Published in R. Duit, F. Goldberg, H. Niedderer (eds.), Research in Physics Learning - Theoretical Issues and Empirical Studies (pp. 74-98), Proceedings of an International Workshop in Bremen, Kiel: IPN

Towards an explicit description of cognitive systems for research in physics learning

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> *"We can't consider education a science until we can say what is in the mind, how that relates to what is in the world, and how what we do affects what is in the mind.* " (Lawler, 1987, p.17)

1. Introduction

The aim of this paper is to contribute to the development of a theoretical model that can be used to guide analysis and to interpret research results on understanding and learning in physics as constructions about what is going on in students minds. We want to promote the formation of concepts for the description of cognitive systems that are constructions of, and useful for researchers in this field. These concepts should be more closely related to empirical findings in physics education research than to psychological theories. Physics education as a serious science has to establish its own paradigms and research traditions and its own field of practical work: science instruction.

Our research group at the University of Bremen has worked on the explicit description of cognitive elements of students' reasoning in physics for more than ten years. Three doctoral dissertations have been finished on the students' "matrices of understanding" in the fields of mechanics (Schecker, 1985), quantum physics (Bethge, 1988) and philosophy of science (Meyling, 1990). The components of those matrices of understanding provide examples of explicit descriptions of cognitive elements of students. (See Appendices 1, 2, and 3). The data bases were gained from transcriptions of classroom dialogues, interviews, questionnaires etc. The data were evaluated using a heuristic, qualitative interpretive method of forming and validating hypotheses about underlying general traits in students' reasoning.

We believe, that the research results on students' conceptions and alternative frameworks *from all over the world* provide a valuable basis also for the explicit description of cognitive elements of students and their learning processes.

In formulating our model we distinguish between thinking and learning in the following ways:

(1) *Thinking* is described as processes in the mind using *existing* cognitive elements (conceptions, beliefs, frameworks, knowledge) in a new context.

(2) *Learning* is described as the *change* of elements or the change of cognitive processes using cognitive elements, which result from developmental processes of the cognitive system interacting with external situations.

There are at least two purposes of such an explicit description of cognitive systems in special content areas (e.g. mechanics, optics, electricity, quantum physics): *first* to "help teachers to recognize and develop student conceptions" (Minstrell, 1991) and so foster good conceptual change-teaching and *second* to describe *physics learning* on the basis of explicitly described hypotheses about cognitive elements and processes, aiming at generalizable results about the researcher's constructions of what is going on in students' minds during learning processes within special domains of physics.

We want to promote the description of research results of physics education explicitly in terms of cognitive structures. We are convinced that explicit concepts and propositions about knowledge representations and cognitive processes in the mind will make empirical research and interpretation of data more powerful.

Let us draw a parallel to the role of physics concepts in talking about physics phenomena (see Fig. 1): If we use the theoretical term "charge" in a statement like "the PVC-film is charged" this is more than just the operational statement "the rubbed PVC-film causes a swing of the needle of the electrometer".

	objects, observations	**concepts**
physics	rubbed PVC-film a swinging electrometer needle	charge attractive force
science education	actions of students	elements of cognitive systems

Fig. 1: The use of theoretical concepts

The use of the term "charge" activates a whole network of inter-connected ideas which involves electric forces, types of charge, measuring of charge etc. Theoretical terms help us to structure, comprise and exchange ideas about the nature of an observed system. We suggest that explicitly forming and using general concepts about cognitive systems in physics learning studies would serve a similar function as using a concept like charge in electrostatics.

So we are looking for researchers' representations of students' representations of the world in physics-related areas (mechanics, optics, electricity, atomic physics). To promote discussion about our ideas we have structured our paper along the following issues:

- Discuss the theoretical level in some descriptions of current research results in physics education
- Describe an outline of a model of cognitive elements in a cognitive system with a graphical representation, related to previous research results in physics understanding and learning, and related to some basic concepts of knowledge representation from computer science and psychology
- Give some general comments on describing *thinking* and *learning* as processes in a cognitive system model
- Discuss two examples of reformulating research results using this model, one for understanding (Schecker, 1985) and one for learning (Brown & Clement, 1987)

We also want to point out clearly what we do not intend to do in this paper: We do not intend to present a new general theory of learning. Only over a very long time scale could this be a final result of many investigations using explicit models like the one we propose.

2. Research on understanding and learning in physics: Operational and theoretical descriptions of empirical results

Titles like "the architecture of cognition" (Anderson, 1983), "mind design" (Haugeland, 1985), "mental models" (Gentner & Stevens1983), "representation in memory" (Rumelhart & Norman, 1983) show that general explicit models of mind have been developed in psychology and cognitive science. Researchers in science education on the other hand often use more operational descriptions of their results on understanding and learning. We do not believe that general models can be simply applied to understanding and learning in physics, but we strongly suggest using *explicit models and descriptions* of what we think - on the basis of our broad selection of research data - to be going on in students' minds.

On the following pages we analyze the kind of descriptions in some selected recent research papers to clarify what we mean by "explicit theoretical descriptions" of results. While "operational descriptions" give reports of student behaviour in specific situations (e.g. tasks in tests), "theoretical descriptions" try to make inferences about conceptions, concepts, ideas, schemes or abilities students show over a range of different situations.

Operational descriptions of empirical research results on understanding document students' behaviour in special situations, often in an interview or test setting. Typical formulations are: "Students answering the XY-problem correctly ..." or "students who give the correct response to ..." or "failure to recognize ..." or "students who are unable to relate concepts of physics to ...".

These results show students' behaviour in great detail and closely related to what is directly observable. They do not try to construct hypotheses about corresponding elements of the cognitive system which supposedly generates this behaviour and could be applicable to a group of similar situations. We give some examples:

> *"Failure to recognize that accelerations, not forces, must be used to compare motions and that therefore mass must be taken into account."* (McDermott & Somers, in these proceedings)
>
> *"All of the students initially answering the table problem incorrectly and who received the experimental explanation answered the post question about the book on the table correctly and with high confidence."* (Brown & Clement, 1987).

In a second example from Bendall and Goldberg (1988) there is a relation to a set of situations in an interview, but the formulation of the results is given in the form of a negation of understanding in the sense of physics. This negation again tells us little about the authors' hypotheses on underlying general elements of students' cognitive systems which could form the background for the students' problems:

> *"The analysis of the data from the assessment of the students' prior knowledge indicated that the students had no significant understanding of image formation by a converging lense before working through the lesson."*

On the other hand we also find explicit theoretical descriptions of elements of cognitive systems as a result of empirical studies on understanding. Bendall and Goldberg in the same study give the following description of understanding after a teaching process:

> *"Table 2 shows the percentage of students in each group who, when giving a verbal justification for their predictions, made consistent use of the basic ideas developed in the instructional lesson."*

The "basic ideas" are described in table 2 explicitly, e.g. idea 1: "lense required for image formation", idea 2: "image formation where light is converged to a point". These are ideas of physics, but they are used to make hypotheses about what is going on in the students' cognitive system during thinking and learning in this investigation. Empirical results on understanding have often been theoretically described by formulating alternative conceptions as elements of students' cognitive systems. A short overview of such conceptions in the domain of electric currents is given by McDermott (1991, p.309):

> *"We were able to identify several common misconceptions that have also been identified by other investigators. These include the following: Current is used up by the bulbs in the circuit; the battery is a constant current source; the direction of the current, the order of the elements and the physical placement of the elements all matter."*

In this statement alternative conceptions of students are explicitly described as potential elements of cognitive systems of students. As another example from the domain of mechanics, many researchers have contributed to the explicit formulation of the alternative concept 'force'. Schecker (1985) comes to the following general description of students' understanding of force: "Force is a general activity potential. Bodies in motion possess force. There is always a force in the direction of motion. Motion occurs in the direction of the resultant of all acting forces. (...) Force is not restricted to acceleration" (c.f. Niedderer, 1987a, p. 342). More examples are given in appendices 1 to 3, where explicit formulations of candidates for cognitive elements are described in the fields of mechanics, quantum physics and philosophy of science.

3. Towards a model of "cognitive elements in a cognitive system" for physics learning

3.1 Basic concepts

A cognitive system is our construction of elements and processes of the mind which we assume to underlie a student's thinking and learning. It is useful to have a general notion like this in contrast to specialized constructions like *scheme* (Jung), *alternative frameworks* (Driver), *matrix of understanding* (Schecker, Niedderer) or *subjective domains of experience* (Bauersfeld), because there is a great variety of such which need to be brought together for further development. Thinking and learning are processes inside the human mind. There is no direct access to a cognitive system. The data from which one can start the construction of hypothetical elements have to be gained from different types of interviews, questionnaires, classroom observations. The focus of data analysis in science education research has been shifting from quantitative, statistical methods to a wider use of qualitative methods of *protocol analysis*.

The basic concept of our model is a *cognitive system* which contains *cognitive elements* and *cognitive processes* operating on them and interpreting them. Cognitive systems are descriptions of "states of the mind". They contain "representations of knowledge" and "representations of meaning" (Rumelhart & Norman, 1983, p.1ff). Using the word "system" we also want to open the field explicitly to system theory: The cognitive system is seen as a selfreferential system which develops itself by its own dynamics and by interacting with other systems such as knowledge systems of teachers and scientists or the system of individual actions. To look at learning as a selfdevelopment of the cognitive system is a clear way to take a constructivist view of learning into account (Wolze, 1989, Fischer & v.Aufschnaiter, in this volume).

From the needs of research in physics education the following extensions seem to be essential:

- to use units of description for cognitive elements which have been developed in successful research on students' alternative frameworks during the past decades; we think e.g. of more complex systems than only knowledge, e.g. *frames of thinking* and *interests* (see 3.3).
- to distinguish between *current constructions* and stable elements of a *deep structure*. This relates to similar differences between a "working memory" on the

one hand and the "declarative memory" and the "production memory" on the other in Anderson (1983, p.19). We start with the latter extension in 3.2.

3.2 Current constructions and deep structures

If we abstract from domain specific factors there is a wide consensus about some findings of empirical research on students' ideas in physics:

i) Students' concepts are very resistant against change (e.g. Driver, Guesne & Tiberghien, 1985, Brown & Clement, 1987).

ii) Domain-specific investigations all over the world show very similar results about students' alternative concepts (e.g. about force, heat, current) (c.f. Duit, 1990).

iii) A limited number of core alternative concepts is sufficient to explain a wide variety of student actions in different situations.

iv) Students activate different concepts or different facets of concepts in situations which the physicist classifies as structurally equivalent.

v) Students adapt their ideas very flexibly to new problems. The concrete meaning of a broad concept develops within the situations it is applied to (*cluster concepts*, cf. Schecker, 1985).

vi) There are no "obvious" effects to be observed in "critical" experiments or "natural" conclusions to be drawn from physical data. Students' observations are concept-laden (as scientists' observation are theory-laden) and differ with slight changes in the situational setting.

These findings give evidence for a *duality* within the cognitive system: While i), ii) and iii) hint at stable elements, iv) v) and vi) refer to transient, context-bound elements. This leads us to propose a distinction in the cognitive system between the deep structure and current constructions (see Figure 2).

Wittrock (1985) reflects on the same differentiation:

> *"We must understand how students use their previously learned, often naturally and informally acquired, conceptions of science and ways of thinking to generate meaning for events that scientists explain in alternative and more sophisticated ways."*

We consider "previously learned conceptions of science and ways of thinking" as *stable elements* of the cognitive system and we see the "generation of meaning for events" as a process in the cognitive system related to a student acting in a present situation.

The process of formulating hypotheses about the deep structure of cognitive systems can benefit from a long and successful research tradition in physics education on misconceptions, alternative frameworks, subjective spheres of experience or matrices of understanding. In a more theoretical perspective Driver, Guesne & Tiberghien (1985, p.4) use the term 'scheme'. The authors emphasize the meaning of this term as a stable element of a cognitive structure stored in memory: "Thus, the term 'scheme' denotes the diverse things that are stored and interrelated in memory".

3.3 Types of cognitive elements from research on understanding and learning physics

The categorization of cognitive elements into *types* has to considered as a preliminary one. We are not yet able to give a satisfactory or even final description of such *types*. There are at least two problems:

- More specific elements may later on be explained by more general elements.
- The distinction between elements and processes of the cognitive system is not always clear, in fact they may be "so tightly intertwined that clear distinctions are impossible" (Rumelhart & Norman, 1983, p.9)

Furthermore we have to take into account different levels of cognitive elements (e.g. bits of knowledgde versus frames of thinking) and to differentiate between those elements which seem to be content specific (e.g. a concept 'force') and those which are not (e.g. the 'GIVE schema').

Many types of cognitive elements have been used in physics education research, and yet there is no theory available to reduce this complexity. Research in physics education itself has to decide which units are most important to understand student understanding and learning. So for the moment we take a more pragmatic view looking at those types of elements which so far have played a major role in physics education research. We see the following: concepts, conceptions, facets of students' knowledge; ideas and intuitions; schemes and schemes, semantic networks; objects, properties, events, relations; frames of thinking; interests.

Facets of knowledge

With this term Minstrell (see contribution in these Proceedings) aims at a similar general term as we do with "cognitive elements", perhaps being more oriented towards knowledge pieces and driven by the need of being useful in practical instruction: "A facet is a convenient unit of thought, a piece of knowledge or strategy seemingly used by the student in addressing a particular situation." Minstrell stresses similar points which are important in our work to find cognitive elements: "using students language as they justify their answers, predictions, or explanations"; and, "a facet may generalize several students' comments".

Concepts, conceptions

"Conceptions" are often used to describe the alternative concepts students have, such as current consumption in electric circuits or the relation of force to motion. It is important however to realize that the term 'concept' also has a cognitive meaning: At least during the historical process of development of a concept it is a cognitive entity in the mind of researchers. Later on in the process of theory development 'concepts' are formulated as the consensus of many researchers and this meaning of the concept is propagated in textbooks. At this point 'concepts' get kind of an objective and noncognitive meaning more related to matter than to the mind. The concept 'force' thus can have four different meanings: The official meaning of textbook definitions (non cognitive), the cognitive entity of a single physicist, cognitive entities of students having reached a sound physical understanding and students' cognitive entities in their alternative ideas of 'force' bound to motion. This relates to considerations of Lawler: "I suggest we establish a parallel terminology relating what is in the world to what is in the mind of the individual and to what the practice of education entails." (Lawler, 1987, p.17)

Semantic networks

Semantic networks have been used in psychology as representations of concepts or conceptions. They represent knowledge structures by schemes of nodes and relations, where the "nodes stand for concepts" (Rumelhart, Norman, 1983, p.21). In these proceedings this type of representation of cognitive systems is used by Fischler & Lichtfeld and Schwedes & Schmidt.

Ideas and intuitions

Perhaps 'ideas' will not remain as cognitive elements after a careful analysis but will be derived from other more general elements and cognitive processes. This might especially hold for spontaneous "ad-hoc ideas". But from a pragmatic view the formulation of hypotheses about ideas of students as their cognitive elements seems to be one of the most powerful steps in analyzing students behaviours with the aim of explaining it by cognitive elements. This step is e.g. used in investigations on learning in physics of Driver & Scott, Fischer & v.Aufschnaiter, and Jung (all in these proceedings). Sometimes the term "intuition" is used in a similar meaning.

Schemes, Schemata

'Schemata' have been developed as a form of cognitive elements also by psychologists: "Schemata are data structures for representing the generic concepts stored in memory." (Rumelhart. Norman, 1983, p.42). Their special explanatory power results from the fact, that schemata "are packets of informations that contain variables". Thus schemata can be applied in very different content areas by simply using different variables. E.g. the 'GIVE schema' (X gives Y to Z) (Rumelhart & Norman, 1983, p.42) can be applied to many everyday life situations as well as to electric circuits (the battery gives current to the bulb). In physics education schemata or schemes have been used as cognitive elements for explaining student behaviour by Driver, Guesne & Tiberghien (1985, p.4) and by Maichle and Jung (e.g. Maichle, 1985).

Objects, properties, events, relations, rules

Representations of these entities are to be viewed as elements of the cognitive system especially from a constructivist view (see Fischer & v.Aufschnaiter in these proceedings). For example, in grappling with the "book on the table" problem (see below), learning occurs when students construct a new meaning of 'table' in relation to 'force'.

Frames of thinking and interests

These cognitive elements seem to be important for learning in physics. Research in our group has always included more general elements of cognitive systems which we call "general frames of thinking" (in contrast to specific conceptions). One of those elements is closely related to an epistemological view of the structural differences between everyday-life thinking and scientific concepts and theories. We call this element the students' view of "the task of physics":

> *"Students tend to see the task of physics in investigating single problems of the everyday-life world with sophisticated methods. They tend to work on theoretical and abstract problems by transforming them into one special situation of the real world. They are not oriented towards looking for abstract and general concepts and principles"* (Schecker, 1985, pp. 152ff)

We have furthermore tried to formulate *interests* as elements of students' cognitive systems. We denote the whole set of cognitive elements belonging to the deep structure (see below) of the student's cognitive system his matrix of understanding (MOU). Figure 3 is using components of the MOU in mechanics to describe a cognitive system for collisions (see also Appendices 1-3).

The following graphical representation of the model (Fig.2) shows an overview of a cognitive system and its elements in current constructions and deep structure. It makes visual our assumptions in distinguishing between thinking and learning.

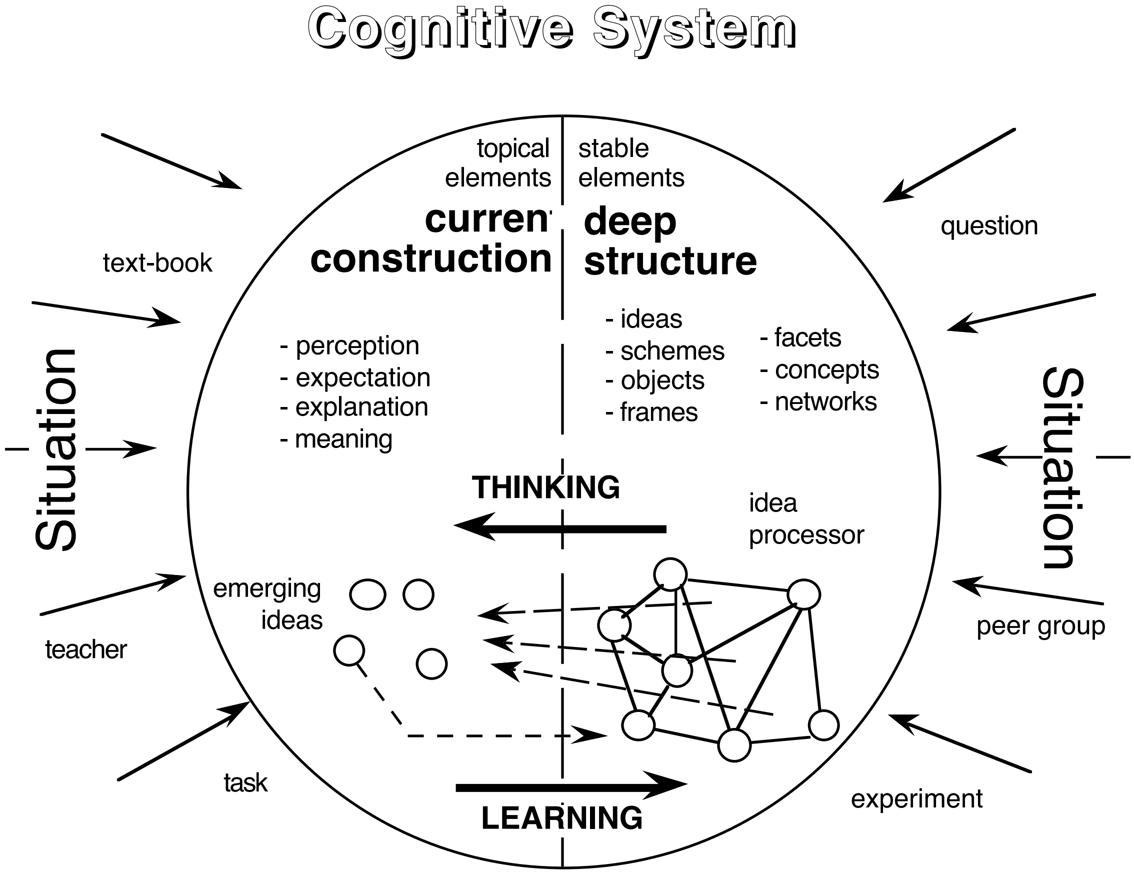

Fig. 2: Model of a cognitive system for science education research

The cognitive system model in Figure 2 shows perceptions, expectations, explanations, and meaning as current constructions. As mentionend above, the border between current constructions and stable elements and the related distinction between processes and representations in memory in many cases is not yet clear. So ideas in some cases might to be seen as kinds of stable elements, in others they are "emerging ideas" based on well known stable cognitive elements of the deep structure.

4. Modelling brain processes (*Thinking* and *Learning*)

An explicit model of cognitive systems has to deal with processes in the mind which explain

- the way cognition is *organized* in the mind: discrete "chunks" of knowledge vs. networks from which ideas emerge; hierachical structures vs. parallel domains of subjective experience, concept-bound ideas vs. episode-bound ideas),
- the way cognition is *generated*: the learner as an information recipient vs. the learner as an autonomous meaning processor; the interaction between the learner's existing cognitive structure and new experiences,
- the process of change: different formulations of the assimilation/accomodation process; the role of discrepancy between expectation and observation; conceptual change vs. coexistence vs. awareness of concepts.

One important idea for learning process studies is to distinguish between processes of *thinking* and processes of *learning*.

(1) For *thinking* we generally assume no changes in the "deep structure" of the cognitive system. The individual uses cognitive elements which already exist to make *current constructions* for the sensory input from a new situation, by this process also developing a (first) meaning of the situation. So *thinking* is based on priviously developed cognitive elements now being used in a new context.

> *Reasoning is dominated by a process of recognition in which new objects and events are compared to stored sets of expected prototypes, and in which specialized reasoning strategies are keyed to these prototypes.* (Rumelhart. Norman, 1983, p.50)

Current constructions guide actions, statements and even expectations in a given concrete situation. We believe that these constructions can potentially be traced back to an interaction between elements of the cognitive system's deep structure with sensory experiences. Schecker (1985) has discussed such interactions using word protocols from actual physics lessons. Still, we will not be able to cover all the potential elements of an individual's deep structure. Often we start an interpretive analysis by formulating hypotheses of students' ideas which we think could have produced their reasoning and statements. Then we try to explain each idea using other stable cognitive elements of the deep structure, elements which are perhaps already formulated. If we succeed in giving such an explanation, we consider the idea to be a current construction. If we do not succeed in this way, we either call the idea a stable element itself - if the same idea seems to come up rather often; or we call such a current construction an *ad- hoc-idea* , if it is only seldom to be observed. Empirical studies on understanding show many examples of ad-hoc-ideas which need to be considered more closely.

From a more constructivist perspective the spontaneous construction of perception and meaning is very relevant both for the process of thinking and the process of learning. Meaning is not transported by sensory experiences but generated within the individual's cognitive system (cf. Fischer & v.Aufschnaiter in these proceedings). Current constructions determine the meaning of words used by students, the perception of objects, and the rise of new ideas, i.e. they govern the process of reasoning. "The key idea of understanding understanding is that of meaning" (Strike & Posner, 1985, p.222).

One mechanism in this process of meaning construction could be to find relations between earlier experiences and a given new situation, i.e. between stable elements of the cognitive system and perception. Finding analogical relations could be one special form of this relationship. Current constructions which prove to be successful for problem solving can develop into stable elements of the deep structure. Changes in the deep structure of a cognitive system which progress the individual's problem solving competence can be considered as *learning* .

(2) *Learning* is seen as *stable changes* in the cognitive system which allow to explain stable changes in the individual's behaviour. White and Fredericsen speak of "modelling possible evolutions in students' reasoning about electrical circuits as they come to understand more and more about circuit behaviour" (1987, p.282). It remains to be investigated how "stability" evolves. We do not expect sudden shifts from an old conception to a new candidate but a fluctuating process of pondering concurrent conceptions in which the "new" one slowly gains strength.

We assume, that learning in an explicit model of cognitive systems could be explained by using elements of cognitive systems. Some ways of describing learning with relation to cognitive elements are:

- developing *new* cognitive elements with new meanings related to semantic networks (see Fischer & v.Aufschnaiter in these Proceedings).
- employing existing cognitive elements in a (new) context area, in which they had not been used before (see Schwedes & Schmidt in these procedings).

- changing the probability of existing elements to be activated, e.g. upgrading or downgrading the "status of conceptions" (see the paper of Hewson & Hewson in these Proceedings)
- developing new cognitive processes to deal with problems of a certain context area (e.g. make predictions about electric circuits only *after* thinking in terms of a theoretical model)
- increasing generality and concistency of the application of certain cognitive elements in explanations.

5. First example: Understanding in mechanics

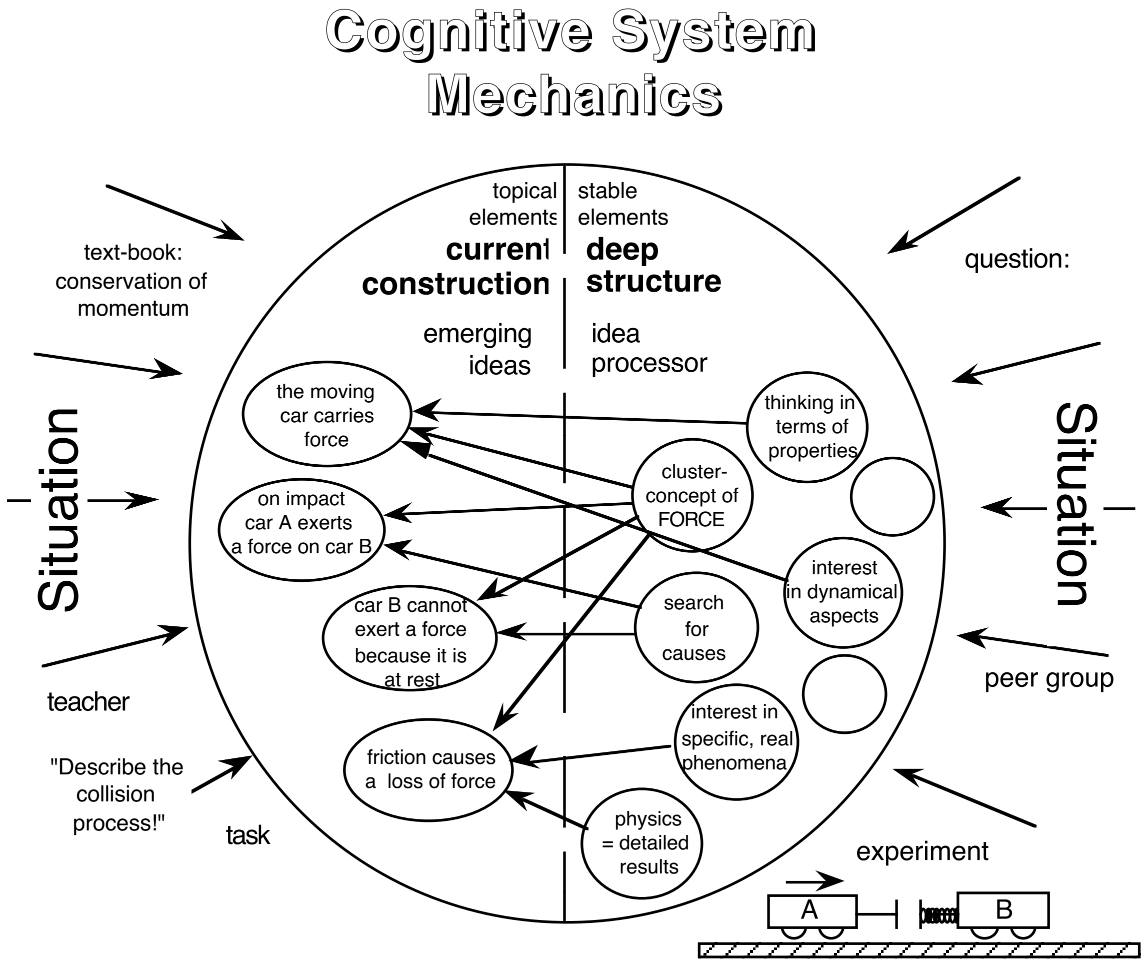

Fig. 3: Excerpts from the cognitive system *mechanics* (see also Appendix 1)

Figure 3 shows a specific example of the above cognitive system model applied to students' reasoning about collisions. While from the physicist's point of view the focus of attention fpr collision phenomena should lie on comparing the velocities before and after collision (later to be explained by the principle of conservation of momentum), students tend to think in terms of exertion and transfer of 'force'. This can be traced back to a general interest in dynamical aspects of motion in contrast to purely kinematic considerations. 'Force' is used by students in its *cluster concept* meaning (Schecker, 1985, pp. 270): 'Force' is a general activity potential: Moving bodies carry force (cluster facet 1), that can be activated and exerted (facet 2) and transferred (facet 3) to other bodies. Students do not use 'Force' simply as the same label to denominate concepts which they implicitly distinguish. 'Force of motion', 'kinetic energy', 'exerted force' etc. are different modes of one universal explanatory scheme. They are considered to be essentially the same things. Newtonian force is just added as another facet to this cluster. Its meaning is context-bound. The concrete situation determines the specific meaning of force. A student asked whether he found it necessary to discriminate between energy, force and momentum answered: "Well of course it is necessary. After all, they are different forces." (Schecker 1985, pp. 274)

Force in moving or living bodies is considered as a property of the body: *forcefulness*. Thinking in terms of quasi-material *properties* of bodies instead of *interactions* between physical entities is a very general feature of students' cognitive systems. It is also applied to colour, heat or weight. As car B in our example is neither moving nor living, it cannot exert a force on car A. All it can do is resist. Resistance in students' reasoning is different from an avtive force. A second deep structure element which prevents students from considering a 'force' of B on A lies in their search for the *cause* of events. For them the collision process has a clear direction: Car A plays the active part. It causes car B to move. This perspective is opposed to relational and functional descriptions which characterize the physicist's view. The search for causes is particularly misleading in the case of Newton's third law. The terms 'action' and 'reaction' fit well into the students' tendency to distinguish between active and reactive, resp. passive bodies (cf. 'book on the table' problem below).

Another candidate for deep structure elements of the cognitive system is the widespread idea that physics deals with detailed examinations of specific phenomena. Together with students' interest in such considerations this leads to their over-consideration of friction. While the physicist constructs an overlay of the pure phenomenon of uniform motion with friction effects, students follow a kind of 'holistic' path. For them friction losses are an integral part of motion. It makes no sense to abstract from them. For the physicist the actual collision experiment is just a prototype, a typical example to exemplify the universal principle of conservation of momentum. For students it is a specific phenomenon in its own right which has to be evaluated in detail.

So far we have considered the process of thinking: from the deep structure to the emerging ideas. This direction can be discussed on the basis of 20 years of research on students conceptions. A comparison of the deep structure elements of students' cognitive systems relating to mechanics shows that conceptual development demands not only learning new specific concepts like Newtonian force, but also developing new basic problem solving schemes and new perspectives on physical phenomena.

But how do such new ideas emerge? And how do they develop into new stable elements of the deep structure? The first question refers to learning strategies and learning environments which facilitate conceptual development. The second question has to be answered by studies about detailed and at least medium-term investigations of learning processes. Both questions can be subsumed under *learning studies*.

6. Second example: Learning Newton's third law

We briefly present here a reinterpretation of data from a "learning study" of Brown & Clement (1987)

The purpose of this reinterpretation is to explicitly formulate elements of the cognitive system and processes of change in a concrete example of one of the first *single student learning process studies* (Brown, 1987). This will be done by stating cognitive elements ('preconceptions') of the pre-instructional state and showing how the learning process can be explicitly described in terms of changes related to these elements.

In the first part of our reinterpretation we propose a set of cognitive elements of the cognitive system before teaching (everyday life view). We list them as following:

Concept 'force'
The structure of this preconcept is well-known from many research results (c.f. a summary up to, 1985 in Schecker, 1985, p.344 to 399). We use 'force' in its *cluster concept* meaning (cf. Schecker, 1985, pp. 270; see previous examples for details).

Object "book"
Material objects have the property of weight. Weight makes the book potentially active (downward) so that it can exert a force on the table. Related concepts: gravity, force

Object "table"

A table has the *property* and the *purpose* to hold things we put on top; it is rigid, not moving, and therefore can not exert an upward force. Related structure: objects in everyday life have *purposes*.

Object "spring"

A spring is flexible and potentially active when compressed, therefore it can exert a force. Related concepts: springiness, force.

Object "finger", object "hand"

Those objects are parts of living bodies and can therefore exert forces. Related concepts: living bodies, force.

These descriptions of cognitive elements show interesting interrelations: the meanings of the objects are partly determined by the concept 'force' in this context.

In the second part of our reinterpretation we try to model essential parts of the learning process observed using the elements formulated above. Brown uses the so-called "bridging strategy" (Clement, 1987). To come to a better understanding of a target task students start with a task that is analogous from the physics point of view. In the case of the "book on the table" being the target they start with discussing a finger pressing down on a spring. From the explicit formulation of cognitive elements given above, it seems clear that in this case students have no difficulties recognizing a down force from the finger to the spring and an up force from the spring to the finger. This, in our view, means a *thinking* process using the formulated cognitive elements (concepts, objects) in a new situation.

The "bridging strategy" now goes on with more examples and the research results suggest, that students sometimes have difficulties seeing an analogy between the different examples. The analogy between the "book on the table" situation and the "finger on the spring" situation for most students is difficult, it does not make sense to them (Brown, 1991, p.16, Clement, 1987, p.86). From our point of view this can be explained, because "table" and "spring" in students' cognitive systems have different meanings with respect to "force". This leads to a new interpretation to the effectiveness of the bridging strategy in this example: the "intermediate bridging cases" book on a spring, book on a flexible table and a microscopic spring model of the table are steps for a new construction of meaning for the object "table" and have probably little impact for a conceptual change of 'force' and Newton's third law. The result of the learning process for students is to see *also tables* have the property of springiness. This can be found in a student's statement: " ... I also know that the molecules of the table are springy and flexible." (Brown, 1991, p.10).

7. Conclusion

In this paper we have discussed the explicit formulation of hypotheses about physics-related cognitive elements and cognitive processes within a cognitive system model. We claim that the explicit representation of researchers' constructions of what goes on in students' minds is a powerful tool for analyzing and describing research results on understanding and learning in physics, and at the same time a frame of orientation for teaching.

> *"... in order to teach, one must construct models of those 'others' who happen to be the students."*
> (v..Glasersfeld in these Proceedings)

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Elements of cognitive systems: Excerpts from three doctoral dissertations at the University of Bremen.

Appendix 1:

Elements of cognitive systems in mechanics

Selected from a list of 27 items described by Horst Schecker (1985):

A) Generals frames of thinking and general interests

Transformation on realizations

- Students tend to transform problems that are meant as abstract thought-experiments on imagined everyday-life experiments: "What would happen if the experiment was really done?"
- This leads to a reinterpretation of tasks, taking into account those conditions which were meant to be neglected, e.g.. friction effects.
- Students resist against "unrealistic" abstractions in the teacher's reasoning.

The task of physics

The subject matter of physics are phenomena from the everyday-world. Physics gives precise explanations for single phenomena closely related to direct experience.

Formula orientation

Formulas are the central features of physics. Any problem can be solved if the right formula is at hand. Verbal descriptions of the meaning of concepts and their scopes or qualitative assessments of problems are only decorating accessoires and can soon be forgotten.

B) Specific preconcepts

Cluster concept 'force'

The word 'force' is used in great variety of physically different, context-bound meanings: Newtonian force, momentum, potential and kinetic energy, torque, time integral of force etc. This *indexicality* or vagueness is a power of everyday life concepts. It enhances communication in these contexts. The concrete meaning only sharpens out in a concrete context where the student uses 'force'.

Students do not simply take the same word to denominate concepts that they implicitely distinguish. The cluster-concept 'force' covers a wide field of phenomena and problems. For students "force of motion", "force of impact", "accelerating force" are different modes of on universal explanatory scheme. They are considered as essentially the same.

Motion and rest

Motion and rest are two qualitatively completely different states. There are natural frames of reference for the motion of bodies.

Action and reaction

Action and reaction act on the same body. Reaction is a force of the body by which it resists outer influences.

Appendix 2:

Elements of cognitive systems in quantum mechanics

Selected from a list of 15 items found by Thomas Bethge (1988).

A) Generals frames of thinking

Models are no "pictures" of reality

For students, models do not represent the "true picture" of atoms. They use different models of electrons and atoms in different contexts and for different purposes - even if the models contradict each other. These contradiction is seen and accepted by students.

Models are made for visualization

Students take models as visualizations and explanations in a macroscopic scale of reality. They aim at a high amount of exactness and plausibility of a model.

B) Specific preconcepts

Alternative conceptions referring to different groups of students or different states of the learning process.

Orbits (trajectories) in quantum physics

- Electrons move along in orbits or in oscillations. The classical notion of trajectories is conserved.
- Specific casees of "trajectories" are "regular orbits", such as circles or ellipses. These orbits do not exist in quantum physics - which does not mean "trajectories" in general are forbidden.
- Students strongly express the non-existence of "trajectores" as a major postulate of quantum physics. Nevertheless they still refer to the "motion" of electrons when they think about probability distributions.
- The concept of "trajectory" is combined with notions of "probabilty" and "wave function" from wave mechanics in several ways:
    - the orbits are "smeared", not exactly determined, "fuzzy"
    - the probability for a special orbit is given
    - the probability of parts of the orbit is given

"Probabilty" in quantum mechanics

- Students use "probability" as a pure formalism to solve physics problems. It is not connected to qualitative conceptions.
- Students want to understand "concretely" how the probability distribution originates. The ask for a causal explanation or a "mechanical" process.
- Students connect the meanings of "inaccuracy" and "events by chance" to their conception of probability.

The concept of energy in quantum physics

- The quantization of energy is readily accepted by students. They soon start to use it as a basis for their own reasoning. They do not ask for a physical explanation of this fact. Students seem to have no "need" for a more sophisticated atomic model. To the contrary: A more simple "model" can be based on this assumption.)
- "Energy levels" can be explained by any model of the atom. In different situations Students use different models to explain energy levels.
- "Energy levels" are lines in an energy level diagram
- Students use the concept of energy actively in their own reasoning. The conservation of energy plays an especially important role in students' own explanations, e.g. related to emission and absorption of light in atoms or molecules.

Appendix 3:

Elements of cognitive systems in science philosophy

Selected from a list of 40 items found by Heinz Meyling (1990)

A) Students' understanding of central concepts of science philosophy.

Alternative conceptions refer to different groups of students or different states of the learning process.

Laws of science are

- descriptions of basic natural facts, such as the rotation of the earth
- true pictures of laws of nature
- hypothetical propositions of science, gained by inductive or deductive methods, they may change in time

*An explanation of a phenomenon i*s given by .

- a description or clarification in a model or a theory
- describing the cause of the event or phenomenon
- relating it to wellknown and accepted laws or theories
- an exact description of reality as it really is

Hypothesis and theory

- Hypothesis and theory are synonyms, theory is preferred.
- A hypothesis is a guess which after being tested and approved becomes a theory
- A theory is far away from reality, of little practical value
- Theories are used for explanations, not for predictions

Models are

- representations of a scientific subject matter for the purpose of explanation and visualization
- made to represent certain aspects of reality
- taken for reality. The limitations are not clear

B) Students' understanding of the scientific process

Rationality of scientific processes

- Speculation and intuition have a negative meaning: they are of little value for science.
- Starting the process with hypotheses and then working with deduction is rated low.
- The scientific process should be theory-guided with experimental testing afterwards.
- The influence of general philosophy on the scientific enterprise is rated low

The meaning of experiments

- Students like to make their own experiments, but they want theory and experiment to be balanced in physics instruction.
- Experimental results have one unique interpretation.
- Experimental results can be interpreted in different ways: therefore scientists should hold back their personal view
- A statement of physics is true once it is successfully tested by an experiment

The pathway of scientific discovery

- The pathway is linear
- It begins with
    - a basic law of science
    - an experiment
    - a hypothesis
    - an observation
- The end point of science is
    - a basic law of science
    - a theory

C) *Interests of students*

- Students are very interested in "reality". (This reality has to be discovered by science.)
- Students are very interested in explanations of specific phenomena, observations of everyday life and technical processes.
- Students are very interested in technical applications of physics.
- Students are not so much interested in
  - the history of physics
  - discussing issues of philosophy of science in physics lessons.

D) *Pre-knowledge about different approaches in philosophy*

Students have little prior knowledge in this area. They develop ad-hoc interpretations like: "materialism" is the aim of financial and material welfare.