Symposium

Learning process studies

Overview

In this symposium, learning processes in different sub-domains of physics will be analysed as "evolution of student's ideas about gases" (Givry & Tiberghien), as "change of a student's photon model" (Asikainen et al.) or as "student learning in quantum atomic physics" (Budde & Niedderer) on a timescale of several hours. The idea is to follow students' constructions "during" the whole process of learning in more detail as in studies, where mainly conceptual change from "before" to "after" teaching is studied.

In the first contribution, Hans Niedderer will give an overview of research development since the Bremen workshop in 1991 on "Research in Physics Learning - Theoretical Issues and Empirical Studies" (Duit, Goldberg & Niedderer 1992). He will start from "needs" formulated as consequences from the Bremen workshop and follow the research development along these needs up to today.

In the second contribution, Damien Givry & Andrée Tiberghien will study the evolution of students' knowledge during a teaching sequence on gases at the upper secondary school level (15 years old, grade 10). They are interested both in how student's ideas about gases evolve during a teaching unit and what are the teaching elements that support this evolution. They use video extracts with a focus on use of words about gas by teacher or students (i.e. air, gas, molecule) and on experiment handling used by students. The researchers from these data constructed student's evolving ideas about gases.

In the third contribution, Mervi Asikainen et al. will present the evolution of a single student Esko's photon models during a quantum physics course. She uses data from pre- and post-tests as well as from five subsequent interviews and from videotaping class activities. Typical for Esko's learning process about photons is that even though he uses three qualitatively different models to describe photons, all the models seem to be fundamentally classical. After Interview 1 he did not show any evidence of understanding quantisation. Despite the fact that Esko adopted only few properties of the taught model of the photon, his conceptions of photons developed towards the scientific ones.

In the fourth contribution, Marion Budde and Hans Niedderer report a study, in which earlier results about a learning pathway of students in quantum atomic physics were taken as a starting point to analyse learning effects of content specific elements of the learning environment on single students learning. The relation between learning environment and students' constructions is theoretically described as different forms of resonance, using an idea of von Glasersfeld during the Bremen workshop in 1991.

All three learning process studies presented in contributions two, three and four use the methodology of case studies with one or two students. This is due to the fact that the amount of qualitative data from the whole learning process is huge and that these data have to be interpreted by defining new intermediate conceptions of some stability. Not every statement of a student is a new intermediate conception, so the important action in interpreting the data is to find the most distinctive features, which allow for describing the most relevant learning steps constructed by students themselves. This is to be seen as a first step in a research program, which in follow-up studies should aim at investigating learning processes in specific topics of whole classes.

Bibliography

(See contribution one)

Research on learning processes - a review of issues and studies

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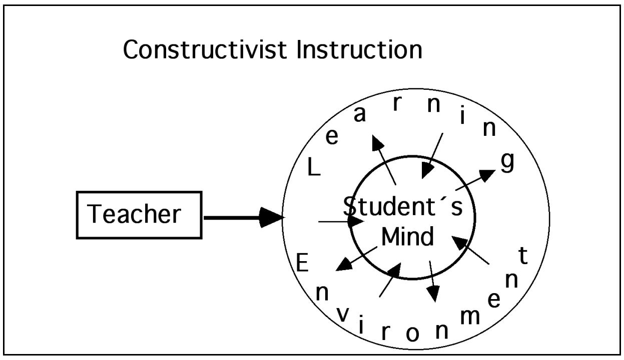
Introduction

In 1991, an international workshop on "Research in Physics Learning - Theoretical Issues and Empirical Studies" was held in Bremen with the aim of initiating learning process studies with data not only from pre and post but also from during the teaching and learning process. These studies describe conceptual pathways (Scott 1992), learning pathways (Petri & Niedderer 1998), or conceptual evolution (Psillos & Kariotoglu 1999). In this paper, I shall try to follow up studies, which have been published since then according to similar aims and similar theoretical background.

Theoretical background: Basic consequence of constructivism on learning

A constructivist understanding of teaching and learning can be shown in the following figure:



It means that the teacher is in control to build up the learning environment, but has no direct control what is happening in students' minds. As a rule, students' constructions of meaning - students' conceptions - are different from teachers' constructions and intentions. This is an empirical fact found quite often (see for example Galili et al. 1993; Psillos & Kariotoglu 1999; Petri & Niedderer 1998). It was called the "gap" between what we teach and what is learnt by McDermott (1993). This gives a special task to learning process studies: they have to follow students' own constructions ***during*** instruction. An underlying assumption of this type of studies, which is related to conceptual change theories, is the following: Students' learning pathways or conceptual evolution can be described most efficiently using a limited number of different "conceptions" or "ideas" or "intermediate conceptions". A "comparison of the intended sequence with student teachers' actual constructions in the course of teaching revealed unexpected intermediate steps in their evolution towards differentiation of the intensive variable pressure and the extensive variable force" (Psillos & Kariotoglu 1999).

Research development according to "needs" from 1991

The papers and discussions at the Bremen Workshop suggested several issues that need to be addressed through further research on student learning of physics. Nine special issues were formulated as "needs" (Niedderer et al. 1992):

(1) Need "to document learning pathways for different content areas in physics"
(2) Need "to construct ways of describing cognitive systems that are useful to researchers in physics education"
(3) Need "to develop research methodologies that would be appropriate for carrying out learning studies".
(4) Need "to document changes in student's conceptual ecology".
(5) Need "to examine issues regarding conceptual change".
(6) Need "to develop instructional strategies and materials based on results of learning studies in specific content areas".
(7) Need "to consider the appropriate role of the teacher in a constructivist classroom".

(8) Need "to promote teachers' (pre-college and college) awareness of research on student learning".

(9) Need "to promote communication and collaboration among cognitive scientists, psychologists, science educators and others involved in physics learning".

In this paper I will take the "needs" (1) to (5) as a starting point to discuss some trends of research from 1991 until the present state.

The first need formulated in 1991 was "to document learning pathways for different content areas in physics". Research in this direction of "promoting students' … conceptual evolution towards a suggested scientific model" (Psillos & Kariotoglu, 1999) was going on in the area of electric circuits (Niedderer & Goldberg 1995, Clement & Steinberg 2001), in the area of fluids, gases and pressure (Psillos & Kariotoglu 1999; Meheu 1996; Givry 2003), in the area of atomic physics (Petri & Niedderer 1998; Asikainen et al. in this symposium), in the area of bond conceptions in chemistry (Taber 2001), and in others. Two investigations of this kind are reported in this symposium (Givry & Tiberghien and Asikainen et al.). Their main importance is to describe students' own constructions (e.g. as intermediate conceptions), and by doing so to inform researchers or teachers what was learnt in different phases of the teaching learning process, and what is learnable.

The second need was "to construct ways of describing cognitive systems that are useful to researchers in physics education". Here, it must be clearly stated that there is no agreement yet in this direction. The disagreement is whether to use cognitive models at all, and if yes what kind of cognitive framework is most promising. This can be seen e.g. in the special issue of IJSE on "learning process studies in physics - an integrative perspective" (Roth 1998). One suggestion has been formulated by Niedderer (2001).

The third need was "to develop research methodologies that would be appropriate for carrying out learning studies". In 1991 (Niedderer et al. 1992), the following types of studies were described: "Learning process studies (LPS)", in which the data is collected continuously during the learning process, "learning states studies (LSS)", in which selected states before, during and after teaching are described, and "learning outcome studies (LOS)", which focus mainly on describing the state of student understanding at both the beginning and the end of the learning process. The LPS methodology has so far been used with some case studies with single students (see references above, under first need). Of special interest are some studies, which used a mixture of LPS and LSS (Petri & Niedderer 1998; Psillos & Kariotoglu 1999; Clement & Steinberg 2001; Taber 2001). This might be a possibility to develop a methodology for investigating learning processes even of whole classes.

The fourth need was "to document changes in student's conceptual ecology". "A student's conceptual ecology consists of many different types of knowledge that provides the context in which a student will respond to specific learning opportunities" (Hewson and Hewson 1992). Taber (2001) and Petri & Niedderer (2003) have followed this line of thought, and Hartmann's doctoral dissertation results (Hartmann & Niedderer 2005) can be interpreted along these lines.

The fifth need was "to examine issues regarding conceptual change". This theoretical framework has become the dominant scheme to analyse learning processes (Duit & Treagust 1998). On page 13, these authors also stated, "that real learning pathways are very complex and cannot adequately be described by just conceptual growth or conceptual change".

Conclusions

The results of learning process studies may lead to reconstruct the curriculum, either by adapting the objectives of the "knowledge to be taught" to be closer to what is learnable, as "steps of learning" (Tiberghien 1997), or to revise certain elements of the learning environment. This might be even more relevant once a methodology for learning process studies of whole classes will be achieved.

Another direction seems relevant: to extend learning process studies to the question of learning effects by certain elements of the learning environment (see Budde & Niedderer in this symposium). This could show certain elements to be especially fruitful for students to construct conceptions, which are closer to the intended ones.

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Studying the evolution of student's ideas in a physics classroom

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Context of the research

Since the late 1970's there have been major efforts in science education research to identify physics students' conceptions (e.g., Pfundt and Duit 2004). This body of literature demonstrates: (a) that students' conceptions differ from the standard views of science, and (b) the robustness of students' conceptions in the face of efforts to change them. Different models have been proposed for describing the conceptual change students undergo (e.g., Vosniadou 1992) and some studies identified conditions that would support the evolution of students' initial conceptions towards scientifically correct ones (e.g., Strike and Posner 1992).

Theoretical background

Based on previous theoretical model (Minstrell 1992), we develop a model (called "*idea*") to continuously study student's learning (defined as evolution of student's ideas). In this way, each student can use a set of ideas (which could be contradictory between themselves): each idea can be expressed in several situation (defined as a question and the material elements in the setting), the set of these situations represent the domain of validity of an idea. This definition allows us to follow the evolution of student's ideas through: (a) the time (Niedderer, 2001) and (b) the situations (Givry, 2003). Furthermore, we can describe three kinds of evolution, which could appear on our data: (1) a student uses a new idea, (2) the domain of validity of an idea increases or decreases, and (3) a student establishes a link between several ideas, called: "network" of idea.

We use the French concept of "*milieu*" to study the factors, which support the evolution of student's ideas. It is composed of several elements with which students could interact to learn (Brousseau, 1998). Based on a socio-constructivist approach and literature from didactics of physics, we define the milieu with three kinds of interaction (Figure 1):

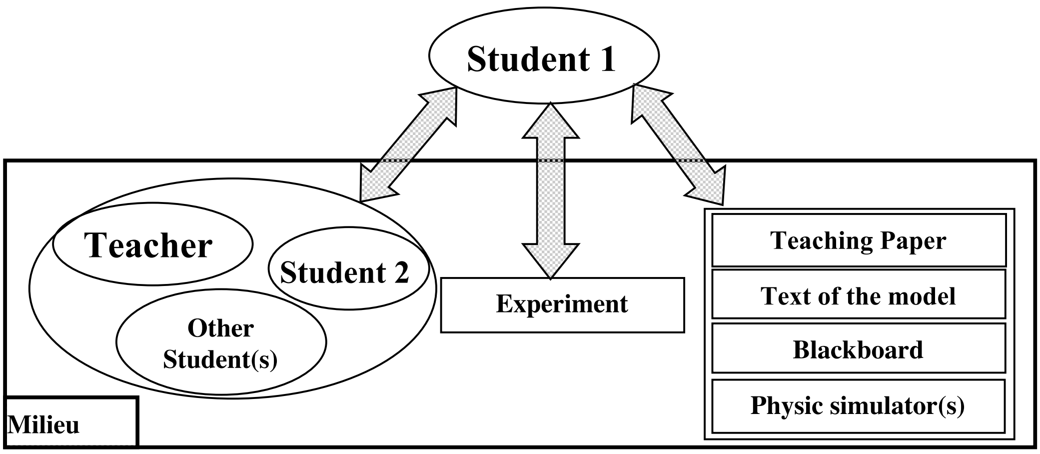

Figure 1: *Milieu* composed by different elements
(social, experimental, teaching material), which student could interact to learn.

Research questions

The purpose of our presentation is to give new elements to follow students' conceptual change and the factors that support this change. Providing empirical results from a longitudinal study in a French physics classroom, we answer the questions: How do student's ideas about gases evolve during a teaching unit? What are the elements that support this evolution? .

Research design

School context and participants

A group of physics teachers and researchers (including both authors) designed the curriculum to be taught over a one-month period (6 lessons) for students at the upper secondary school level (equivalent to tenth grade [15-year-old students]).

Curriculum

The teaching unit[1] consisted of six lessons: two sessions (1 hour, whole class) and four laboratory sessions (1 hour 30, half-class). It adopted a socio-constructivist approach with respect to three main dimensions: (a) modelling activity (Tiberghien, 2000), (b) semiotic registers (Duval, 1995), and students' conception on gas (i.e., Benson & al. 1993). The purpose of the unit was to allow students to use (a) macroscopic variables (pressure, volume, temperature and quantity of matter), and (b) their interpretation at the microscopic level (molecules' collision and velocity) for describing and explaining gas behaviour.

Data collection

Different types of data were collected including videotaped interviews and lessons and questionnaires sampling student responses to questions about gas behaviours. Altogether, the database comprises 420 questionnaires, one-hour taped interviews with 14 students, 48 hours of classroom video featuring the same 14 students, and approximately 160 pages work sheets. Following the approach of the Learning Process Studies (Niedderer & al., 1992), fourteen students were videotaped *continuously* during one month of the lessons in classroom. The 14 students featured were interviewed prior to and after the unit in videotaped sessions.

Data analysis

We selected video extracts based on two observable criteria: (1) use of words about gas by teacher or students (i.e. air, gas, molecule) or (2) experiment handling used by students. We transcribed each video extract and our transcription included: (a) the context and (b) student's: speech, gestures, manipulation, and written works. Then, we construct student's ideas about gas based on (a) his (or her) written works and (b) his/her speech, gestures and salient elements of the setting. For each idea, we tried to identify, which elements of the *milieu* (social, experimental, teaching material) are explicitly used by the student to support his/her idea.

Results

With our methodology, we followed the different kinds of evolution of two students' ideas about gas (called Anne and Ellen) during the entire teaching unit. Furthermore, we identified several explicit elements of the milieu, which support this evolution.

The first kind of evolution - *to express a new idea* about gas - appears 12 times for Anne and 9 times for Ellen during the teaching unit. This kind of evolution could be supported by some specific elements of the milieu. Indeed, new ideas about the meaning of words (like macroscopic, pressure) are supported essentially by the teacher's discourse and the teaching paper. Furthermore, the text about the model of a gas supports new ideas about the properties of gas (i.e.: homogenous distribution, choc of molecules).

The second kind of evolution - *to increase the domain of validity of an idea* (e.g. student expresses the same idea in another situation) - appears 19 times with Anne and 20 times with

[1] The teaching unit can be download at URL: http://pegase.inrp.fr/

Ellen during the teaching unit. A situation is new, when (1) the question changes (e.g. new question about the same material) or (2) the material (objects or events) changes (e.g. a syringe and a balloon). This kind of evolution is the most frequent for the two students during the teaching unit. However, no specific kind of elements (social, experiment or teaching material) of the milieu supporting this kind of evolution appears. Indeed each element of the milieu could support the increase of the domain of validity.

The third kind of evolution - to *establish a link between several ideas and develop a network* - is used 9 times by Anne and 7 times by Ellen during the teaching unit. This kind of evolution is supported essentially by the manipulation of experiment.

The other kind of evolution - to decrease *the domain of validity of an idea* - is used 1 time by Anne and 3 times by Ellen. This kind of evolution is particularly important, however it appears only a few times during the teaching unit and it necessitates the use simultaneously of several elements of the milieu (essentially discussion between students and manipulation of experiment).

Conclusion

Our results show that the principal evolution is the increase of the domain of validity of an idea. This kind of evolution is implicitly developed by the teachers, by giving different exercises. However, this kind of evolution is rarely assessed. Consequently, we propose to design teaching units, in which the same concepts are studied in several situations. Furthermore, our results about the elements of the milieu showed that each kind of element could support an evolution of students' ideas. Consequently, we propose to make available the maximum of elements to students. Other results show that the discussions between students are particularly important, because they support (a) the new ideas about all the aspects of gas (meaning of word, gas actions, distribution, molecules...) and (b) all the kind of evolution (domain of validity, links …).

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Physics teacher students' photon models during a quantum physics course – a case study of a single student

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Background

The concept of photon has an essential role in explaining and understanding quantum phenomena, but to understand the concept can be problematic (Mannila et al. 2001, Jones 1991). Photon and phenomena related to photon are described in, for example, textbooks using different types of models, and models in general have an essential role in understanding photon as a concept (Greca and Freire 2003). However, the photon as an entity differs entirely from the classical entities and their properties. To understand photon as a quantum entity, students should have a profound understanding of the models in physics, of the epistemology of models and modelling, and of the ontological discrepancies between the classical and the quantum world.

To find solutions to the previously mentioned problems, a research-based quantum physics course was designed and implemented, and the students' learning processes were studied. The stated research question in this paper is:

How do students' photon models change during the course?

The aim of this paper is to describe the development of a single student's photon models during the teaching intervention. We are interested in finding out, which photon models the student has and how he uses them. For this purpose, we present and evaluate the learning process of a single student, Esko, from a theoretical perspective. Students' learning processes have been studied earlier, for example, in the context of atom physics by Petri and Niedderer (1998).

This research-based quantum physics course is designed for preservice and inservice physics teachers. The empirical background of quantum physics (temperature dependence of specific heats of di-atomic molecules, black body radiation, the photoelectric effect, the Compton effect, the double-slit experiment, and the Stern-Gerlach experiment) forms the basis of the course. The need for quantum explanations and the motive for learning them is created by using an instructional design, which helps the students to recognise a conflict situation between a classical hypothesis and empirical evidence. The emphasis on the course is on qualitative representations of knowledge, conceptual understanding, and acquiring a reasonable level of theoretical understanding. In addition, the students' prior knowledge and the reported problems in learning quantum physics have been taken into account. Furthermore, a meta-level aim is to help teachers to explicitly reconstruct the photon concept through examining quantum phenomena and their properties. An earlier paper on the topic presents more details about the course (Asikainen 2005). This paper and the reported study is a part of a research project that concerns teaching and learning quantum physics in physics teacher education.

Methods and the Sample

This study is a case study, in which selected students are individual cases. The whole cohort is also considered a case. The study consists of two implementations. This paper focuses on the first implementation in spring term 2004, in which the students are preservice physics teachers (N=8). The second implementation was started in September 2004 and ended in June 2005. These students are inservice teachers (N=21) who are mostly mathematics majors.

All the lectures and exercises were videotaped in order to monitor the teacher's speech and behaviour. A pre-test was implemented at the beginning of the course. Based on the results of the pre-test, five case students were selected. The case students were interviewed three times during the course; in the second, the fifth and the tenth week. They were also interviewed a week after and 25 weeks after the final exam to detect long-term learning effects. The interviews consisted of open-ended and problem-based questions, and they were videotaped. The pre- and post-tests and interviews 1, 2, 4, and 5 contained questions related to the photon. Interview 3 did not have any questions related to the concept of photon.

Esko is a case student on the first implementation. He was in the middle of his physics studies and had already completed his teacher training. On the basis of the pre-test, he was an average student.

Findings

Esko's speech and written responses have been examined to find out which models he uses and how he uses them. The properties of different photon models in Esko's learning process were identified.

<u>Pre-test and Interview 1</u>. In the pre-test, Esko defines the concept of photon as a constituent of light (*corpuscular photon model*). After the pre-test, Esko attends lectures that discuss models in physics. In the first interview, Esko specifies his conception of photon by telling that photons have properties that are untypical for classical particles. So, he seems to have an idea of the properties of quantum entities. He also has a rough idea of quantisation of energy, even though he does not use the concept. However, he seems to have some problems with the understanding of the concepts and their relationships.

<u>Interview 2</u>. After the previous interview, the lectures have covered temperature dependence of molecular heat capacities and black body radiation. Esko uses the corpuscular photon model. In addition, he concludes that photons have wave properties, although they are corpuscular particles (*dual photon model).* Instead of referring to empirical evidences of photon's properties, Esko uses simple circular reasoning and draws a conclusion that photons have essentially the same properties than light. Again, Esko misunderstands some relationships between concepts.

<u>Post-test and Interview 4</u>. Since Interview 2, the photoelectric effect, the Compton effect, the double-slit experiment, and the Stern-Gerlach experiment have been covered in the teaching. Esko defines photon as an *interaction carrier*, but he does not seem to understand the concept properly. However, he has developed an idea of photon's existence in the interaction. Esko's written answers do not include any references to the corpuscular photon model, and he uses the dual photon model in a more epistemologically acceptable manner. In interview 4, Esko does not show any evidence of new information related to photon. Esko does not express any problems with conceptual relationships.

<u>Interview 5</u>. Esko uses the *interaction carrier model* to describe photon. In addition, he refers to the photoelectric effect as an experimental evidence of photon' existence. He also seems to have adopted an idea of Heisenberg's uncertainty principle.

Conclusions and Implications

This paper describes Esko's learning process of photon by describing his photon models. According to the results, it is difficult for Esko to describe the concept of photon without using classical concepts at the beginning of the course. He uses the corpuscular photon model together with the dual photon model even at the midpoint of the course. Similar difficulties in changing the viewpoint from the classical to the quantum physics one are reported in previous studies (Mannila et al. 2002, Greca and Freire 2003). Although Esko has difficulties with understanding the dual nature of photon at the midpoint of the course, at the end of the course his conceptions seem more organised. Esko expresses problems with understanding concepts and their relationships in the pre-test and in Interviews 1 and 2, but not in the second half of the course. In the second half of the course, Esko starts to use the interaction carrier model together with the dual photon model. He uses the interaction carrier model also in the delayed Interview 5.

Typical of Esko's learning process of photon is that even though he uses three qualitatively different models to describe photon, all the models seem to be fundamentally classical. After Interview 1 he did not show any evidence of understanding quantisation. Despite the fact that Esko adopted only few properties of the teaching model of photon, his conceptions of photon developed towards the scientific ones.

The designed course was an optional course and Esko, as many other students on the course, had already studied a traditional quantum physics course. However, the level of his conceptual understanding was moderate after the traditional instruction. It seems that despite problems in understanding photon, this ontologically and epistemologically emphasised quantum physics course assisted him to develop his meta-conceptual awareness. This is essential, when the aim is to understand quantum physics and its entities. Teaching approaches that use students' pre-knowledge are valuable, if the meta-level goal of quantum physics teaching is to help students to construct a coherent idea of photon.

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Influences of taught content on student learning in quantum atomic physics

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Introduction

According to von Glasersfeld (1992), the relation between teaching and learning can be seen as a resonance between learning environment and students' mind. In this paper we report case studies about resonances between certain elements of taught content as part of the learning environment and the evolution of students' conceptions as part of their cognitive system. The teaching approach uses two alternative quantum atomic models: a probability density interpretation of the ψ-function for bound states of an atom alongside with the "electronium" interpretation (Herrmann 2000), which is similar to a charge cloud model.

The design of the study

The case study data, which are presented here, were collected as part of a project to evaluate the Bremen teaching approach (Niedderer and Deylitz 1999). Alongside the evaluation of the learning of the full cohort of students (26 students in total), exploratory case-studies, focussing on two 18-years old students (Thomas and Klaus), were carried out to obtain a better understanding of the influence of the teaching on the development of the individual student's conceptions. The results of the evaluation and of other studies about students' conceptions allow estimating to what extent the (evolving) conceptions of the two students are representative. Both students were about average in their school achievement in physics.

Approach to analysing the students' learning

By carefully following the talk of individual students and relating it to the content of teaching, it is possible to test these teaching hypotheses. Observations are made to ascertain whether, and after how many repetitions and discussions, the students construct the intended conceptions. In this way, the opportunities and difficulties presented by different teaching approaches can be evaluated against each other, and principled decisions about the planning and design of teaching can be made. Such an approach contrasts with more common practices in designing teaching approaches, which often involve following traditional teaching paths or relying on thoughtful, educated guesswork.

A mode of data analysis was developed which considers the influences of both the individual student's preconceptions and the taught content on the learning of the student. This approach is summarised diagrammatically (see figure 1) in such a way that differences between the contents that are taught (on the left side) and the conceptions that the students construct (on the right side) are made explicit. The influence of the taught contents on each student's conceptions is described in terms of the concept of 'resonance' (Budde et al. 2002; Budde 2004). The term 'resonance' is used to signal the fact that learning outcomes depend on the extent of 'fit' between the taught contents and the preconceptions of the student (von Glasersfeld 1992).

The analysis was based on definitions of different types of resonances (see Budde 2004). We present here for illustration a few of the defined categories:

<u>Congruent resonance</u>: the student constructs in his own independent thinking conceptions, which are essentially equal to the content presented in the learning environment before.
<u>Disgruent resonance</u>: the student constructs in his own independent thinking conceptions, which are essentially different to the content presented in the learning environment before.
<u>Spontaneous (congruent) resonance</u>: Already after the first presentation of a certain content a congruent resonance is happening.

Alongside these categories, graphical symbols such as thick and thin arrows and others, were defined.

Results

Only few results can be presented here. We chose results about the acceptance of the two alternative quantum atomic models by students.

For Thomas the electronium model shows a congruent resonance from the early stages of teaching. After the pre-questionnaire, in which both models were introduced briefly, Thomas took the initiative in using a charge cloud model in an intuitive way.

Although Klaus preferred a probability model at the beginning, he finally switched to the electronium model. After the probability and electronium models were discussed in detail, both Thomas and Klaus, and all their classmates, agreed that they preferred the electronium model. One repeatedly expressed reason, from both students, for this preference of the electronium model focussed on its substantial, visual appearance. Thus Thomas commented:

"Me too. I also rather prefer the model of Friedrich Herrmann. It is more descriptive. It is easier to imagine. In this model, the electron does not disappear and appear again without one knowing, how it managed this [like in the probability model]."

For all nine students in the class, the electronium model achieved a high acceptance. Furthermore both Klaus and Thomas were still able to outline the electronium model in the control-interviews two years after the end of the instruction, which proves the stability of the electronium conception. Klaus even mentioned that he had given up the old shell conception rather than giving up the new conceptions, which is what is normally observed when only teaching the probability model. Klaus made the following comment about the shell model:

"I don't know, because I have discarded that [spatial shell] model, I do not precisely know it anymore."

There were two further aspects of quantum atomic models in general, which were frequently and spontaneously referred to by both students and thus constituted a strong congruent resonance for the students. These conceptions achieved a high acceptance for the students and were stable. The two aspects are:

- Concerning the charge or probability distribution in the ground state (1s-state): The charge or probability density is the highest at the nucleus and decreases to a higher radius.[2]
- Concerning the change of the distribution in the case of a transition between two stationary states: The charge will move away from the nucleus (the charge will be distributed more distant from the nucleus) if energy is added.

The majority of all students (17 of 26) mentioned spontaneously the decreasing charge or probability density to a higher radius in the post-questionnaire. It is assumed that the high acceptance outcome results from the fact that the new ideas build upon students' preconceptions. Many explanations were given by students for this characteristic trait of the distribution.

The findings for Klaus and Thomas are summarised in Figure 1. They explained the charge distribution in terms of attractive or repulsive electrostatic forces. The students also used analogies between atoms and their ideas about the atmosphere or water, where the density decreases with height or increases with depth. The effect of the electrostatic force is seen as

[2] Although this description is correct for all states (if the region with nodal areas is disregarded), it is assumed that the students especially imagine the 1s-state. One indicator for this is that the students always draw the 1s-state when asked for their image of an atom.

being equivalent to the effect of pressure, which is interpreted as compression: the higher the force or pressure, the more the substance is compressed, the higher is its density.

The main argument for the characteristic distribution given by the two students is, that it is simply logical that the charge or probability is distributed like the electrostatic force or field. In using a lines of force representation to illustrate the distribution in the atom (see Figure 1, right side), the distribution is reciprocally proportional to r^2 like the acting electrostatic force, but in fact the distribution follows an exponential function.

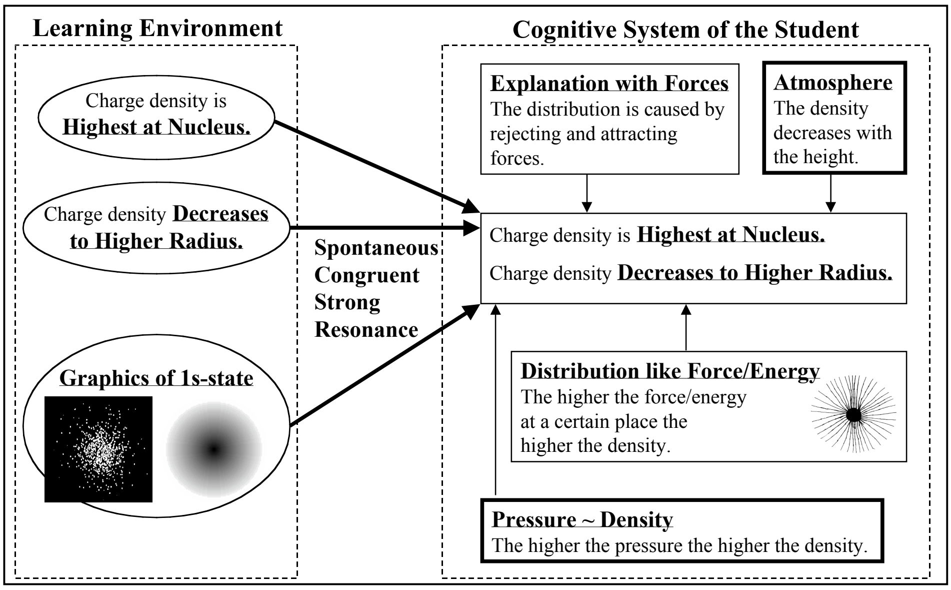

Figure 1: Examples of spontaneous congruent strong resonances

It appears that if the teaching focuses on the aspects that are plausible to the students (distribution in the 1s-state; the uptake of energy causes a more distant distribution), this supports a high acceptance for a quantum atomic model.

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