Towards Learning Process Studies: A Review of the Workshop on Research in Physics Learning

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Aims and Issues

Since the late 1970's there have been major efforts in physics education research to identify students' ideas about scientific phenomena, both prior to and following formal instruction (Pfundt and Duit, 1991; Carmichael et. al., 1990). Very few studies, however, have focused on student learning processes. In March 1991 thirty physics education researchers came together for an intensive four-day workshop in Bremen, Germany, to promote a new orientation in research towards empirical investigations of students' learning processes that would lead to a deeper and more robust understanding of physics.[1]

It is assumed that this research will be informed by the results of previous studies of student understanding and effective teaching strategies, will be guided by appropriate theoretical frameworks, and may require new experimental methodologies. To promote this new research orientation, four specific aims were set for the workshop:

(1) to analyze theoretical frameworks for the investigation of student learning processes in physics;

(2) to propose and consider new methodologies and standards for qualitative empirical research on student learning processes in physics;

(3) to discuss new teaching strategies that promote a deeper understanding of physics concepts; and

(4) to develop an agenda for research in physics learning.

To achieve these aims, the workshop was structured around a set of four major issues. Participants were asked to prepare papers in which they were to discuss some of their recent work in light of one or more of these issues, which are listed below.

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Empirical Studies of Student Understanding: Structure of the Results and the Role of Students' Conceptions

How have the results of empirical investigations of students' understanding been structured? What levels of description have been used? What is meant by student "understanding" in specific content areas in physics? What is the impact of specific prior knowledge and general frames of thinking on students' conceptions of formal physics?

Describing Physics Learning Processes

How can learning processes in physics be described? What is the relation between the students' prior knowledge and the new knowledge acquired during instruction? Should learning be viewed as a process of conceptual change or conceptual growth? Which theoretical frameworks and models can serve as a basis for structuring learning environments as well as empirical investigations about learning processes?

Hypotheses about the Promotion of Physics Learning

What assumptions about learning are incorporated in a constructivist or student-centered teaching strategy? How important is it to engage students in contrasting their alternative conceptions with formal, scientific conceptions? What is the role of the status of students' conceptions (i.e. their intelligibility, plausibility and fruitfulness)? What suggestions might be proposed for how different presentations of topics might effect student learning? What hypotheses can provide guidance on how learning environments should be structured? What role does social context play in learning? What is the role of metalearning and metacognition?

Methodological Issues Regarding Empirical Studies of Learning

What are the different characteristics of research performed in a clinical environment and research performed in the naturalistic environment of the classroom? What kinds of information about student thinking and learning can be obtained in each research environment? What are the various dimensions on which research investigations can be designed? Some considerations might include: assessing student knowledge before, after, and long after instruction versus direct analysis of the learning process itself; short time investigations (on the order of one hour) versus long time investigations (weeks, months and years); and analyzing single students versus the development of whole classes. How can one classify the various empirical methods used for design and analysis, for example, qualitative versus quantitative or interpretative versus objective? What experimental techniques and methods of analysis that were used in empirical studies of student understanding can be applied in studies of student learning? What other techniques might be appropriate?

The papers presented at the workshop collectively address most of the questions raised above. Following the workshop the participants were asked to revise their papers in light of the other presentations and the intensive discussions that characterized the four days of interaction. The Proceedings present the revised versions of those papers.

We have organized the Proceedings into four parts, and have grouped the papers accordingly. The four parts are: Theoretical descriptions of learning processes in physics; Metacognition and beliefs about learning and the nature of science; Empirical studies of learning processes; and Instructional strategies based on research. Below we provide an overview of the four parts and summaries of the papers included in each part. Following that we discuss in some detail the research agenda that emerged from the Workshop discussions.

Summaries of Papers

Part I: Theoretical Descriptions of Learning Processes in Physics

The papers in this part focus on different theoretical issues. The first two contributions (von Glasersfeld, Dykstra) address basic problems of a constructivist view of teaching and learning in physics and come to a specific understanding of conceptual change: concepts can not be transmitted (e.g. by language), they have to be built or constructed by the learners themselves. The third paper (Hewson and Hewson) describes a specific theory of conceptual change and relates it to a change in the status of conceptions. The remaining three papers (Niedderer and Schecker; Reiner; Minstrell) have a common focus on the question of what kind of units and cognitive structures are to be used in describing learning processes.

In the first part of his paper, *A constructivist's view of learning and teaching,* **von Glasersfeld** discusses the meaning of *radical* constructivism, focusing on a clarification of the concept of knowledge. In the second part he discusses three points about teaching and learning that are suggested by a constructivist theory of knowing. The first point clearly distinguishes the notion of *training*, which aims at the trainee's performance, and *teaching*, which aims at student conceptual understanding. Although performance can be evaluated by observing the trainee's behavior, a student's conceptual understanding can only be inferred by the teacher on the basis of compatibility with the teacher's understanding. The second point concerns language and emphasizes that each individual must construct his or her own meaning for words. The implication for instruction is that it cannot be assumed that concepts can be transferred from the teacher to the student (or between any two people). The third point involves the social component: teaching is a social activity whereas learning is a private activity. To promote successful learning, von Glasersfeld argues, the teacher must have a good idea of what concepts the students might already have and then engage students in activities that would help them construct the desired understanding.

Dykstra, in *Studying conceptual change: Constructing new understandings*, takes a constructivist view in focusing on many important theoretical and empirical issues regarding conceptual change. He discusses, in turn: (1) describing conceptual change; (2) the issue of what is actually changing; (3) developing a taxonomy of conceptual change; (4) the nature and role of disequilibration; (5) nurturing conceptual change; and (6) assessing conceptual change. Each of these chapter subsections leads to a question that Dykstra suggests needs to be examined as part of future research. He draws heavily on his own classroom experience to illustrate many of his points. One particularly interesting example centers around Dykstra's description of students' development of an understanding of the relationship between force and motion as a sequence of intermediate conceptions.

In *The status of students' conceptions*, **Hewson and Hewson** outline the major features of a model of conceptual change developed by Posner, Strike, Hewson and Gertzog (1982). The two major components of the model are the conditions needed for conceptual change and a person's conceptual ecology. The conditions refer to the degree to which a conception is *intelligible*, *plausible* and *fruitful* to the learner. These conditions determine the *status* of the learner's conception, and a central prediction of the model is that conceptual change cannot occur without a corresponding change in the status of a conception the learner is holding. Several ways of determining status are discussed, including situations in which the technical language of the model is and is not used. Examples are drawn from interviews and classroom discourse.

Niedderer and Schecker, in *Towards an explicit description of cognitive systems for research in physics learning*, argue for the explicit formulation of assumptions about what is going on in students' minds. They suggest using the results of empirical research on alternative frameworks as the cognitive entities for describing a model of "cognitive systems," and to use those cognitive systems to describe learning processes. A distinction between two kinds of cognitive structure elements (stable elements of a "deep structure" and actual "current constructions") leads to a differentiation of thinking and learning processes. Niedderer and Schecker illustrate their theoretical approach by re-describing research results from the domain of mechanics.

In *Patterns of thought on light, and understanding commitments,* **Reiner** discusses empirical research results on students' understanding of light. She analyzes students ideas with two theoretical hypotheses: students create clusters of ideas ("patterns of thought"); there are two types of ideas, "deep structure ideas" and "surface structure ideas". Reiner defines "powerful" ideas as those which are applied frequently in many situations, and argues that they are a feature of students' deep structure knowledge. An example, related to a more general epistemological commitment of a materialistic belief is that light is made-up of particles, or is thought of as a stream or fluid. Surface structure ideas on the other hand are more context dependent. Taking into account the various types of students' ideas, Reiner argues that students' ideas are not always incoherent, fragmented and context-bound.

In *Facets of students' knowledge and relevant instruction,* **Minstrell** finds it convenient to describe students' classroom knowledge in terms of facets. He defines the term *facet* as a "convenient unit of thought, a piece of knowledge or a strategy seemingly used by the student in addressing a particular situation." Minstrell argues that facets are a useful grain size of knowledge that teachers can identify and use to prescribe useful instruction that addresses students' problematic knowledge. Analyzing students' knowledge in terms of facets suggests that students' reasoning is more consistent than what might be suggested by the formal physics content of their comments. Minstrell discusses how classroom instruction could be aimed at helping students to add new facets or to modify existing facets, and describes a computer-based program called DIAGNOSER that can facilitate this process.

Part II: Metacognition and Beliefs About Learning and the Nature of Science

The three papers in this part all share one hypothesis: Learning is widely influenced not only by content specific preconceptions but also by more general beliefs about learning, about the nature of science and about epistemology. They are all called metacognitive beliefs.

In *Constructivism and metacognition: Theoretical issues and classroom studies,* **Gunstone** emphasizes the importance of having instructors help students *change* their own conceptions about learning and teaching and about the roles they should play in these processes. This is because students' beliefs about teaching and learning can be barriers to learning. Gunstone describes the process of metacognition and argues that a learner must be metacognitive in order to undertake the constructivist processes of recognition of existing ideas, evaluation of those ideas, and reconstruction of existing ideas.

Solomon, in *Images of physics: How students are influenced by social aspects of science*, reports on two projects, one focusing on discussion of issues in school science (DISS), and the other focusing on students' understanding of the nature of science. In the DISS project students are encouraged to discuss with their friends issues related to science in the context of watching television, and these discussions are recorded. An important outcome of the study was the recognition that public understanding is not simply related to the information provided by the media. Misunderstanding, prejudice, commitment and personal values all play important roles in the reconstruction of messages. The second project focuses on the social and cultural influences of theory making as well as students' understanding of how scientific explanations are constructed. In both projects, Solomon emphasizes how school science learning is embedded in a social construction process of everyday life.

In *The epistemological turn in science education: The return of the actor*, **Larochelle and Désautels** describe results on students' epistemological beliefs about science. The authors use a pedagogical strategy which integrates opportunities for reflection ("metalogues") into a normal classroom teaching process. The data is from a first year college philosophy course, where the students had reasonably good science backgrounds. The authors' main claim is that students need to be given an active role in scientific knowledge production, for example, by postulating, supposing, and appreciating the plausibility of results.

Part III: Empirical Studies of Learning Pathways

As mentioned previously, empirical research in physics education in the last twenty years has, to a large extent, been aimed at documenting student understanding in various domains. The focus of this kind of research was to understand the differences between an expert's way and a student's way of understanding. This was mostly done related to one state of the learning process, either investigating the pre-instructional or the post-instructional alternative conceptions and frameworks of students.

The basic idea of the Bremen workshop was to promote a shift of focus towards empirical investigations of the process of learning in physics, for example, the documentation of "learning pathways" in different content areas of physics. We call empirical studies which focus on the process of learning, *learning studies*. The empirical studies included in this part of the Proceedings are examples of those learning studies. Whereas studies on understanding can be seen as snapshots of students' development at one point, learning studies try to provide a stroboscopic picture of the learning process, or even a continuous one. These studies describe processes of learning in physics in great detail (see the first four studies in this part).

Learning studies can also have a slightly different design. Instead of providing time-dependent snapshots of the learning process, learning studies can also provide detailed descriptions of how selected concepts or notions change (see the second four studies in this part). There is, however, no sharp distinction between those types of learning studies; most studies include both aspects in their detailed descriptions of cognitive change.

The learning studies reported here differ in many ways: they differ in their basic notion of learning, as well as in their methodological design. Some of these issues will be discussed in the section on the Research Agenda.

In *Making status explicit: A case study of conceptual change*, **Hewson and Hennessey** provide an extensive set of transcription excerpts of one six grade student's thinking about the "book on the table" problem at different times during and following a unit of instruction on force and motion. These excerpts were drawn from a wider study that aimed at addressing two important questions related to the conceptual change model described in the previous paper by Hewson and Hewson: "Can students determine the status of their own conceptions? If so, how do their determinations interact with their learning of science content?" During the first phase of the study the students in the class built up a consensus on a set of descriptors for the terms intelligible, plausible and fruitful. During the second phase the students responded to specific tasks by audio recording comments about content and status. The authors analyze the statements of the student described in this paper to provide evidence for asserting that a student can determine the status of her own conceptions and for determining whether the student's evolving ideas could best be described in terms of conceptual capture and/or conceptual exchange.

Schwedes and Schmidt, in *Conceptual change: A case study and theoretical comments,* describe a learning process study on electrical circuits. The authors describe a 'concept' as a set of connected ideas determined by a nucleus. They see the learning process in electric circuits as a conceptual change from an old concept with a nucleus 'current consumption,' to a new concept with an Ohm's type of nucleus, having the central ideas of propulsion and resistance. Current is a component of both concepts. A group of students are given instruction on electric circuits in a clinical environment, and the entire process is video recorded. The authors describe the whole learning process of one student over about six hours as a case study within an interpretive theoretical framework. They also discuss more general issues of conceptual change in the light of their results.

In Conceptual pathways in learning science: A case study of the development of one students' ideas relating to the structure of matter, **Scott** describes the development of a single six grade student's ideas relating to the structure of gases, fluids and solids. The author presents snapshots of dialogues and drawings through several stages of the teaching process. At the end the student holds both a 'macroscopic view' and a 'microscopic particle view.' She is able to differentiate between both, making different use of both views. She has developed a new way of looking at the world, but this has not been at the expense of her original, informal perspectives. Scott also discusses more general issues of conceptual pathways and the status of 'prior conceptions' in relation to his results.

Fischer and von Aufschnaiter, in *The increase of complexity as an order generating principle of learning processes--case studies during physics instruction*, also focus on the learning process of one student. Their study takes place in a classroom environment with a very open-ended approach for teaching electrostatics, with many hands-on experiments by students working in small groups. The entire process of 13 double-lessons (90 minutes each) of one group is recorded on video tape. The authors describe and analyze the whole learning process of one student from this group on the basis of a view of radical constructivism related to that espoused by von Glasersfeld. They start the interpretation with an explicit formulation of their constructions of the student's ideas. In the following analysis of these ideas they use categories like 'object', 'property', 'event', 'relation' and 'program' to describe their view of a step-by-step construction of meaning and growing complexity in the mind of the student.

In *Learning quantum mechanics*, **Fischler and Lichtfeldt** report on a learning study, which combines an empirical study with a large student population from eleven courses with case studies of single students. In this paper they present an analysis of the development of 'dynamic networks of ideas' of two students, who are each given a different treatment during the course. The authors discuss the networks of ideas of each of the two students both before and after instruction. The analysis clearly shows differences in the concepts acquired by the two students, as well as the increasing density and complexity of the students' networks after teaching.

Séré, in *Learning by giving and receiving explanations*, describes a learning study with one student learning about the particle model of matter. She follows this one student through the didactic sequence, but her interpretations are not aimed primarily at showing changes in the student's ideas over time. Rather, she describes changes along different analytical dimensions: how the student attributes the status of "object" to air, gas and finally to particles; how the student establishes relationships between movements observed and movements imagined. Finally, the author draws conclusions about the roles of giving and receiving explanations in the learning process.

In *Probing acceptance: A technique for investigating learning difficulties*, **Jung** describes single cases of interactions between a student and a researcher, in which a combination of micro-teaching and interviewing has been developed. The topic of his study is optics (light and seeing). The author studies in great detail the effects of a student's own ideas on his or her understanding of information given by the interviewer. Learning processes are also described in which a student produces new ideas, becomes uncertain, and finally comes nearly to a scientific understanding. From the interviews it seems clear that all students understood something, but their understanding was not the same as that of a physicist. In some cases the researchers also observed striking examples of the student switching between old and new views. Jung concludes by discussing some consequences for teaching.

Grob, Pollak and von Rhöneck, in *Computerized analysis of students' ability to process information in the area of basic electricity*, describe the learning effect of providing various kinds of feedback during the midpoint of a test on electric circuits. The test was administered on a computer and consisted of a set of paired exercises, each pair member appearing either before or after the feedback. The test was given to 15 to 17 year olds some months following a teaching unit on electric circuits. In general, the gain achieved with any of the versions of feedback (no information, right/wrong information, short information, detailed information) was small, and sometimes even negative. The authors conclude that the influence of pre-existing cognitive structures seemed to be more important than the feedback information presented. They then briefly discuss some variations they performed using the computer that was aimed at improving student performance: changing sequences of exercises, recapitualizing basic concepts and rules, and introducing interposing additional exercises.

PART IV: Instructional Strategies Based on Research

Whereas many of the papers described in the previous section focus on learning studies, the focus of the papers presented in this last section is on instructional issues. The first paper in this set presents a literature-based review of general conceptual change teaching strategies. The following three papers discuss specific instructional strategies. What is common about all these strategies is that they are based on research on how students learn physics.

Scott, Asoko and Driver, in Teaching *for conceptual change: a review of strategies,* discuss instructional strategies reported in the literature that are broadly based on a view of learning as conceptual change. Two main groupings of strategies are identified: those based on cognitive conflict and the resolution of conflicting perspectives, and those which build on and extend the students' existing ideas. The authors discuss several theoretical issues that emerge when considering conceptual change teaching. They discuss the importance of acknowledging students' ideas, the nature and the role of conflict, the process of construction of scientific conceptions, and the evaluation of new conceptions. The paper concludes with some comments about the demands placed on both students and teachers in those cases where a conceptual change teaching strategy is to be practiced.

The basic premise of *Building a research base for curriculum development: an example from mechanics,* by **McDermott and Somers**, is that effective design of instructional materials and strategies requires knowledge about the nature of conceptual and reasoning difficulties students encounter in studying physics. The authors argue that substantive research is needed to provide this knowledge base. They draw on the work of the Physics Education Group at the University of Washington to provide an example of the kind of research needed and how this research could inform decisions about instruction and materials development. The example they use is the Atwood's machine. McDermott and Somers describe how they documented specific student difficulties through carefully designed tasks administered during individual interviews. Tasks similar to, or identical with, those administered during the research interviews then provided the focus for a series of tutorials that were designed to address common students' difficulties. These tutorials were incorporated into an existing university level introductory physics course.

In *Computer-video-based tutorials in geometrical optics,* **Goldberg and Bendall** discuss how they have used computer-videodisc technology as a means to address difficulties students exhibit in making explicit connections between optical phenomena and diagrammatic representations of those phenomena. They developed a set of computer-video-based tutorials in geometrical optics in which students, working in small groups, are presented with tasks asking them to make predictions about changes in an optical system. The students reason with their own conceptualization of image formation and their own diagrams (which they construct on the video monitor on top of video pictures of the apparatus used in the task). The actual experimental outcome of the tasks are often different from that predicted by the students, and the tutorials then guide students in their development of the formal physics conceptualization and corresponding standard ray diagrams. The authors provide a detailed description of one of the tutorials: Real images formed by a converging lens.

Brown and Clement, in *Classroom teaching experiments in mechanics*, describe the evolution over a two-year period of a set of instructional strategies and materials focusing on the topics of inertia and gravity. Following a first year trial in which there appeared no significant differences between experimental and control groups the authors revised the lessons. During the second year trial the experimental group did significantly better than the control group. Much of this paper focuses on elaborations of hypotheses concerning the sources of improvement. Possible sources included: (1) design of more "conceptually focused" examples; (2) splitting units up into sections separated in time by weeks, to enable students to revisit the topics a second time; and (3) requiring students to give more oral and written explanations. One strategy the authors found successful was to focus on intermediate conceptions that could serve as useful stepping stones to the formal target conception. In helping students develop a robust understanding of inertia the authors (and their colleagues) found it very useful to have students consider and discuss separately two intermediate aspects of inertia, the "holdback" tendency and the "keeps going" tendency.

Research Agenda

The papers and discussions at the Bremen Workshop suggested several issues that need to be addressed through further research on student learning of physics. Some of these issues will be discussed in the following section and placed in the context of a research agenda. (Names in parentheses refer to authors of papers in this volume. The citations provide examples of the type of research being proposed.)

1. *Need to document learning pathways for different content areas in physics*

As has been mentioned already, much of the research during the past fifteen years has focused on documenting students' knowledge prior to and following instruction. Little research has been reported that documents student understanding *during* the learning process. In a constructivist framework of teaching and learning it becomes important to have information about how the ideas of individual students and groups of students emerge during learning. This suggests a shift in research focus from pre-post "snapshots" of understanding to "strobe" pictures of the learning process.

There are many types of research studies that could benefit from systematic monitoring of the learning process. One type of study would be descriptions of pathways of learning in specific content areas; that is, documentation of how students' ideas within a given domain develop during sequences of learning activities (Scott). Another type of study could provide information useful in identifying intermediate states of learning. Research has shown that providing instruction that explicitly builds on intermediate states (or intermediate conceptions) can facilitate students' attainment of the target state of knowledge. For example, Dykstra discusses how students thinking about force and motion changes from an initial "motion implies force" conception to (something close to) the full Newtonian "acceleration implies net force" conception. As an intermediate step in the learning process they might first be led to differentiate "motion" into constant velocity and changing velocity. Thus, an intermediate conception might be represented by the statements: "increasing velocity implies increasing force; constant velocity implies constant force." Another example is provided in the paper by Brown and Clement. In order to guide students to a deep understanding of the concept of inertia, the authors found it helpful to have students first differentiate between two intermediate aspects of inertia, the "holdback" tendency and the "keeps moving" tendency.

Information obtained by carefully monitoring an individual's or a group's activity during learning can also provide important evidence for deciding the status of students' conceptions (Hewson and Hewson; Hewson and Hennesey), for describing the growing complexity and stability of concepts (Fischer and von Aufschnaiter), for describing the role of conflict (Scott, Asoko and Driver) and for describing changes in students' epistemological beliefs, beliefs about the nature of learning, the nature of science, etc. (Gunstone; Larochelle and Desautels; Solomon). Furthermore, there is a growing awareness that scientific knowledge as a way of "seeing the world" should be developed in a community environment, suggesting an instructional focus on group work, peer interaction and collaborative learning. Studying such interactions would require systematic monitoring of the group learning process.

2. Need to construct ways of describing cognitive systems that are useful to researchers in physics education

An important theoretical issue involved in describing students' cognitive systems is the decision regarding what "cognitive entities" should be used to describe the learning process and to communicate the results to others. This choice determines the "grain size" of analysis and description. A basic cognitive entity used in many studies is the verbal description of an underlying idea of a student that the researchers find by interpretation of student's comments (e.g. McDermott and Somers; Jung; Scott). These ideas can be further analyzed to produce other cognitive entities: formal categories, for example, networks or concept maps (Fischler and Lichtfeldt), or hierarchical levels of complexity (Fischer and v.Aufschnaiter); descriptions of intermediate states of learning (Dykstra, Clement and Brown); notions of a concept with a hard core or "nucleus" (Schmidt and Schwedes); researchers' constructions of cognitive systems (Niedderer and Schecker).

Some significant issues arise with studies aimed at providing primarily *formal* categories of description of research results. If the ultimate goal of the research is to promote student learning, then the description of research results must be in a form easily understandable by, and useful to, the scientific community. Thus, reports of studies focusing on highly formalized descriptions of learning should also include summaries of the results in terms more closely aligned with the observable behavior of students. Also, although a very fine-grained analysis would be important for capturing complete information about the learning process, larger units of analysis and description may provide more useful information for guiding instructional decisions. Finally, regardless of the level of description of the data, researchers' discussion of cognitive entities needs to be accompanied by concrete examples of student behavior.

3. Need to develop research methodologies that would be appropriate for carrying out learning studies

The ideas of students are most important, as they manifest themselves in students' verbal comments when making predictions, providing explanations or experimenting. Thus, qualitative interpretative methods of research are needed. In view of this, there are important methodological issues that arise in carrying out those qualitative research studies. It is important to bear in mind that the data interpretations are constructions of the researcher. Data must be analyzed in ways that will produce results that are relevant and reliable. Although the learning process studies mentioned below can provide the most detailed information about student learning, the researcher must find an adequate level of description and arrive at results that are valid for more than just one student. There is also the need to ensure that the results of this qualitative research are communicable to other researchers.

The empirical learning studies described in the papers in this volume have various methodological designs. These designs can be described along four different dimensions. One of these dimensions involves *when and with what frequency* the data are collected during the learning process. Along this dimension there are three types of studies:

> **Learning process studies** (LPS), in which the data is collected continuously during the learning process. The aim is to capture and be able to describe the entire process;
>
> **Learning states studies** (LSS), in which selected states before, during and after teaching are described. The aim is to monitor student understanding at a few crucial points in the learning process. These studies could be used to identify intermediate states of learning; and
>
> **Learning outcome studies** (LOS), which focus mainly on describing the state of student understanding at both the beginning and the end of the learning process, or perhaps only at the end of the process.

A second dimension along which empirical research on learning can be designed involves the *units of study*. Learning process data can be collected from individual students, small groups of students, entire classes, or some combination of individual and group collection strategies.

A third dimension involves the *duration* of the learning study. This can vary from studies focusing on short time teaching processes of approximately one hour in duration, to long time teaching processes lasting several weeks, or even an entire semester.

A fourth dimension along which learning studies vary involves the actual *setting* in which the learning takes place. Learning taking place in a controlled lab situation provides the setting for tutorial studies or clinical learning interviews. Learning can also be studied in the natural setting of a classroom situation, and the observations can possibly be augmented by administering additional interviews in a clinical situation.

The following table gives an overview of the methodological designs of **empirical learning studies** presented in this volume:

		Type	Unit	Duration	Setting
(1)	Hewson/Hennessey	LSS	1 student	weeks	natural
(2)	Schwedes/Schmidt	LPS	1 student	6 hours	clinical
(3)	Scott/Driver	LSS	1 student	weeks	natural
(4)	Fischer/v.Aufschnaiter	LPS	1 student	weeks	natural
(5)	Lichtfeld/Fischler	LSS	1 student & class	weeks	natural
(6)	Sere	LSS	1 student	weeks	natural
(7)	Jung	LSS	1 student	1 hour	clinical
(8)	von Rhoeneck	LOS	classes	weeks	natural
(9)	Clement/Brown	LSS	classes	weeks	natural

Table 1: Methodological design of empirical studies

Learning process studies like (2) and (4) above give the most detailed data on learning processes. But, as mentioned above, there are issues regarding finding an appropriate level of description and reporting results that have some generalizability. From these considerations it might be useful for future investigations to combine studies of single students and of whole classes or groups, as in (5). Furthermore, learning states studies (LSS) with whole groups of classes (9) might seem best for providing reliable information about intermediate states of learning.

4. Need to document changes in student's conceptual ecology

A student's conceptual ecology consists of many different types of knowledge that provides the context in which a student will respond to specific learning opportunities (Hewson and Hewson). Some of these types of knowledge include a student's epistemological commitments, metaphysical beliefs, beliefs about learning and teaching and beliefs about the nature of science.

Epistemological commitments are beliefs about the basis in which knowledge should develop; e.g. looking for consistency or generalizability in constructing new knowledge. Metaphysical beliefs are beliefs about the natural world that, by their nature, are not subject to direct empirical refutation. (Scott describes how the epistemological commitments and metaphysical beliefs of a 6th grade student influences her learning of a particulate model of matter.) Students' beliefs about learning and teaching, for example, the beliefs that the teacher is the source of authority and the student's role is to "get" the information transmitted by the teacher, can strongly influence learning in the classroom (Gunstone). Likewise, students' beliefs about the nature of science, for example their beliefs about the relation between theory and experiment, can also influence their learning (Gunstone; Larochelle and Desautels; Solomon).

5. Need to examine issues regarding conceptual change

One of the basic questions of the workshop can be summarized as follows: What do we mean by "physics learning"? It is well recognized in the science education research community that there is a big gap between what is taught and what is learned. This actually is one of the basic observations that should be explained by constructivism. Although workshop participants often seemed to use the term learning synonymously with conceptual change, it was not clear that everyone shared the same meaning for conceptual change.

In his paper, Dykstra raises many questions about conceptual change that should be addressed in future research: How can conceptual change be described? What is it that is changing; that is, what are conceptions? Are there categories of conceptual change which are functionally useful in the classroom?

Among the different ways of thinking about conceptual change are the following:

(1) going from one concept to another, either by exchange, or by restructuring, or arriving at a peaceful co-existence; having students change their existing conceptions in terms of status, probability of usage, generalizability and consistency of use; and

(2) going from simple lower levels of thinking to more complex and interrelated higher levels of thinking; going through a process of development in cognitive systems by constructing new meanings with higher complexity and growing stability.

The empirical learning studies contained in the Proceedings represent some of these different views. Whereas the studies of Hewson and Hennessey, and Schwedes and Schmidt, assume a classical conceptual change from an everyday life concept to a more scientific concept, the study of Fischer and von Aufschnaiter assumes learning is a developmental process involving constructions of meanings of objects, properties, events and finally concepts. The study of Scott shows an explicit example of a reasonable and clearly understood co-existence of old and new concepts. Other studies more or less take combinations of those views on learning.

6. *Need to develop instructional strategies and materials based on results of learning studies in specific content areas*

Several of the papers in this volume include descriptions of instructional strategies and materials that are based on research on student learning (Minstrell; Schwedes and Schmidt; Fischler and Lichtfeldt; McDermott and Somers; Goldberg and Bendall; Brown and Clement). McDermott and Somers argue that effective design of instructional materials requires an understanding of the nature of conceptual and reasoning difficulties students encounter in learning physics. The formative evaluation of instructional strategies and materials can be carried out within the context of studies designed to document learning pathways for different content areas in physics (see the first need identified above).

Several hypotheses were explicitly discussed at the workshop about how to promote teaching towards understanding physics concepts. These included:

(1) Starting with elicitation of students' ideas;
(2) Using different forms and ways of introducing the scientific view;
(3) Introducing conflict and confrontation between different views and different expectations;
(4) Explicitly discussing intermediate concepts which lie in between naive and expert conceptions;
(5) Following a "bridging strategy," using positive intuitions as a starting point, and using analogies to promote understanding of the science concepts in more difficult cases;
(6) Discussing explicitly the "status" of new physics concepts and related epistemological beliefs; and
(7) Using several different representations of knowledge (hands-on experiments, interactive video, computer microworlds and models), especially in ways that help students to see connections between them.

The question of how to promote learning for understanding has aspects more pragmatically related to the improvement of physics instruction, and also aspects more theoretically related to problems of a content specific cognitive model of learning. An important issue for further development of research in this field would seem to be to more clearly separate this second aspect from the first.

7. *Need to consider the appropriate role of the teacher in a constructivist classroom*

According to the constructivist view of learning the teacher cannot transmit knowledge directly to the student; the student must construct the knowledge himself or herself. This raises the question about what the role of the teacher should be in helping students construct this knowledge. Aspects of this issue are discussed in several of the papers in this volume (von Glasersfeld; Dykstra; Minstrell; Scott, Asoko and Driver).

The final two research agenda items below are not explicitly discussed in the papers presented in this volume. However, they were raised on the final day of discussions at the Bremen workshop.

8. *Need to promote teachers' (precollege and college) awareness of research on student learning*

It seems very important for the improvement of physics teaching to bring teachers on to the inner side of the teaching/learning problem, in the same way that it is important to bring students to the inside of their learning problem. Teachers need to be involved on research on the learning of their own students.

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

An issue discussed at the workshop was the question: Does it make sense to have both pure and applied research in this field of learning in physics? What are the differences? It seems clear, that basic research in this field has to work on developing explicit hypotheses of mental models of what is going on in students' minds, related to specific subject areas of physics. Here collaboration among different disciplines seems most important. Applied research, being more pragmatically oriented, will aim directly at achieving improvements in teaching and learning.

Other questions raised at the Workshop involving issues of communication include the following: How are researchers from all over the world going to maintain contact with one another? How can we establish and maintain links? How are we to share our findings with each other? How can we maintain links within our own educational community that involve both the teachers at all educational levels and the students? These are difficult and important questions, but as a research community we must address them if we are to make progress.

Bibliography

Carmichael, P., R. Driver, B. Holding, I. Phillips, D. Twigger and M. Watts (1990). Research on Students' Conceptions in Science: A Bibliography. Children's Learning in Science Research Group, CSSME, University of Leeds, England.

Pfundt, H. and R. Duit (1988). Bibliography: Students' Alternative Frameworks and Science Education, 3rd edition, IPN, Kiel, Germany.

Posner, G.J., Strike, K.A., Hewson, P.W. & Gerzog, W.A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, **66**, 211-227.