system. Many respondents hold intuitive mental model that distance between molecules should steadily grow during a heating of the system and corresponding phase transitions.

To describe comparatively velocities of the particles in three phases was quite easy for all students. Many of them also pointed out relation existing between molecular motion and interactions. In the gas state interactions are weakest and particles’ speed is highest while in the solid state there is strongest interactions and lowest motion intensity.

However, there were some students that had difficulty with interpretation of the question. Some students thought about water as a macroscopic object and could not present its microscopic structure.

We found in our teaching that many students have general difficulty in using *the particulate perspective* to explain properties of matter and physical processes. Meanwhile, this ability is critically important for science teachers.

Q6. *energy chain*

Most of the students were able to draw and describe the energy chain between sun and a coffee machine via a hydroelectric station. The number of links in the chain and the language in which they were presented**,** i.e. degree of precision**,** varied but most of the respondents appeared to possess a general understanding of the energy transformation process. The *gy*-group of students was much better in using the correct physics terminology when describing phenomena. A number of students faultily specify energy of sun as *chemical* instead of *nuclear* as a starting point in the energy chain.

Q7. *seasons*

The question about different seasons is based on the Swedish Natural Science curriculum at primary and secondary level, though not taught independently on the physics courses at secondary schools. 28% of the respondents revealed conventional misunderstanding of seasons as dependent on changes of the distance between the sun and the earth. About half of the students gave common-sense everyday explanations of the seasons with reference, for example, to height of the sun, a place on the earth in relation to the equator or as a relationship between the earth and the sun without clarification. The *bc*-group students outperformed the other two groups in this question. About 30% of them gave an apparently correct explanation connected to the earth's axis inclination. This can probably be explained by the fact that the teacher usually pays attention to this issue in the natural science course, which is part of the social studies stream at secondary schools. An analysis of the presented word and pictorial descriptions shows however that nobody could *clearly* illustrate "physics of seasonal changes", i.e. connect it with amount of energy per illuminated area or incident rays' angle. Therefore we cannot be sure if there is a real understanding of the phenomenon behind the reference to the earth's axis inclination. Further research is needed on this issue.

Conclusion

This paper presents some results of a project aimed at gaining insights into the students' understandings of common physical and technical phenomena before entering into university physics courses. All the students were in the process of transition between school science and university physics, though through different routs. A number of trends in the data are of interest for us as educators trying to improve student teachers' confidence in interpretation of common phenomena.

The preceding data analysis indicate that students from all three groups encounter difficulty in using conceptual tools demanded by the school science syllabus. They have superficially learned a broad variety of concepts but did not acquire the ability to interpret them in practical situations. Following Reif (1995), we can state that teaching needs to be explicitly focused on qualitative interpretation of scientific concepts so that students can learn to apply them in different contexts and develop confidence with their meanings. However, it is well recognised (Loughran, 1997) that the assessment students face at the end of the course influences their view of learning and their understanding of what is important to learn, which also inevitably affects how they learn. The poor performance of all three groups of students in our questionnaires could be indicator that teachers' assessment in school and university science bridging course were not focused on students' conceptual understanding.

The respondents had problem to describe the phenomena/situation in terms of technical physics concepts, they rather stack to everyday language. Willams (1999) suggests that "language of physics presents one of the main difficulties for students in learning physics at university." The results of our study show that students emerge in physics courses profoundly confused about the meaning of the many important and often used notions such as magnet's poles, electric current, energy, waves, et al. Moreover, we found through discussions during our physics classes that they are reluctant to acknowledge that operating with wrong physics terminology reflects (and even can induce) confound understandings of the phenomena. Many students were unaware that "learning science means becoming familiar with a discourse which inescapably differs from the language of everyday life. It not only requires the learning of the meaning of a wide range of terms, e.g. force, power, watt, joule, field, energy, but also learning the appropriate use of the word and its meaning within the restricted set of contexts that make up the discipline of science" (Osborne, 1996). This inability to situate themselves within the discourse and context of physics was probably one of the main factors affecting students' interpretation of our questions and their ways of thinking and using vocabulary in responding to the questionnaire.

Our findings suggest that students often misunderstand fundamental principles and are not able to distinguish them from the less significant knowledge. For example, naming differences between light and sound nobody mentioned that these two wave-phenomena have essentially different nature (electromagnetic vs. mechanic). According to the research published in the international magazines, superficial learning is a quite common problem in the school science education that preoccupies educationalists all over the world. Some of them relate this problem to the teachers' scientific competencies and choice of priorities within teacher education. Moore (1999) wrote, at the pre-college level, the attention paid to subject-matter expertise is often minimal, the assumption being that someone who knows how to teach can do so without knowing what students ought to be learning.

We believe that it is important for all students to have a real understanding of basic concepts and phenomena, such as electric circuits, seasons, light and sound, energy transformation, and be able to interpret and draw simple models. However, even more important that student learn to think physics, in terms of identifying fundamental relations, understanding advantages and limitations of fundamental models, knowing ways of acquiring and verifying scientific knowledge.

The secondary school students revealed slightly better reasoning in relation to our questions than teacher students who finished school some years previously. This illustrates weak retention of physics knowledge (concepts, language and ways of thinking) which are gradually substituted by everyday interpretations of phenomena.

We suggest that our questionnaire study had pedagogical value in itself showing students that basic physics concepts and ideas imbedded in daily phenomena may seem simple at first sight, yet actually be difficult to understand and use. The questionnaire helped student make his or her own tacit knowledge, misconceptions and thinking processes explicit through own words and pictures. Thus, the research would hopefully encouraged student to pay attention to "physics thinking tools", such as concepts and models in their forthcoming university courses.

At the university, tutors face the challenge of ameliorating students' inaccurate conceptions about diverse phenomena, which form part of their daily experiences. This is especially important when it is concerns student teachers. Teacher educators should help them to develop scientific tools for reasoning and interpretation that they can use in the future professional life as science teachers.

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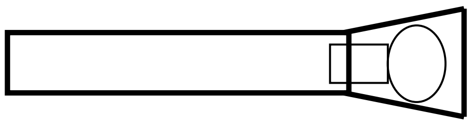
Appendix: Questionnaire (*translated from Swedish and presented in a condense form*)

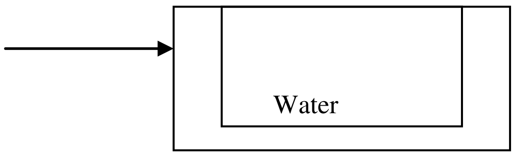
Sex __, age ___, study background ________________

My experience of physics:

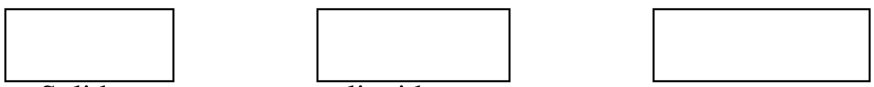
1. Complete the drawing of a torch to show how it functions. Draw an inner structure of a lamp and show how it is connected. Mark the current's way using arrows.



2. With help of an magnet, it is possible to pick up drawing (metal) pins that are spread on the floor. Explain the physics of this process in words and drawings.
3. Light and sound are two common phenomena. Describe how you understand differences and similarities between them. Use drawings.
4. A light ray hits an aquarium straight on (see picture). Draw the ray's way through the aquarium. Describe the speed of light under it passes through glass and water.



5. Describe with pictures (in the boxes bellow) and words how molecular structure of water and its molecular movements can vary in three phases.



Solid liquid gas

6. When we cook coffee we are dependent on electricity. Draw and explain about the energy chain from the sun to coffee machine via a hydroelectric station.
7. When we are skiing in Sweden there are also people on a beach in South Africa. Describe using words and drawings why we have the different seasons in different parts of the world at the same time.