A model of the cognitive aspects of physics instruction

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A MODEL
OF THE COGNITIVE ASPECTS
OF PHYSICS INSTRUCTION

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SUMMARY

Two objectives are sought in this study: a systematic description of the cognitive activities involved in teaching physics, and an investigation of cognitive activities found in real life teaching of this subject. In order to construct a model of instruction in physics, one needs a model of the cognitive activities involved in learning physics, and also a model of the knowledge base which is the foundation of expertise in that subject.

Earlier research has provided a model of an adequate knowledge base, that is a knowledge base meeting the requirements of problem solving in physics. This model distinguishes four types of knowledge on the basis of their function in problem solving. The structure of the knowledge base is described in terms of problem schemata. This explicit description of an adequate knowledge base made it possible to formulate a model of the cognitive activities involved in acquiring such knowledge.

The present study extends this line to modelling instruction in physics. Like the model of knowledge acquisition, the model developed here has two dimensions, one of process, and one of content of the process. The process dimension is based on the fundamental principle of cognitive psychology that meaningful learning is an active and constructive process. Stimulation of this process is seen as one of the central tasks of instruction. This leads to the distinction between providing information and stimulating the deep processing of this information, that is to say the construction of knowledge. A further distinction is given by the concepts of integration and connectedness, introduced by Resnick and Ford to describe the quality of the structure of a knowledge base. The content dimension is described by the types of knowledge.

In the model so created three main categories of instruction processes are defined: presenting new information, integrating (that is bringing structure into) new knowledge, and connecting elements of new knowledge to prior knowledge. Each of the main categories has been divided into a number of specific instruction processes. In this way any limited and specific cognitive teacher activity can be described along the two dimensions of process and type of knowledge.

This model of physics instruction was validated by application to real life teaching at the level of first year university courses. Lectures and problem solving classes were recorded and analyzed as to instruction process and type of knowledge. Results indicate that teachers do indeed involve in the various types of instruction processes defined, and do divide their attention between different types of knowledge. Individual differences were demonstrated. The importance of this study, however, is not the possibility of comparing the teaching of individuals, but the creation of a terminology which makes it possible to reason about instruction in an explicit and specific way.
A MODEL OF THE COGNITIVE ASPECTS
OF PHYSICS INSTRUCTION

In recent years research has collected a large amount of information on the cognitive aspects of expertise, especially in domains such as mathematics and physics. One of the results is that the knowledge base of experts, as contrasted with that of beginners, is well structured, generally in a hierarchical pattern, and tuned to typical applications in the field. In accordance with these results, current theories of meaningful learning emphasize that learning is an active, constructive, and complex process. Information supplied to the learner by books, lessons or lectures has to be processed, that is critically assessed, structured, and practiced, in order to yield knowledge.

This has implications for the task of instruction. Before the days of reasonably cheap books, it used to be the task of instruction to supply information to students. In the present situation of abundance of information carriers, however, this task has become secondary to that of supporting students in the process of learning. In this study we have attempted to extend earlier research on knowledge and learning in the domain of physics into the cognitive aspects of the task of supporting learning in this domain. Speaking with the words of Laureen Resnick (1989), we attempt to move from theories of expertise and acquisition to a theory of intervention.

1. THEORIES OF INSTRUCTION

A theory of instruction needs to be based on a theory of learning, which, in turn, needs a basis in a theory of the knowledge base that forms the foundation of expertise at various levels, especially the level of the successful beginner. The well-known instruction theories of Ausubel (1978) and Gagné en Briggs (1979) are examples of this type of three-fold theories.

Ausubel, Gagné and Briggs all approach the teaching-learning process from the point of view of educational psychology and formulate theories of learning and instruction which are claimed to be independent of the content and structure of the knowledge base to be acquired. They give opinions on the general form of the knowledge base but not on its quality. With the growing emphasis of recent research on the role of subject matter knowledge in expertise (see for instance the overview in Chi, Glaser and Farr, 1988, or Achtenberg, 1990) there is reason to question the validity of general theories of learning and instruction, at least when teaching at university level is considered. Consequently, this study approaches the teaching-learning process from the point of view of content and
structure of the knowledge base to be acquired. We describe a model of instruction which is tailored to the needs of physics and other subjects where knowledge has to be applied in new situations such as problem solving and experimental work. More specifically, the study investigates instruction in a physics subject, Electricity and Magnetism, at the level of a first year university course.

Cognitive theories of learning stress the central role of the cognitive activities of the learner (Resnick, 1983, 1984, 1989): knowledge acquisition requires processes of bringing structure into new information and relating it to prior knowledge, processes which go much further than simply encoding information provided by the teacher. As a consequence, the result of the teaching is strongly dependent on the active processing of the content by the learner. The teacher does not shape the result of the learning process in the sense that the student acquires a copy of what is taught. All the same, the teacher can play an important role in stimulating students to carry out learning processes which are essential in knowledge acquisition. This can be done in instruction activities which explicitly demonstrate various ways of structuring knowledge, and which stimulate students to carry out this type of process on their own. In this study we use the term instruction process to denote one specific cognitive instruction activity of the teacher, for instance comparing the validity of two formulae.

This discussion illustrates the close relation between the instruction process of the teacher and the study process, or specific cognitive activity of the student. Before attempting to give a systematic description of instruction we therefore recapitulate the taxonomy of study processes which was used in earlier research (Ferguson-Hessler & de Jong, 1990) and the description of knowledge on which it is based.

2. A MODEL OF KNOWLEDGE AND LEARNING IN PHYSICS

2.1. Knowledge versus information.

Typical of the knowledge base required at secondary and university level in subjects such as physics is that students must be able to apply their knowledge in new situations, such as problem solving and experimental work. Reproduction of information is not sufficient to carry out the tasks used in examinations: a knowledge base which is adequate for these tasks must possess certain specific qualities. In an earlier study of the subject matter of a typical physics subject at the level of a first year university course, Electricity and Magnetism, we have given an epistomological description of the content and structure of a knowledge base which is suited for problem solving (Ferguson-Hessler & de Jong, 1987).

In such an ‘adequate knowledge base’ four types of knowledge are distinguished on the basis of their function in problem solving:

- Declarative knowledge; this is ‘static’ knowledge about definitions and facts, principles and formulae that apply within a certain domain.
- **Knowledge of procedures** and actions which can be carried out on the declarative knowledge of the domain.

- **Knowledge of situations** as they typically appear in problems in a particular domain.

- **Knowledge of strategy**, helping the student to organize his problem solving process by knowing which stages should be passed through in order to reach a solution.

The first three types of knowledge are typically bound to specific parts of the subject matter, while knowledge of strategy is more general and applicable to a wide variety of problems within a domain.

Success in problem solving is not guaranteed by the presence in memory of the four types of knowledge. A crucial step in the solution is relating the given problem situation to elements of declarative and procedural knowledge which are relevant and which could contribute to the solution. Evidently, the **structure** of the knowledge in memory is decisive for the possibilities of the solver to carry out this part of the solution. Resnick and Ford (1981) have distinguished different aspects of the quality of a knowledge structure. Two of these aspects are related to the way in which the content is organized:

- **Integration** or the internal relatedness of the knowledge base.

- **Connectedness** or the relation of the knowledge base to other things the person knows.

One way of organizing knowledge so as to realize 'integration' and 'connectedness' is building problem schemata. This concept was used by Chi, Feltovich and Glaser (1981) to describe expert knowledge of Mechanics. A problem schema consists of elements of knowledge, centered around a fundamental concept or law, and containing all the knowledge necessary for the solution of a certain type of problem, procedural and situational as well as declarative. A set of problem schemata is considered to form a model of an adequate knowledge base. Such a model describes both the aspect of content (knowledge types) and the aspect of structure of the knowledge base. A more detailed description with an application to the field of Electricity and Magnetism is to be found in Ferguson-Hessler & de Jong, (1987) and Ferguson-Hessler, (1989).

An experiment with a knowledge base covering part of a first year course on this subject showed that students who are good problem solvers do indeed organize their knowledge in a way which is more akin to a set of problem schemata than poor students do (de Jong & Ferguson-Hessler, 1986).

### 2.2. Learning: creating knowledge from information.

The acquisition of a knowledge base consisting of a set of problem schemata requires a considerable amount of cognitive processing of incoming information and attention for all four types of knowledge. In an earlier study we investigated the cognitive aspects of the real learning process by observing individual activities of first year students learning physics from a text (Ferguson-Hessler & de Jong, 1990). For the analysis of the student...
activities we introduced the concept of study process, a limited and specific cognitive activity, considered to be the manifestation of a cognitive process. As a theoretical basis for a taxonomy of study processes we used:

1. The description of the content and structure of an adequate knowledge base given in the previous paragraph.
2. The concepts of integration and connectedness, as introduced by Resnick and Ford.
3. Cognitive theory of knowledge acquisition as an active processing of information.
4. Theories of text processing, as formulated by Marton and Säljö (1976,a,b).

As a logical consequence study processes are classified along two dimensions: the type of process and the type of knowledge the process acts on. Three main categories of processes are defined:

1. **Collecting and encoding new information** by reading a text, listening to a lecture, or watching a film, a video- or computer demonstration.
2. **Integrating new knowledge**, that is bringing structure into the new knowledge by noting main issues and relating different elements.
3. **Connecting new knowledge to prior knowledge**, thereby giving sense to new information.

The first category is typical of what Marton and Säljö call 'superficial processing' (reading the text, comparing symbols in text and figure, memorizing, etcetera), whereas the second and third categories correspond to their 'deep processing'. By subdividing the three main categories and defining specific study processes within these, such as 'drawing conclusions', 'verifying a derivation' or 'thinking of examples' we created a taxonomy which defines the process dimension of the model.

This model of learning shares the basic idea of knowledge compilation with the ACT* theory of Anderson (1983): integrating and connecting new knowledge means building and tuning a knowledge structure in a way analogous to the way new productions are acquired by 'experience' in ACT*. Other aspects, however, are fundamentally different:

- our model has a separate dimension, describing the types of knowledge involved, thereby defining knowledge of procedures as part of the content of the knowledge base and not as a quality of declarative knowledge,
- our model is one of acquisition of abstract knowledge, whereas the ACT* is, in essence, one of skill acquisition (Ohlsson, 1990),
- the learning process is approached from the perspective of the knowledge base to be acquired, not from the perspective of cognitive psychology; as a consequence the terminology is specific and directly applicable to observation of real life learning.

With the aid of this model we were able to classify the study processes observed along the two dimensions of type of process and type of knowledge. The result of the
observations of students and the comparison of two groups of good and poor performers can be summarized as follows:

1. It was possible to describe all cognitive activities of the subjects in terms of study processes belonging to the taxonomy.
2. Students who were good performers showed more study processes belonging to the second and third main categories, especially those requiring in-depth processing of information given in the text (such as confronting).
3. Poor performers tended to concentrate on declarative knowledge, whereas good performers had attention for procedures and situations as well.

These results are consistent with those of the measurement of knowledge structures of good and poor performers, mentioned in the preceding paragraph: problem schemata can only be built by deep processing and attending to all types of knowledge. These activities, however, require knowledge of the way in which various elements of subject matter function in problem solving and how to structure them in an efficient way, that is to say meta-knowledge. Furthermore, learners must be able to monitor their own cognitive activities so as not to allow themselves to be carried off by chance in the direction of one aspect of subject matter and to forget other aspects. This type of knowledge is often referred to as 'self-regulatory skill', 'monitoring skill' or 'performance control strategies'.

2.3. Research questions.

On the basis of the preceding discussion, the objective of investigating the cognitive aspects of supporting learning in physics, mentioned in the introduction, can be specified into the following research questions:

1. Is it possible to create a taxonomy for instruction processes, analogous to that for study processes, which makes it possible to describe in a systematic way the cognitive teaching activities of teachers giving physics instruction?
2. Can this description be validated from actual teaching?
And if so,
3. Do teachers engage in instruction processes, which are appropriate to demonstrate and stimulate deep processing of subject matter?
4. Do teachers give explicit attention to procedures, situations and knowledge of strategy in their teaching?

As was the case in the studies discussed in earlier sections, we applied these research questions to the teaching of physics. The investigation was carried out at the level of a first year university course.
3. A SYSTEMATIC DESCRIPTION OF PHYSICS INSTRUCTION

3.1. The specific needs of physics.

From the point of view of the university teacher, the taxonomy of study processes can be considered to form a task analysis (excluding the time component) for the student learning the subject. Using the two-dimensional description of this taxonomy as a starting point, we looked at available literature for guidance in our attempts to give a systematic description of the cognitive teaching activities involved in instruction in a subject such as physics.

General theories of instruction, such as those mentioned in section 1, the Component Display Theory of Merrill (1983, 1987), the Elaboration Theory of Reigeluth (1983, 1987) and the Algo-heuristic Theory of Instruction of Landa (1983, 1987) offer little or no possibility of including the dimension of subject matter knowledge. The performance-content classification of objectives and tests, introduced by Merrill, does distinguish between types of content, such as facts, concepts, principles and procedures, but has no space for the intrinsic structure of the subject matter or for complex objectives, such as problem solving. In Reigeluth's Elaboration Theory, instruction starts with the most general concepts of the subject and works 'top-down' to the more detailed elements of content. Such an approach is unfeasible in physics, where the most general concepts are often abstract, and can only be made meaningful by working 'bottom-up'. The heuristics of Landa pay no attention to deep processing and are not applicable in our case.

Shuell (1986) formulates the need of a theory which relates principles of instruction to content as follows:

"Consequently, we need to know more about the way in which specific content and instructional procedures engage and/or elicit the psychological processes and knowledge structures appropriate for the desired learning outcome." (p. 430)

This relation between psychological processes and specific knowledge structures has been stressed recently by Perkins and Salomon (1989), who emphasized the need of teaching cognitive skills in the context in which they are to be used, and not as general but as yet empty cognitive activities. In other words: instruction must not only be tailored to the structure and content of the subject matter to be learned, but also to the relevant metaknowledge.

Reif, Larkin and Brackett (1976), in an interdisciplinary study, have developed a method of teaching learning and problem-solving skills in physics. They conclude that by this method, consisting of programmed instruction, practice and feedback, students can be taught cognitive skills which are essential in physics, but which are not acquired by students in usual lecture courses. Hestenes (1987), being a physicist, has approached the problem of teaching from the point of view of the cognitive skills needed in problem solving in physics. He stresses the important role of modelling as a strategy, and concludes that this type of strategy is what students need to be taught. His principles were
tested in an experimental course on mechanics. Weak students turned out to profit from this approach (Halloun & Hestenes, 1987). Recently, Caillot and Dumas-Carree (1990) have reported on an experiment of the same type, where secondary school students were taught specific 'cognitive aids' for the building of problem representations in mechanics. Students of the experimental group showed better conceptual understanding and performed better than students from the control group.

These experiments indicate that it is possible to design instruction that fosters students' understanding and performance. Keeping in mind the central role of learner activities in acquisition of knowledge, we conclude that the stimulation of cognitive activities in the learner must be central in this type of instruction. Our study of learning in physics indicated that two types of intervention are needed in this process: demonstrating and stimulating deep processing, and directing attention to procedures, situations and strategy. This instructional principle is what Glaser and Bassok (1989) call "the teacher as model and coach": in addition to presenting examples of well integrated and/or connected elements of knowledge, the teacher demonstrates deep processing activities and the active construction of meaning. An accurate and systematic description of these activities, however, is still missing. In the present study we attempt to fill this gap by developing a systematic description of the cognitive teaching activities needed to produce efficient learning, and investigating the activities actually found in university teaching.

3.2. A model of physics instruction.

Using the taxonomy of study processes of section 2 as a model for learning skills, we construct a model of physics instruction, defining the concept of instruction process as a limited and specific cognitive activity of the teacher, analogous to the study process of the student. Consequently, instruction processes are divided onto three main categories:

1. Presenting new information.
2. Integrating new knowledge.
3. Connecting new knowledge to prior knowledge.

Presenting new information can take on several forms, such as: describing a phenomenon, introducing a law or relation and explaining its meaning, demonstrating a procedure on the blackboard, such as choosing the path for a line integral, mentioning symmetry properties of a situation. Live experiments, film, television, video(disk), computer simulations, and other techniques can play a role in this category of instruction processes. Text-books and lecture notes form an additional source of information, but lectures and classes offer a better possibility of alternating the stream of information with activities from the second and third category above.

Integrating as an instruction process is a teacher activity bringing structure and meaning into new information and thereby contributing to the creation of knowledge; this is the central task of the teacher. Structure and meaning are no ready-made products that can be transferred from teacher to student. What the teacher can do is to stimulate students to construct meaning and structure themselves; for instance by indicating main issues,
relating elements (for instance a formula to the characteristics of situations where it is valid and useful), comparing situations or laws, drawing conclusions, and giving explicit arguments for choices. As the construction of meaning is more difficult in physics than in many other subjects, this is a crucial aspect of physics instruction.

Connecting new information to knowledge already present helps to bring sense and understanding, and thereby contributes to the creation of knowledge. Examples of instruction processes are: introducing real-world examples, offering a new explanation for a well known phenomenon, and showing how known results are special cases of a new, wider theory.

The content of each instruction process can belong to any of the four types of knowledge or be a combination of types of knowledge. Of special importance is knowledge of strategy, which is seldom found in text-books and often treated in an implicit way in problem solving classes.

In addition, instruction processes are needed that teach meta-knowledge and monitoring skills. For instance, reference to the various types of knowledge and to the role they play in the steps of the problem-solving strategy are essential for the construction of problem schemata. Stating these steps explicitly, and stressing the role of each step in the solution, demonstrate the importance of monitoring one's own activities, both in learning and in problem solving.

By thus demonstrating active processing of information as opposite to an attitude of 'information duly noted' the lecturer can support the student in the process of creating knowledge from information.

3.3. A taxonomy of instruction processes.

The three main categories described above have been subdivided into specific instruction processes, thus forming a taxonomy, which could be used for the classification of cognitive activities. In order to describe all aspects of instruction it was necessary to add a fourth main category, containing processes of organization and motivation, which are intended to create suitable conditions for learning, such as 'specifying learning goals' and 'activating prior knowledge'.

For the description of the process dimension, the main categories of the previous section were divided and specified into a number of categories such as 'confronting or evaluating' and 'relating new information to prior knowledge'. For the dimension of content the concept of knowledge types was used. To each category a possible example was added from the subject of Electricity and Magnetism. A few examples of instruction processes so defined are:
0. Creating suitable conditions for learning.  
0.1. Specifying the learning goal of the lecture/class or the coming part thereof.  
Example: "What would happen in this situation if......? That is what we are going investigate."

1. Presenting new information.  
1.1. Presenting new facts or definitions, laws or phenomena, procedures or situations; demonstrating an experiment, live or via film, television or video, using a computer simulation.  
Example: Demonstrating the fact that E = 0 inside a conductor by placing a volunteer inside a large Faraday cage with a bunch of thin paper strips in his or her hand.

2. Integrating knowledge.  
2.3. Relating, comparing, formulating expectations.  
Example: "Now, this is true for an isolated conductor, but is not valid for a conductor connected to ground."

3. Connecting new to prior knowledge.  
3.1.2. Relating to knowledge of other subjects.  
Example: Comparing an electrostatic field to the field of gravity.

A complete list of the 19 instruction processes so defined is to be found in the Appendix.

The second dimension of the model is identical to the knowledge dimension of study processes, described in section 2.1.

The taxonomy, so created, can be considered to form a tentative answer to the first research question, on the possibility of creating a taxonomy for instruction processes.

4. OBSERVATION OF TEACHING

Validation of the model of physics instruction was only possible by observation of physics instruction, given in practice by experienced university teachers to first year students. The data so collected would also make it possible to answer the third and fourth research questions, on what instruction processes and knowledge types teachers employ in their teaching.

4.1. Sources of data.

By the co-operation of a number of colleagues it was possible to record and analyze lectures and problem-solving classes in various first year courses on the subject of Electricity and Magnetism, given at the Eindhoven University of Technology.

Lectures (n = 4) and classes (n = 5) were audio-taped and notes were taken of what was written on the blackboard. The time was noted for each item; this made it possible to relate the notes to the content of the audio-tape. One deviation from this technique was the video-recording of a couple of lectures given by a senior lecturer in the last term before his retirement; at that moment the preparations for the observations were not finished and we decided to collect as much information as possible.
A special case was a so called 'press-the-button' lecture, where each student could answer questions on problems during the lecture by pressing a button. A problem situation was posed by the lecturer, and the students were guided through the solution in a series of yes/no or multiple choice questions.

4.2. Analysis of protocols.

Prior to analysis the integral text of the protocols was entered into a text-processor. In order to avoid the problems a secretary would have in understanding the formulae and symbols appearing in the protocols, the typing was done by a fifth year physics student who assisted in this project.

The taxonomy described in section 3.3. was used as a first version of a classification scheme for the analysis of the protocols. It was tried out on the lectures which had been video-recorded. A couple of problems, typical for this type of protocol, had to be solved before the cognitive activities found could be classified.

The first problem was to define the unit of protocol text that was to be classified. The examples of instruction processes given in section 3.3. show the complexity of the processes defined in the scheme and demonstrate the impossibility of scoring each proposition separately. In analogy to the method used in our observations of study processes (Ferguson-Hessler & de Jong, 1990) we introduced the concept of a meaningful unit, the smallest unit of text that made sense from the point of view of the context. The limits of a meaningful unit are not always self-evident, which makes it impossible to carry out a straight-forward measurement of inter-rater reliability. This problem was circumvented by having each protocol scored by two persons who decided together on the limits of meaningful units and their classification as to type of process and type of knowledge.

The second problem arose from the need to define instruction processes in such a way that they were of the same complexity. Following Gagné and Briggs (1977), educational psychologists often use a hierarchy of cognitive skills, ranging from 'recognizing' or 'indicating main issues' to 'analyzing' and 'synthesizing'. For the classification of meaningful units however, it was necessary to use only elementary processes, (that is processes that could not be subdivided) such as 'indicating main issues', 'relating', or 'concluding'. Consequently, the taxonomy was limited to this type of processes, and a complex process such as the analysis of a problem situation was considered as a sequence of processes from the taxonomy.

The classification scheme thus defined made it possible to describe all cognitive activities in lectures and problem solving classes as recorded in the protocols. The resulting classification scheme for instruction processes is to be found in the Appendix.

All recorded lectures and problem solving classes were analyzed with the aid of the final classification scheme: meaningful units, each making up an instruction process, were defined and coded as to process in accordance with the classification scheme and to content according to the type or combination of types of knowledge. In addition to the
text file of the word processor, the notes taken during lectures and classes were used to follow the activities of the teacher in detail. During the course of the analysis, a few minor additions to the classification scheme turned out to be necessary; they were recorded and entered into all protocols. The result of the classification was a protocol of the type shown in Figure 1.

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<th>Cat.</th>
<th>ToK.</th>
<th>Seq.</th>
<th>Text</th>
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<td>1.1</td>
<td>DSP</td>
<td>Start</td>
<td>Thus, this sphere, having a charge $Q$, will assume a potential $Q/4\pi\varepsilon_0 R$. In other words: in this case, what is $Q$ divided by the potential of that thing? That is $4\pi\varepsilon_0 R$, and that is the capacity of a sphere. And then, on the sly, I add: with respect to infinity.</td>
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<td>2.1</td>
<td>DS</td>
<td></td>
<td>What I am really calculating is the capacity of a system of bodies; the sphere being one and something at infinity the other body. I am not interested in the shape because that does not make any difference.</td>
</tr>
<tr>
<td>3.1.1</td>
<td>DSP</td>
<td></td>
<td>But somebody might be so clever as to say: a couple of weeks ago you just told us that one can make a choice of one's own as far as potential goes. We could very well fix the potential of the sphere at zero; only differences of potential make sense, is that not so?</td>
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<td>2.2</td>
<td>D</td>
<td></td>
<td>And with a potential zero $Q/U$ becomes infinite, and I would have a capacitor with infinite capacity. But, obviously, it does not work that way.</td>
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<tr>
<td>3.1.1</td>
<td>DS</td>
<td></td>
<td>Because when we are talking about potential in this context, we really talk about the work I have had to carry out in order to charge that sphere; that is the concept of potential that plays a role here. And that charge comes from infinity; it does not come from this surface.</td>
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<td>2.4</td>
<td>SP</td>
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<td>And that is the reason that I have to take the potential with respect to infinity. So, really, I am calculating the system sphere with respect to infinity.</td>
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<tr>
<td>1.1</td>
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<td></td>
<td>The capacity of such a sphere is also called the self-capacity to indicate that there is something special with this concept.</td>
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Cat. = (sub)category of instruction process.  
ToK. = type of knowledge.  
Seq. = Sequence of instruction processes, e.g. An = Analysis.

**Figure 1.** Part of the protocol of a lecture (translated from Dutch).

Contrary to the usual habit of discarding protocols used for the development of a classification scheme in the further analysis, we reused the video-tapes, the reason being the small number of protocols available (which is, of course, inherent to this type of study).

In view of the small number of protocols available we chose an explorative approach to the data collected. With the aid of a conversion program each protocol was translated into a 'stream diagram' like the one of Figure 2, which made it possible to follow the changing processes and their content as time passed. The information from each protocol was condensed into a frequency matrix, specifying the frequency of each combination of
Fig 2. Part of a 'stream diagram'. Horizontal: instruction processes; vertical: sequence in time.

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Thus an answer has been found to the second research question: the taxonomy constructed for instruction processes could be validated as a description of physics teaching given in practice.
5. RESULTS

A primary result of this study is the construction and validation of a model of the cognitive aspects of physics instruction, as mentioned in the first two research questions. The answer to the third research question, on the instruction processes teachers engage in, could be found in the information contained in the stream diagrams and in Table 1. A selection of this information has been collected in the bar diagrams of Figures 3 and 4.

Table 1.

Distribution of instruction processes: type of process; percentage.

The types of processes belonging to the codes are given in the appendix.

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<th>Instr. process</th>
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</table>

* 'press-the-button lecture'.

13
Main categories of instruction processes; percentage.
a. Lectures.

b. Problem solving classes.

Figure 3. Main categories of instruction processes. COND: Conditions for learning; PRES: presenting; INTER: integrating; CONNECT: connecting.
A first glance at Table 1 makes it clear that the total number of instruction processes in a period of twice 45 minutes shows a large variation. Partially this is due to differences in style of teaching; one teacher will move through the subject matter with a greater speed than the other, or will have the habit of interrupting the presentation for an example or an association, thereby engaging in a larger number of instruction processes. Lecture 4 is the 'press-the-button' lecture; inherent to this method is a great number of short instruction processes. In the case of the problem solving classes the differences in numbers of processes are partially accounted for by the fact that some teachers let the students work in couples or small groups during part of the time allotted for the class.

Looking into the main categories of instruction processes we see from the stream and bar diagrams that all teachers engage in all main categories of instruction processes in a pattern of constant change. Presenting new information plays a greater role in lectures than in classes, whereas integrating and connecting are more important in problem solving classes than in lectures. This is not true for lecture 4, the 'press-the-button' lecture, which is not accompanied by problem solving classes. These results wholly agree with the different teaching goals of traditional and 'press-the-button' lectures and problem solving classes. Individual differences between teachers can be seen in the attention given to presenting new knowledge, integrating this, and connecting it to prior knowledge. The variations are not very large and have their origins not only in the individual difference but also in the subject matter treated: starting a new chapter will lead to a somewhat different pattern of instruction processes than continuing the story of last week.

Table 1 indicates that two of the instruction processes belonging to the main category 0, 'creating suitable conditions for learning' are rare in all the protocols: 0.2, motivating students, and 0.3, specifying and activating prior knowledge.

In Figure 4 we look more closely into the instruction processes related to deep processing. Three types of processes have been selected: 2.1, specifying main issues, 2.2 - 2.4, relating, confronting and concluding, and 3.1, relating to prior knowledge. Here the bar diagrams show some remarkable differences: the 'press-the-button' lectures give little attention to specifying main issues, one of the lecturers and two of the other teachers have a high percentage of processes of the type 'relating, confronting, concluding' (approximately 25%), but some of the others have very few of these essential instruction processes.

An answer to the fourth research question, on the type of knowledge the instruction processes are directed to, can be found by means of Table 2 and the bar diagrams of Figure 5, which contain information on the way teachers divide their attention between different types of knowledge and combinations of types. Lecture 1, for instance, devotes relatively more instruction processes to elements of declarative knowledge than other lectures. Problem solving classes, on the whole, have somewhat more attention for procedures and situations. Lectures 2 and 3, however, have a high percentage of instruction processes where procedures and situations are treated in relation to declarative knowledge or to each other. More generally, lectures 2 and 4 and problem solving classes 7, 8, and 9 have a large percentage of processes directed at combinations of types of knowledge, that is to say relating elements of knowledge which function together in applications. The instruction processes of the remaining lectures and classes
Figure 4. Types of deep processing. MI: Main issues; RELCON: relating, concluding, confronting; RELPRKN: relating to previous knowledge.
tend to treat the different types of knowledge as isolated units. A striking result is the absence of strategic knowledge in all protocols except one (two instruction processes in one problem solving class).

Table 2.

Distribution of instruction processes: type of knowledge; percentage.

D = declarative knowledge  P = procedural knowledge
S = knowledge of situations  Str = strategic knowledge
DP etc. combinations of types of knowledge

<table>
<thead>
<tr>
<th>Type of knowl.</th>
<th>Lectures</th>
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<th>Problem solving classes</th>
</tr>
</thead>
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<td>11</td>
</tr>
<tr>
<td>Str</td>
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<td>0</td>
</tr>
<tr>
<td>Total number</td>
<td>183</td>
<td>161</td>
<td>136</td>
</tr>
</tbody>
</table>

* ‘press-the-button’ lecture.

Looking into the interaction of main type of process and type of knowledge we see that the information presented in problem solving classes is often relevant for knowledge of situations and procedures. Integration, in all cases, is mainly directed at declarative knowledge, isolated or in combination with knowledge of situations. The same is true for connecting new knowledge to prior knowledge. Individual differences are large, partly as a result of the fact that the number of processes involved for each type of knowledge is smaller than in Table 2.
Types of knowledge; percentage.
a. Lectures.

Figure 5. Types of knowledge in instruction processes. D: declarative; P procedures;
S: situations; DP etc. combinations of types of knowledge.
6. DISCUSSION AND CONCLUSIONS

The most important conclusion to be drawn from the results is that the teaching of experienced university teachers could be described in terms of instruction processes belonging to the two-dimensional model developed in this study. It is also important that all types of instruction processes defined are indeed found in this type of teaching. Intuitively, academic teachers do not only supply information but try to stimulate the cognitive activities of students as well; some more often and more consistently than others. In doing this they divide their attention between declarative, procedural and situational knowledge and also treat these three types of knowledge in their relation to each other in the way they are used in problem solving. Knowledge of strategy, on the other hand, is given no attention in the lectures and, strikingly, practically no attention in the problem solving classes either. Nor did we find any form of meta-knowledge or any reference to monitoring skills in the lectures and problem solving classes observed.

The significance of this study is not primarily the possibility created of comparing the teaching of individual teachers, but the terminology that has been created, and that opens up possibilities for reasoning about instruction:

- to evaluate the quality (in the sense of stimulating the learning process) of a lecture or a problem solving class and to relate this to teaching goals and curriculum,
- to document the activities of experienced university teachers, for instance with a view to making these available to novice teachers in courses and supervision,
- to formulate guidelines for the construction of course material, where aspects of instruction such as integration and connecting are included,
- to formulate guidelines for the construction of programs for computer assisted instruction, which are based on a cognitive theory of learning and intervention for the specific knowledge base to be acquired.

A practical example is the student and staff opinion on the high quality of lecture 3, which could be given a concrete and quantitative basis in terms of stimulation of deep processing and attention for the relation between declarative knowledge and procedures and situations.

According to Ohlsson it would appear that the constituting idea of most modern Cognitive Psychology can be summarized as follows (Ohlsson, 1990):

"Cognitive processes are caused by the execution of stored programs that operate on an internal, symbolic representation of the world." (p. 563)

He concludes that this theory is a theory of action rather than of knowledge, and thus can serve as a basis for theories of acquisition of skills, but not of knowledge: such theories are of limited use in a theory of instruction. A theory of the content, structure and growth of knowledge is needed before a theory of teaching abstract knowledge can be formulated; this according to Ohlsson.
The analysis of the current state of cognitive theories of learning and instruction, given by Ohlsson, is wholly in line with the basic principles of research on acquisition and transfer of knowledge in the field of technology, which is carried out at the Eindhoven University of Technology. These principles, as summarized in section 1, have been applied to the field of physics in this study; an extension to other fields of the sciences and to technical subjects is straightforward, but requires extensive analysis:

1. Construct a model of the content and structure of a knowledge base, suited to carry out applications in the field, which are considered typical objectives of the subject.
2. Construct a model of the cognitive processes which are required for the acquisition of this knowledge base, and investigate the processes students engage in when learning the subject.
3. Construct a model of instruction processes which are needed in order to demonstrate and stimulate the necessary cognitive activities in learning, paying special attention to those aspects which are missing in the learning process of poor students.

It is evident that this type of research can only be carried out by an interdisciplinary team: knowledge of cognitive theories of learning and instruction have to be combined with subject matter expertise and teaching experience.

Acknowledgements
We like to express our sincere thanks to the colleagues who trusted us to record and analyze their lectures and problem solving classes and thereby made this investigation of cognitive activities of teachers possible. Thanks are due as well to professor D.W. Vaags and professor W. van Haeringen, who supervised this study, to Christine ter Huurne who assisted in typing and analyzing the protocols and to Niels T. Ferguson who wrote the conversion program.
LITERATURE


APPENDIX

CLASSIFICATION SCHEME FOR INSTRUCTION PROCESSES.

0. Creating suitable conditions for learning.

0.1. Specifying the learning goal of the lecture/class or the coming part thereof.
Example: "What would happen in this situation if......? That is what we are going to investigate."

0.2. Motivating students to acquire the knowledge (to be) presented.
Example: Mentioning a well-known application.

0.3. Specifying the prior knowledge which forms the point of departure in the treatment of a new theme; activating this knowledge.
Example: "Last week I treated......, and we came to the conclusion that......But, as I told you, this is not the whole story, and to-day we are going to look at some other aspects of that law."

0.4. Practical remarks, relevant for the content.
Example: "This question is discussed in the lecture notes on page..."

0.5. Other remarks or activities, which are not relevant for the content.
Example: "There is too much noise in the class."

1. Presenting new information.

1.1. Presenting new facts or definitions, laws or phenomena, procedures or situations; demonstrating an experiment, live or via film, television or video, using a computer simulation.
Example: Demonstrating the fact that $E = 0$ inside a conductor by placing a volunteer inside a large Faraday cage with a bunch of stripes of thin paper in his or her hand.

1.2. Repeating elements of new information without integrating or connecting.
Example: Repeating in other words what has already been said.

2. Integrating knowledge.

2.0. Using elements of new knowledge without any explanation.
Example: Applying a new formula or definition.

2.1. Specifying main issues; indicating relevant elements of a procedure of a situation.
Example: "What you do here is essentially this: proving that $a v^2$ is a constant; then the rest follows logically".
"Crucial in this situation is that the charge of the conductor is a constant."

2.2. Confronting; evaluating.
Example: "With potential $V = 0$ and $C = Q/V$ we find $C$ to be infinitely large, but that is not the way it works!"

2.3. Relating, comparing, formulating expectations.
Example: "Now, this is true for an isolated conductor, but is not valid for a conductor connected to ground."
2.4. Drawing conclusions.
   Example: "We have to conclude, that in addition to the charge on the plates of
   the capacitor an other type of charge is present."

2.5. Posing questions which require an actual answer from the students (in the 'press-the-button' lecture).
   Example: "Who says alternative a is correct?"

3. Connecting new to prior knowledge.

3.0. Using elements of prior knowledge without any explanation, tacitly assuming
   them to be known.
   Example: Applying a formula or a definition which has been treated in an earlier
   lecture or class.

3.1. Relating elements of new knowledge to prior knowledge.
3.1.1. Relating to prior knowledge of the subject, reminding students of this
   knowledge.
   Example: "A couple of weeks ago we concluded that the point where the
   potential is zero can be chosen freely, because only differences of
   potential make sense".

3.1.2. Relating to knowledge of other subjects.
   Example: Comparing an electrostatic field to the field of gravity.

3.1.3. Relating to general knowledge of the world.
   Example: "We fancy an atom to be made up of a nucleus and a cloud of
   electrons, bound together by a rubber band" (polarization).

3.2. Other activities.
   Example: Answering questions of detail of a student.