THE CONSTRUCTIVIST VIEW IN SCIENCE EDUCATION – WHAT IT HAS TO OFFER AND WHAT SHOULD NOT BE EXPECTED FROM IT[1,2]

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Abstract

There is certainly something fashionable about constructivism in science education nowadays. It is further true that constructivism is by no means a consistent movement, there are many variants of this view in use. Furthermore, it appears that constructivism, for some science educators, in any case, has become the new ideology of science education that provides a cure for every problem of teaching and learning science. But without any doubt constructivism has become also a most valuable guideline for science education -- for science teaching and learning as well as for research in these fields. This paper attempts to review the myths, the misunderstandings, the polemics and the serious critiques concerning constructivism. It will be argued in favor of a consistent and "moderate" constructivist view in science education that in fact may provide substantial progress in our field and which major features will be among the valuable views of science education even after the term constructivism will have gone out of fashion.

Key-words: constructivism, science education, conceptual change.

Resumen

Seguramente hay algo de modismo respecto al constructivismo en enseñanza de las ciencias en los días de hoy. Es también cierto que el constructivismo no es, de ninguna manera, un movimiento consistente; existen muchas variantes de esa visión en uso. Además, parece que para algunos educadores en ciencias el constructivismo se ha convertido en una nueva ideología capaz de curar todos los problemas de enseñanza y aprendizaje de ciencias. Por otra parte, sin duda, el constructivismo se ha convertido en una valiosa guía para la educación en ciencias - tanto para la enseñanza y el aprendizaje de ciencias como para la investigación en estas áreas. Este artículo intenta revisar los mitos, los malentendidos, las polémicas y las serias críticas acerca del constructivismo. Se argumentará en favor de una visión constructivista consciente y "moderada" en la educación en ciencias, que de hecho pueda fornecer un progreso sustancial en el área y que cuyos rasgos principales puedan permanecer entre las posturas valiosas en la educación en ciencias, aún después que el término constructivismo haya pasado de moda.
Palabras-clave: constructivismo, enseñanza de las ciencias, cambio conceptual.

[1] Invited paper.

[2] Proccedings of the International Conference "Science and Mathematics for hte 21st century: Towards Innovatory Approaches". Concepción, Chile, 26/9 - 1/10, 1994.

On the meaning of the constructivist view in science education

It has to be pointed out from the outset that the constructivist view primarily concerns a particular way of conceptualizing knowledge and knowledge acquisition (i.e. learning). It is a view of the nature of knowledge and its development, it is based on a certain epistemology (i.e., a theory of knowledge). The constructivist view comes in many variants in science education literature on students' learning (Good, Wandersee, & Julien, 1993). It is based on a number of quite different philosophical perspectives that share a common "constructivist core". Matthews (1993) mentions the following positions: Piaget's genetic epistemology, the new theories of science movement in the '60s and '70s that may be indicated by names like T.S. Kuhn, Feyerabend, Lakatos and others, the new sociology of science, postmodernist views about science, Kelly's (1955) theory of personal constructs, and social constructivism, especially the theory of language acquisition by Vygotsky. The common constructivist core is a "view of human knowledge as a process of personal cognitive construction, or invention, undertaken by the individual who is trying, for whatever purpose, to make sense of her social or natural environment." (Taylor, 1993, 268). In other words: knowledge is not viewed as some sort of a true copy of features of the world outside but as construction of the individual. Knowledge acquisition (i.e. learning) is not the transfer of "nuggets of truth" (as Kelly, 1955, put it) to the individual but a personal construction by the individual. The learner is not seen as a passive receiver but as an active constructor of knowledge.

Radical constructivism

In science (and mathematics) education von Glasersfeld's radical constructivism (von Glasersfeld, 1989, 1992, in press) is most often employed as reference position of the constructivist view. Radical constructivism deliberately is an epistemology, a theory of knowledge, more precisely a theory of "experiential" knowledge. This knowledge is seen as tentative human construction on the basis of the already existing knowledge. The tentative, provisional character of experiential knowledge is of great importance. It leads to the denial that there may be ultimate truth for this kind of knowledge. That there may be such a kind of truth in the field of religious beliefs, however, is not questioned. The tentative character concerns every kind of experiential knowledge, knowledge constructed by the individual and science knowledge as well. Also the latter is viewed as human construction on the basis of the conceptions and ideas the individual scientist or the respective scientific community holds.

There are three key principles of radical constructivism. The first states that *knowledge is not passively received but is built up by the cognizing subject*. According to this principle it is not possible to transfer ideas into students' heads intact, rather students construct their own meanings from the words or visual images they hear or see. What the learners already know is of key importance in this construction process.

The second principle states that *the function of cognition is adaptive and enables the learners to construct viable explanations of experiences*. Knowledge of the world outside, hence, is viewed as human tentative construction. A 'reality' outside is not denied but it is only possible to know about that reality in a personal and subjective way. There is sometimes the misunderstanding that this principle argues in favor of "anything goes" so to speak, that every human construction is allowed. This is definitely not the case. The constructions have to be "viable". This term is based on an analogy to the development of the species in evolution. Only those species "survive" that are adapted best to the environment. Per analogicam: only those constructions are "viable" that prove to be useful for the constructor.

Von Glasersfeld likes to call the first principle the trivial constructivist principle in order to lead attention to the crucial importance of the second one. But the term "trivial constructivism" appears to be "ill-chosen" (Ernest, 1993; see similar arguments by Solomon, 1994, 14). First, it is far from being trivial to put this principle into practice as will be outlined below. Secondly, there are strong logical relations between the two principles. The key idea is in some way already in the first principle, the second one may well be viewed as a further elaboration of the first.

Radical constructivism as proposed by von Glasersfeld implicitly includes a third principle. It highlights that although individuals have to construct their own meaning of a new phenomenon or idea, *the process of constructing meaning always is embedded within a social setting of which the individual is part*.

Critiques of radical constructivism

Radical constructivism has come under attack recently from a number of philosophical and pedagocical perspectives (for a review of these critiques see Duit, 1993a). Suchting (1992) provides a most rigorous critique of that approach. Very briefly summarized (Duit, Treagust, & Fraser, in press), he concludes that constructivism has to be seen as a doctrine that is simply unintelligible and confused and does not successfully address the key problem of intersubjectivity. The weakness of radical constructivist philosophy's terminology allows trivializations of the main ideas in such a way that at the very end they are shared by everyone. In fact, there are key weaknesses in von Glasersfeld's position as is worked out in a number of other publications (Nüse, Gröben, Freitag, & Schreiber, 1992; Matthews, 1993). But a certain number of the problems addressed in the critiques appear to concern philosophical subtleties. The key ideas as included in the above principles of radical constructivism seem not to be questioned in principle by the critics. The claim that they are shared by almost everyone and hence are without any value (see also Strike, 1987) needs a closer look. Of course, this line of critique should be taken seriously in order to develop the epistemological underpinnings of constructivism further. But in view of science instruction it has to be regarded that the principles of radical constructivism as stated above are not at all shared by everyone who is involved in science education. It is a well established empirical finding now that at least many science teachers (and students alike) hold rather naive views of knowledge construction and limited views of the nature and range of science (Lederman, 1992; Baird & White, in press). There are further findings (e.g. Fischler, 1993) that teachers who "learned" the constructivist view, i.e., expressed this view in interviews, do not necessarily act according to it in classroom situations. In general, there are many difficulties to set constructivist principles into practice (Tobin, 1993a).

It is a common feature of critiques on radical constructivism that this position is accused of leading to the denial of the existence of the physical world outside (Goldin, 1989; Suchting, 1992; Matthews, 1993). Ernest (1993) points out that this is an incorrect conclusion, because von Glasersfeld points out in a number of articles that radical constructivism is ontological neutral (von Glasersfeld, 1992, 32). All it denies is the possibility of any certain knowledge of that reality. That means that the constructivist view does not necessarily lead to an idealist position but is also compatible with a critical realist view.

Another line of critique that is of great importance for employing the constructivist view in science education concerns the interplay of the individual and the social in radical constructivism. It appears that radical constructivism puts its main emphasis on the individual and hardly pays only to the social aspects (Solomon, 1994, 15). Social issues are usually of a marginal type in writings on radical constructivism -- although von Glasersfeld (in press) always explicitly admits that the social context which the individual learners are part of when they construct knowledge is an important issue. Phenomenological (Marton & Neuman, 1989) as well as social constructivist perspectives (Glasson & Lalik, 1992) argue that the radical constructivist approach leads to the separation of the individual from the world. O'Loughlin (1992) adds another important issue. He admits that the emphasis on students' own activity in constructivism in fact may empower students to take responsibility for their own learning but he also claims that it has to be taken into account that a certain amount of power is put on students to be active. The emphasis on the individual is questioned also from another vantage point. Self-activity may lead to overlooking the point that a substantial amount of guidance is necessary to make students able to construct desirable conceptions. Activity theory (Wolze & Walgenbach, 1992) views "self-development" and "being-developed" as complementary issues in knowledge construction. In constructivism there is a tendency to overemphasize the "self-development" side.

On the common core of the constructivist view as used in science education

In summarizing what has been presented above it has to be stated another time that the constructivist view primarily concerns a particular theory of knowledge and knowledge acquisition. Consequences drawn from this view for science teaching and learning in general that are usually discussed under headings like "constructivist science instruction" go far beyond epistemological issues and issues of knowledge acquisition. As will be outlined in more detail below they mostly concern the arrangement of conditions that support students' constructions on the basis of their already existing knowledge. There appear to be four main facets of the view of knowledge under review here.

(1) *Active construction on the basis of the already existing conceptions*. Students have to construct the new knowledge actively by themselves on the grounds of the already existing knowledge. There is no learning from scratch, there is no simple transfer of pieces of knowledge from a certain source to the learner. The already existing knowledge (students' prior conceptions) have proven to be both the necessary building blocks and empediments of learning. As will be discussed below many students' prior science conceptions are in stark contrast to the science conceptions to be learned (compare the list of key findings of students' conceptions research in the appendix). Changing from these conceptions to science conceptions is not easy, sometimes not even likely, because the already existing conceptions provide the goggles, so to speak, for seeing the new conceptions presented by the teacher, a textbook or the like. Ausubel's (1968, vi) famous dictum "The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly" points to the key importance of the already existing knowledge. The more recent developments in constructivist oriented science education research have revealed what the learner already knows in major science domains, and have also led to the development and evaluation of new approaches to what "teach him accordingly" may mean.

(2) *Tentative construction* . All knowledge or ideas constructed by the individual about traits of the world outside or about ideas another may have is tentative in nature. It is hypothetical and may need minor or major changes when other evidences become available. Also science knowledge as accepted today in scientific communities in principle is tentative in nature and open for revision.

(3) *Viability*. Knowledge and ideas that have been constructed need to be viable, i.e., useful for the individual (or a group of individuals respectively). Students may, for instance, construct what they like but then they run the risk of not being understood by others. Only constructs that stand the test of being viable survive so to speak.

(4) *Social construction*. Although every individual has to construct knowledge by her or himself the construction process always also has a social component. Knowledge is always constructed within a certain social setting.

The constructivist view though still in need of further refinements has proven to be a most valuable (viable) guide for student centred pedagogy in science education, i.e., for science education that is oriented towards the needs and interests of students. In the following, first key findings of research on students' conceptions in science that clearly show the importance of prior knowledge as determining factor in learning will be outlined. Afterwards characteristics of new constructivist approaches of science instruction and of teacher education will be presented.

The constructivist view as consistent interpretation pattern for results of empirical studies on students' conceptions and their development

A large number of empirical studies on science related students' conceptions have been published over the past two decades. The recent edition of the bibliography by Pfundt and Duit (1994) contains more than 2000 entries of this kind. The results of these studies (see for a brief summary of key findings the appendix of this paper) may be taken as a convincing set of evidence in favor of the constructivist view outlined above. In other words, the findings may be interpreted in a rather consistent way by that view. In the following main findings concerning the significant importance of the prior conceptions as determining factors of learning will be outlined.

Conception and perception

The constructivist view as outlined above claims that the conceptions held guide or even determine the sense making process, i.e., the interpretation of sense data (like visual or audio data). It is well known from neurophysiological research that our senses like the eye or the ear are by no means passive receivers but are very active in the process of seeing and hearing (Zeki, 1992). In other words, there is no objective one-to-one representation of features outside us when we see or hear something. Every act of seeing and hearing includes interpretation.

Gestalt theory has claimed that perception is very much influenced by conception. Hanson (1965) has created the term of "theory laden observation". He points out that observation is very much influenced by the "theory" employed when observations are made. In fact, it is an everyday experience that different persons observing the same event report different issues. Every judge knows that reports of witnesses of the same event may be very different. The incoming sense data are so rich in information that it is absolutely necessary to reduce this richness, to put emphasis on some facets only.

In science education, experiments play a key role. Usually it is taken for granted that all students actually observe the same facets that are so obviously to be seen from the point of view of the teacher. But there is research showing that this is not necessarily the case. The conceptions students hold, in other words, the way student "view" an event, influence what is observed. Only one example will be given here. A thin metal wire is connected to a battery. When the circuit is closed, the wire is heated and starts glowing. Where does it glow up first? Students were asked to make a prediction, the experiment was then carried out. Students who predicted that the wire would glow up first at the end of the wire where, so to speak, the current enters it, actually observed this (Schlichting, 1991). There are other equally striking examples in the literature that conception influences perception. Recently Brewer and Lambert (1993) have critically analyzed research in the field of psychology that has addressed the theory-ladenness of observation as outlined above. They came to the following conclusion:

"However the data also suggest that top-down influences on perception are only strong when the incoming sensory input is weak or ambiguous. Thus, in cases where the bottom-up sensory evidence is strong and unambiguous, there is little evidence that theory can override observation, and so the data do not support the strong form of the theory-laden position attributed to Hanson and Kuhn." (Brewer & Lambert, 1993, 254)

The results available from constructivist science education research appear to be totally in accordance with this conclusion. That means, that there is only a strong influence of prior conceptions, if the phenomena observed are somewhat ambiguous. This is, for instance, undoubtedly true in the case of the wire glowing up discussed above. It is difficult to see that the wire glows up at all spots at the same time because our eyes always only concentrate on one spot. Nevertheless, the issue of theory ladenness of observation should be given attention in science instruction and in research on students' understanding.

Conception and action

There is a lot of evidence that students' problem solving behavior is very much influenced by the conceptions they hold. A paradigmatic study has been carried out by Karmiloff-Smith and Inhelder (1976). Two groups of children, four years old and eight years old, were asked to find out the equilibrium point of a number of metal bars. All bars looked alike but some had an extra load hidden on one side or a hole in the inner part. Therefore, the equilibrium point of these bars is not in the middle.

The younger children had no problems at all in finding the points of equilibrium. They simply used a trial-and-error-strategy. In contrast, the older children had difficulties. They had a "theory" that namely the equilibrium point has to be in the middle. The study shows that prior conceptions may strongly influence problem solving behavior and also points out that prior conceptions may distort solving a problem totally.

Conception may override empirical evidence

It is a very popular strategy among science teachers to arrange a cognitive conflict by using conflicting empirical evidence. Even if students really observe that there is a conflict that does not necessarily mean that they are convinced that their conception was not adequate. It is much more likely that one single conflict does not convince students. They rather try to get rid of the unexpected outcome by all sorts of ad-hoc arguments. There is, for instance, a 12-year old student in a study by Tiberghien (1980) who is asked to find out whether an iceblock covered with wool or covered with aluminum foil will melt first. The student thinks that the iceblock covered with wool will melt first, because wool "gives" heat (it makes us warm if we wear it). This is an interesting example for the impact of everyday sense experiences on students' conceptions. But even more interesting is the students' behavior when she found out that her prediction was wrong, that the iceblock covered with aluminum foil melts first. She creates a number of arguments that in this particular situation the observed outcome would occur but not in other situations.

Conception guides learning

Research on students' (alternative) conceptions in science has revealed that students prior conceptions severely influence, even determine learning of the science conceptions presented in class, in textbooks or the like. It is one of the "sad" messages from this research that science instruction appears in general not to be too successful in guiding students from their preinstructional conceptions to the science conceptions. Research has also revealed why this is the case. Students are not able to understand the science view as presented because the science view is very often embedded into a totally different framework. Science learning then, in most cases that are of significance, is not of a simple enlargement (or even of a learning by rote) type but needs what has been called "conceptual change" learning (see below). This kind of learning requires a fundamental restructuring of the existing conceptual structure before students are able to really understand the questions asked by the teacher in the classroom and get an idea what a presented information may mean.

Many studies in science education research on students' conceptions are still quite narrow in scope when the impact of prior conceptions on learning science conceptions is involved. First, science learning does not only mean to learn science concepts of a content level type, i.e., concepts of light, combustion, or photosynthesis. Learning science should also include learning about science, i.e, about world views science has to offer (in other words to learn philosophy of science issues), and learning science should also comprise attempts to make students familiar with a view of their learning processes that may contribute to more effective learning in general. Concerning both aspects students usually hold limited and naive views. Research has shown that also here conceptual change learning has to take place that changes from prior everyday views of science and everyday views of learning are difficult because the prior view determine the learning process. Secondly, among the preinstructional conceptions that may influence (impede or support) learning of science concepts and principles are not only students' alternative conceptions of the phenomena, concepts and principles in question but also conceptions of a more general kind, among them general schemes of thinking (like thinking in chains of causal events; see Andersson, 1986; Ogborn, Mariani, & Martins, 1994) as well as "philosophy of science" related beliefs and ideas (for a review see Lederman, 1992). The constructivist view has led attention to the sketched broader view of the significance of prior conceptions on learning as will be discussed later in more detail when characteristics of constructivist science teaching will be outlined.

The hermeneutic circle

It is the key issue of the findings presented in the preceding section that interpretation is only possible on the basis of the conceptions available to be employed in that interpretation process. This leads to a circle of understanding understanding that is known as the hermeneutic circle. The word "hermeneutic" is of Greek origin, the meaning of hermeneutic circle simply is "circle of interpretation". The circle-like nature of interpretation processes is illustrated by the communication situation between two interlocutors, e.g., a teacher (or interviewer) and a student. The verbal and non-verbal information sent out by one participant is interpreted by the other within his or her framework. The response sent out then is interpreted by the other commonly in a slightly or even totally different framework. If the sketched communication situation is analyzed in more detail, there are sense making processes (i.e., understanding processes) involved that are embedded in different frames of reference. The questions posed or the verbal stimuli provided by the teacher or the researcher are embedded in their frame of reference, i.e., in their science point of view. The students are able to make sense of the questions posed or the stimuli provided only on the basis of their preconceptions, i.e., within the frame of reference of their already existing conceptions. The reactions they give, therefore, make full sense only within the frame of reference of their preconceptions. The teacher or the researcher is able to make sense of the students' reactions only on the basis of her or his conceptions. Therefore, the students' reactions in the classroom as well as in research situations are very often interpreted within a frame of reference that is partly or even totally different from the frame of reference in which they were created. Misunderstandings then are unavoidable. If the dialogue continues, an "endless" chain of misunderstandings may be the result.

The circle of understanding is a most important tool for looking at learning in science from a constructivist perspective. It facilitates understanding of many attempts to teach science in that teaching may fail simply because students and teacher only partly understand one another or do not understand one another at all. Endless chains of misunderstandings appear to be a frequent feature of science classes. The circle also provides a powerful tool for planning research and for interpreting the results. Interviews, for instance, are used most often in research studies on students' conceptions in science (they are the "workhorse" of that research as Wandersee, Mintzes, & Novak, 1993, put it). There are several hermeneutical circles involved when interviews are used. Interviewer and student have to make very fast interpretations of the others' responses. Because there is not much time to think about what the other may have meant, in interviews frequently misunderstandings occur (see for examples Duit, 1993b). Interviews are usually tape recorded and then transcribed. It has to be taken into consideration that also this process is an interpretation. A transcript necessarily is not as rich in information as compared to the original situation. Furthermore not all passages are clearly understandable. Therefore, there is the danger that the transcriber writes down something quite different from what has been said.

When the transcript is interpreted the research and the interview documents are the "partners" in the circle. It has to be taken into consideration that what the researcher usually likes to call students' conceptions actually are his or her conceptions of students' conceptions (for the issue of "conception of conception" see also Marton, 1981). Of course, similar considerations concern every method employed to investigate students' conceptions and their development (Duit, 1993b; for a review of methods used in science education research on students' conceptions see Wandersee, Mintzes, & Novak, 1993, and Duit, Treagust, & Mansfield, in press; for an introduction into the practice of using these methods see White & Gunstone, 1992).

Characteristics of constructivist science instruction

Constructivisms as part of a movement towards student-centred science instruction

The common core of the constructivist view as outlined above first and foremost provides a view of learning that allows to interpret (and hence understand) students' learning difficulties as revealed by the many studies available in a consistent manner and also provides guidelines for developing more efficient teaching and learning strategies. In a rigid sense, there is no constructivist learning. Learning whenever it happens (and it happens also, even successfully, in more traditionally oriented approaches) is viewed as active construction by the learner. In that more rigid sense the constructivist view does not favor any approach of learning science. But the idea inherent in constructivism of taking the students' beliefs and conceptions serious has led to developments towards making the constructivist view a genuine part of attempts towards student-centred pedagogy of science instruction. The focus here is on the students, their interests, their learning skills, and their needs in a broad sense. Science instruction from that perspective aims at providing students with science knowledge in such a way that they understand not only the science concepts and principles rather than learning definitions and formulas by heart but also understand in which way science knowledge is of significance for their lives and for the lives of all other human beings. The focus of such a science instruction is not solely the significance of certain content domains in the sciences, i.e., students introduction into the cultural heritage that science knowledge provides but also the significance of science for the individual and society in general. Constructivism therefore has become part of a broad movement in science education towards "science for all" (Fensham, 1986), i.e., towards making science knowledge more meaningful and hence more significant that may be indicated by gender inclusive science instruction, and the developments that take place under the label of STS (the interplay of science, technology and society; Fensham, 1991; Yager, 1993). In the following, key characteristics of such a constructivist science education will be outlined.

Constructivist approaches aim at changes of several facets of science education

The aims of constructivist science instruction are fundamentally different from more traditionally oriented approaches. They are student centred in the above broad sense. Understanding science in the deep way aimed at in constructivist approaches goes far beyond parrot like repetition of definitions, formulas and the like. It includes applications of science knowledge for the mentioned purposes, and also incorporates views about science and meta-cognitive issue. The aim is further a reflective learner who is aware of the strength and limitations of her or his thinking.

In order to address these aims constructivist approaches usually put emphasis on changes at several levels and aspects of science education. In table 1 some key contrasting aspects of traditional and constructivist science education are given. This table stems from a holistic constructivist approach that Duschl and Gitomer (1991) call "portfolio culture". The term portfolio will be briefly explained below (see in the paragraph on assessment), the "label *culture* is meant to convey an image of a classroom learning environment that reflects a comprehensive interplay between teacher, student, and curriculum" (Duschl & Gitomer, 1991, 848).

Traditional Science Culture	Portfolio Science Culture
View of science	
Strict hypothetical-deductive scientific method	Partial Scientific method
Logical Positivism Epistemology	Scientific realism/semantic conception epistemology
Observation/theoretical distinction tenable	Observation/theoretical distinction untenable
Role of learner	
Low student input/nonactive image	High student input/active image
Scientific meanings received	Scientific meanings negotiated
Low level of reflection	High level of reflection
Use student developed strategies	Uses strategic/principled knowledge
Role of teacher	
Disseminator of scientific knowledge	Crafter of scientific knowledge
Nonparticipant in construction of scientific knowledge	Participant in construction of knowledge about science
Strict adherence to prescibed curriculum	Modify and adapt prescribed curriculum
Curriculum goals	
Scientific knowledge What we know	Knowledge about science How and why we know
Emphasize fully developed final form explanations	Emphasize knowledge growth and explanation development
Breadth of knowledge	Depth of knowledge
Basic scientific knowledge	Contextualized scientific knowledge
Curriculum units discrete	Curriculum units connected

Table 1: Contrasting Traditional and Portfolio Cultures in Science Classrooms (from Duschl & Gitomer, 1991, 849)

The view of science content in constructivist science education

It has already been outlined that science knowledge also has to be viewed as tentative human construction from the constructivist perspective. That means that the idea that there is a true content structure in a particular content domain has to be rejected. What is commonly called the science content structure is the consensus of the particular scientific community. Every presentation of this consensus, including the presentations in the leading textbooks, is an ideosyncratic reconstruction by the referring authors informed by the specific aims the authors explicitly or implicitly hold. Therefore, there is no "right" content structure that may form the basis for a certain module of science instruction. If the aims of reconstruction are different, this process will result in emphasizing, at least slightly, different facets. In other words, every science instruction has to be based on a careful reconstruction of the referring pieces of science content structure that is understood as the accepted consensus in the scientific community in the above sense. But the reconstruction is very much influenced by the aims of instruction, there is an intimate interplay of issues of the reconstructer's views of subject matter content, of students' conceptions, of students' interests, and his or her view of learning science in general.

The constructivist view, for instance, does not only provide a new means of thinking about learning but also of viewing science content: "....we knew that our views of learning affect our teaching, but now we see that they also affect our perceptions of content...." (Fensham, Gunstone, & White, 1994, 1). An approach of "educational reconstruction" worked out by Kattmann (1992) and Duit and Komorek (1994) explicitly includes students' conceptions of various kinds in the process of reconstruction of science content. Experiences of mathematics educators (Confrey, 1990 as well as Steffe & D'Ambrosio, in press) could be reconfirmed that viewing science content from the students' perspectives does not only facilitate a more adequate reconstruction but may also enhance the reconstructers' understanding of the referring science (or mathematics) content.

Constructivist approaches usually include careful analyses of traditional reconstructions and the development of new reconstructions under the perspective of the aims set for the particular instructional unit. A careful reconstruction has proven to be of key significance. Brown & Clement (1992), for instance, report of a constructivist teaching approach towards learning issues of Newton's Third Law. This approach was only sufficiently successful after the science content structure had undertaken another attempt of careful reconstruction.

The interplay of pedagogical and science related issues in reconstruction of science content has been extensively discussed under the label of "content specific pedagogical knowledge" (Shulman, 1986). The idea here is that teachers do not only need sufficient science content knowledge on the one and pedagogical knowledge on the other hand but also knowledge of the interplay between the two domains (Cochran, 1991). Teachers' pedagogical content knowledge has proven to be the key factor in new teaching and learning approaches under a constructivist perspective (Wandersee, Mintzes, & Novak, 1993).

Conceptual change and conceptual change supporting conditions

Learning from the constructivist perspective may be viewed in terms of students' pathways from certain pieces of their already existing conceptual structure towards science conceptions. In principle two kinds of pathways may be differentiated: via enrichment (or enlargement), i.e., via minor revisions, or via major restructuring, conceptual change, of the already existing. There are a number of other terms in use to indicate this differentiation (Duit, 1994), namely continuous (or evolutionary) versus discontinuous (revolutionary) pathways (see below). The distinction of evolution and revolution has been employed in alluding to Kuhn's (1970) types of paradigm shift. Quite often similarities of this distinction and Piaget's (1985) differentiation between assimilation and accommodation are also referred to. Undoubtedly the learning of most key science concepts and principles is of the conceptual change type, i.e., is in need of major restructuring of the already existing conceptual structure.

Classroom Constextual factors	Motivational factors	Cognitive factors	Conditions for conceptual change
Task structures	Mastery goals	Selective	Dissatisfaction
Authentic		attention	
Challenging	Epistemic beliefs	Activation of prior	Intelligibility
Authority structures			
Optimal choice	Personal interest		Plausibility
Optimal challenge		Deeper processing	
		Elaboration	
	Utility value	Organization	Fruitfulness
Evaluation structures			
Improvement-based	Importance	Problem finding	
Mistakes as positive		and solving	
Classroom managemnet	Self-efficacy		
Use of time		Metacognitive	
Norms for engagemnte		evaluation and control	
Teacher modeling	Control beliefs	Volitional control	
Scientific thinking		and regulation	
Scientific dispositions			
Teacher scaffolding			
Cognition			
Motivation			

Table 2: Classroom contextual, motivational, and cognitive factors related to the progress of conceptual change (from Pintrich, Marx, & Boyle, 1993, 175)

According to the theory of conceptual change as developed by Posner, Strike, Hewson & Gerzog (1982) there are four conditions of conceptual change (see also

Strike & Posner, 1992, and Pintrich, Marx, & Boyle, 1993, for critical remarks on the initial theory):

1- There must be dissatisfaction with current conceptions.
2- A new conception must be intelligible.
3- A new conception must be initially plausible.
4- A new conception should suggest the possibility of a fruitful research program.

The "mechanisms" of conceptual change are still mainly viewed in Piagetian terms of equilibration of assimilation and accommodation. Dissatisfaction results in disequilibrium of the mental balance so to speak. Assimilation (in case of minor revisions) or accommodation (in case of major restructuring) brings the balance back to equilibrium. The sketched process of conceptual change is not only facilitated by logical considerations but is deeply dependent on a number of affective and emotional factors (see for an overview of such factors table 2). These factors may be viewed as part of conditions that support conceptual change.

What changes in conceptual change? -- towards coexistence of students' conceptions and science conceptions

More traditionally oriented approaches of science instruction often start from the idea that learning science conceptions means to replace students prior (alternative) conceptions for the new science conceptions. Research has shown that this idea is not adequate. Students commonly do not give up their prior conceptions totally. In everyday context they usually trust more in their prior everyday conceptions than in the newly learned science conceptions. Constructivist approaches have replaced the replacement perspective by a coexistence view. It holds that students have to learn that science conceptions are valuable and fruitful in certain contexts whereas students' alternative (everyday) conceptions allow a fruitful (viable) dealing with phenomena in other contexts (Jung, 1986).

Hewson and Hewson (1992) discuss the issue of what changes in conceptual change from a slightly different perspective. They argue that change does not mean exchange (i.e., replacement) but change of status given to conceptions. Learning science then means that students give less status to their everyday conceptions in a smaller number of contexts whereas the status given to science conceptions increases accordingly.

Supportive classroom climate and instructional settings

A large variety of issues may be summarized under the supporting conditions of conceptual change. In general, instructional settings are designed that allow students to take responsibility of their learning processes and allow them to experience that science knowledge may be meaningful and significant for them (compare Pintrich et al, 1993, 181). Project type approaches, more open forms of instruction (e.g., open experimentation; Roth, 1993), and authentic learning environments (Roth, in press) are some labels that may indicate key features of such approaches. Also ideas of situated and socially shared cognition (Brown, Collins, & Duguid, 1989; Resnick, 1991) are among significant supporting conditions of conceptual change that address the aims of student centred science instruction as outlined above. Situated cognition briefly outlined, holds that all cognitive acts are situated in the context of the learning situation. The context is an integral part of what is learned. The context, the learning situation is not neutral so to speak. Situations co-produce knowledge (Brown et al, 1989, 32). What is learned is inseparable from how it is learned.

Taylor and Fraser (1991) have developed a "Constructivist Learning Environment Survey" to assess supporting classroom climates in the above sense. The four scales of their instrument reflect key issues that are also pointed out in many other constructivist approaches:

"The Autonomy scale measures perceptions of the extent to which there are opportunities for students to exercise meaningful and deliberate control over their learning activities, and think independently of the teacher and other students. The Prior Knowledge scale measures perceptions of the extent to which there are opportunities for students meaningfully to integrate their prior knowledge and experiences with their newly constructed knowledge. The Negotiation scale measures perceptions of the extent to which there are opportunities for students to interact, negotiate meaning and build consensus. The Student-Centredness scale measures perceptions of the extent to which there are opportunities for students to experience learning as a process of creating and resolving personally problematic experiences." (Taylor & Fraser, 1991, 2).

A note of caution is necessary. The preference of the above sketched more open and more supportive instructional settings does not mean that more traditional forms of instruction like lecture type periods and whole class activities have no place in constructivist approaches. Also these may be efficient settings for particular purposes if students' needs and conceptions are addressed.

Constructivist oriented development of new media for science instruction

Constructivist perspectives have also influenced the development of new media substantially. Especially the development of computer inclusive designs have to be mentioned here. Linn and Burbules (1993), for instance, report about computers as "lab partners" in approaches to remediate students' alternative conceptions of temperature and heat. Goldberg and Bendall (1992) designed interactive computer-video-based tutorial in geometrical optics. The computer, in general, can provide opportunities for dynamic displays and visualizations, simulations, and model building (see e.g., Schecker, 1993; Henessy, Twigger, Driver, O'Shea, O'Malley, Draper, Hartley, Mohamed, & Scanlon, 1993).

Constructivist textbooks for science instruction?

Textbooks of a traditional type appear not to be suited for constructivist science instruction. Critiques of science textbooks have revealed a number of limitations of this kind of information source. Usually the learner's perspective is not taken into consideration (Gallagher, 1991), and issues of the psychology of learning are neglected (Stinner, 1992). Furthermore, textbooks are usually written in a limited, authorial style (Strube, 1989) and they provide limited empiricist views of the nature of science (Sutton, 1989; Gallagher, 1991). But it appears that also constructivist approaches need some kind of a textbook in order to provide information to the students in an efficient way. Guzetti and Glass (1992) in a meta-analysis of studies on reading science text come to the conclusion that comprehension of science content can be enhanced significantly and that conceptual change can be promoted by the use of textbooks, provided that students' preconceptions are challenged in some way. Examples of what such a constructivist text could look like are provided by Duit, Häußler, Lauterbach, and Westphal (1992) from the development of a new physics textbooks for lower secondary level. In this book, students' conceptions are explicitly addressed as often as possible in different ways. Research on the success of this textbook in enhancing conceptual change has not been carried out so far.

Constructivist assessment procedures

Assessment has manifold functions in school. In more traditionally oriented approaches the pedagogical function, i.e., assessment as a means of helping students to learn, is given only scant attention. Constructivist approaches usually differ fundamentally from more traditional ones in this respect. Here the pedagogical function, the role of assessment among other supporting conditions of conceptual change is given key importance. The metaphor of portfolios (Duschl & Gitomer, 1991) is frequently used to indicate assessment techniques of the sketched type (see also Wolf, Bixby, Glenn, & Gardner, 1991). They allow the students to show different aspects of their understanding in a similar way as an artist may present pieces of her work from a portfolio.

Pathways from students' pre-instructional conceptions to science conceptions

The term conceptual change as understood in the present paper addresses pathways from students' pre-instructional conceptions to the science conceptions, particularly those pathways that need fundamental restructuring of already existing conceptual structures. The basic assumption is the key constructivist idea that construction of new conceptions (learning) is possible only on the basis of the already existing conceptions. Figure 1 presents a classification of pathways that have been used in science education studies on conceptual change. The first key distinction concerns continuous and discontinuous pathways (see also above).

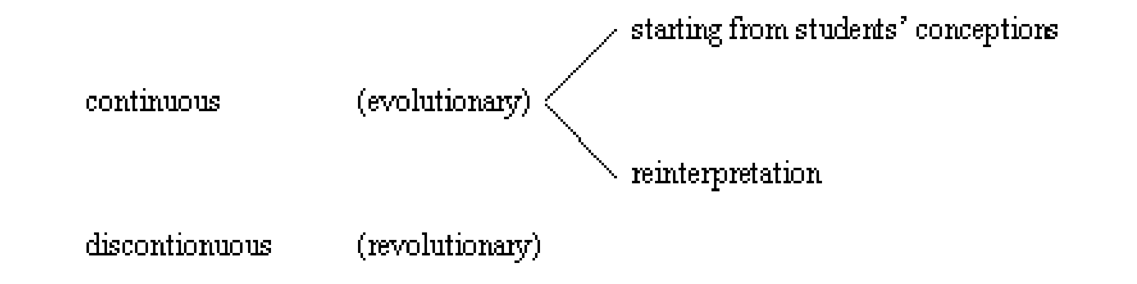

Figure 1: Pathways from students´ conceptions towards science conceptions

Continuous pathways

Continuous pathways try to "avoid" (or bypass) the fundamental restructuring necessary in case of the discontinuous pathways. They start from aspects of students' conceptual structures that are already mainly in accord with the science conceptions or reinterpret students ideas. In the first case, the kernel of harmony between the conception of departure (the "anchor", Brown & Clement, 1989) and the target conception is developed step by step. It is not necessary in every case to start from conceptions that students construct when dealing with the referring science phenomena and principles. It may also be possible to start from pieces of knowledge in domains where analogies may be drawn to structures or features of the science content in question. In the second case of "reinterpretation" (Jung, 1986) the strategy is a little different. Also here resemblances between students' preinstructional conceptions are the starting point but they are interpreted in a new way. It is a key finding of students' conceptions research in physics that students of all ages tend to think that whenever a body is moving into a certain direction that then a force has to act into this direction, that pulls the body so to speak into this direction (McDermott, 1984). This view is not correct from the Newtonian perspective of classical mechanics. Following the reinterpretation strategy students are not told that their conception as sketched is wrong but it is worked out step by step that they have something in mind that also makes good sense from the physics point of view. In fact, there is a physics quantity always pointing into the direction of the moving body. But this quantity is momentum and not force (Jung, 1986). Another example of the reinterpretation strategy is given by Grayson (in press). Concerning current flow in simple electric circuits students usually have the idea that current is consumed when flowing in the circuit, that some current is used up in the bulb so that less current enters the battery than left it. Also here students are not told that their ideas are wrong. On the contrary, the teacher encourages students' way of thinking and works out that they have something quite correct in mind. In fact there is something "used up" while current is flowing, namely energy is transformed into heat and heat is dispersed. It becomes obvious that continuous approaches are in need of very careful reconstruction of the particular science subject matter structure. Usually such approaches are embedded in very basic changes of more traditionally oriented reconstructions of that kind.

Discontinuous pathways

In this case there is a stark contrast between students' conceptions and science conceptions. Cognitive conflict strategies play a key role in all approaches that fall into this category (see the review of such approaches by Scott, Asoko, & Driver, 1992). There are three primary kinds of cognitive conflict. First, there is the kind of conflict that is created by asking for students' predictions and then contrasting these to the experimental results. Secondly, there is a conflict between the ideas of the students and those of the teacher. Finally, there is a conflict among the beliefs of the students. Theoretical orientation of cognitive conflict usually is the above sketched Piagetian idea that mental disequilibrium demands an interplay between assimilation and accommodation until equilibrium is restored (Dykstra, 1992; Rowell & Dawson, 1985). Also Festinger's (1962) theory of cognitive dissonance is referred to (Driver & Erickson, 1983). The crucial issue in cognitive conflict strategies is whether students "see" the conflict. This is very often not the case. What appears to be clearly discrepant from the perspective of a teacher may be viewed only marginally different from the perspectives of the students or not discrepant at all. Also the problems students have in dealing with anomalous data (see the review of Chinn and Brewer, 1993) point to difficulties to really bring the cognitive balance out of equilibrium so to speak and to incite conceptual change processes.

It may be interesting to note that discontinuous approaches that are deliberately based on Piagetian stage theory like the "Learning Cycle" (Lawson, Abraham, & Renner, 1989) and those that explicitly reject this theory (like Driver's, 1989, "Constructivist Teaching Sequence"; see figure 2) are only very marginally different with regard to addressing conceptual change -- because in the very end they are employing the same Piagetian ideas of conceptual change "mechanisms". The *learning cycle* comprises three phases (Lawson, 1989, 26-27):

Exploration

> "Students learn through their own actions and reactions in a new situation. They explore new materials with minimal guidance. The new experience should raise questions or complexities that they cannot resolve with their present conceptions or accustomed patterns of reasoning. In other words, it provides the opportunity for students to voice potentially conflicting and at least partially inadequate ideas (misconceptions) that can spark debate and an analysis of the reasons for

their ideas. Exploration leads to the identification of regularity in a phenomenon..."

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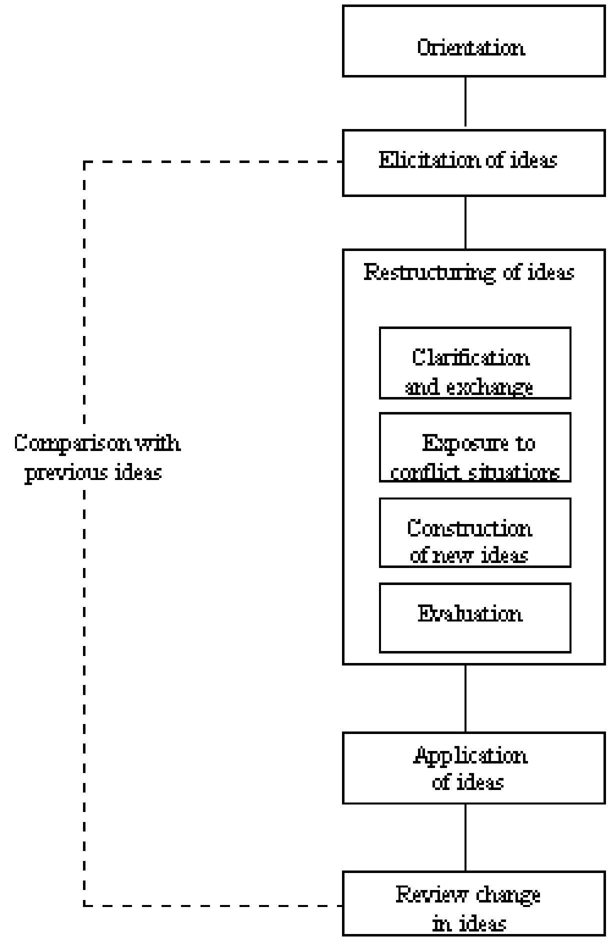

Figure 2: The Constructivist Teaching sequence (from Driver, 1989, 88)

Term Introduction

The new term to label the patterns discovered in the exploration stage is introduced.

Concept Application

"Students apply the new term and/or reasoning pattern to additional examples. The concept application phase is necessary for some students to recognize the patterns and separate it from its specific contexts and/or to generalize it to other contexts..."

The learning cycle and the constructivist teaching sequence share a period in which students are made familiar with the referring phenomena, in which they are also made aware of their ideas with many other approaches in use in science education. At some later stage, the science point of view is brought into debate and there is some sort of negotiation about the values of this view. At the end a review of the learning pathway is included that provides students with possibilities to reflect what they have learned.

As mentioned above the conceptual change core usually is embedded in conditions that support conceptual change. Figure 3 provides a brief look at an example for the Constructivist Teaching Sequence as presented in figure 2 (Scott, 1992; see also Driver & Scott, in press), the outline of teaching the particle model. Students are given many opportunities to make their own experiences and to construct their own meaning of the phenomena observed. Also another key feature of constructivist approaches becomes apparent, namely considerations of the nature and range of scientific theory and theory making (see stage B. in figure 3). Students play a simple rule guessing game here. The teacher writes a number of names at the blackboard following a certain rule (e.g. only names with four letters). Students have to find out the rule via checking their ideas against evidences. The metaphor of a scientist as a detective is employed in another game in which students are provided with facts of a murder case. They work in groups in order to find out who the murder is. They have to check their hypotheses against the evidence provided. In much the same way they are invited later to check their theories of how matter is composed of particles against the evidences as provided in their experiments.

To address or not to address students' conceptions explicitly

In most conceptual change approaches either of the discontinuous or the continuous kind there is some stage where students are made aware of their conceptions. Walter Jung and his co-workers have developed a totally different approach which falls into the category of continuous pathways. In elementary optics, for example, many very deeply rooted alternative conceptions have been found (Jung, 1989). Students, for instance, do not view the process of seeing a lit object like a picture at the wall in terms of light reflected by the picture into the eyes but as something lying at the picture (namely light) that may be seen when turning the eyes to it. In their optic course (Wiesner, 1994) they never speak about this student idea but try to arrange a set of appropriately designed experiments and arguments to persuade students of the appropriateness of the science point of view. They argue against the cognitive conflict strategy that it is too time consuming and may lead students into the wrong direction. Their evaluation results show that their approach was significantly superior a traditional approach given to a control group. These findings point to the importance of conceptual change supporting reconstruction of science subject matter structures another time. If analyzed from the perspective of the above mentioned holistic constructivist approaches it becomes obvious that Walter Jung's approach is limited in scope in that key issues of the above sketched holistic constructivist approaches are not addressed, in particular attempts are missing to support students' abilities to reflect about their own learning and hence to make them autonomous learners.

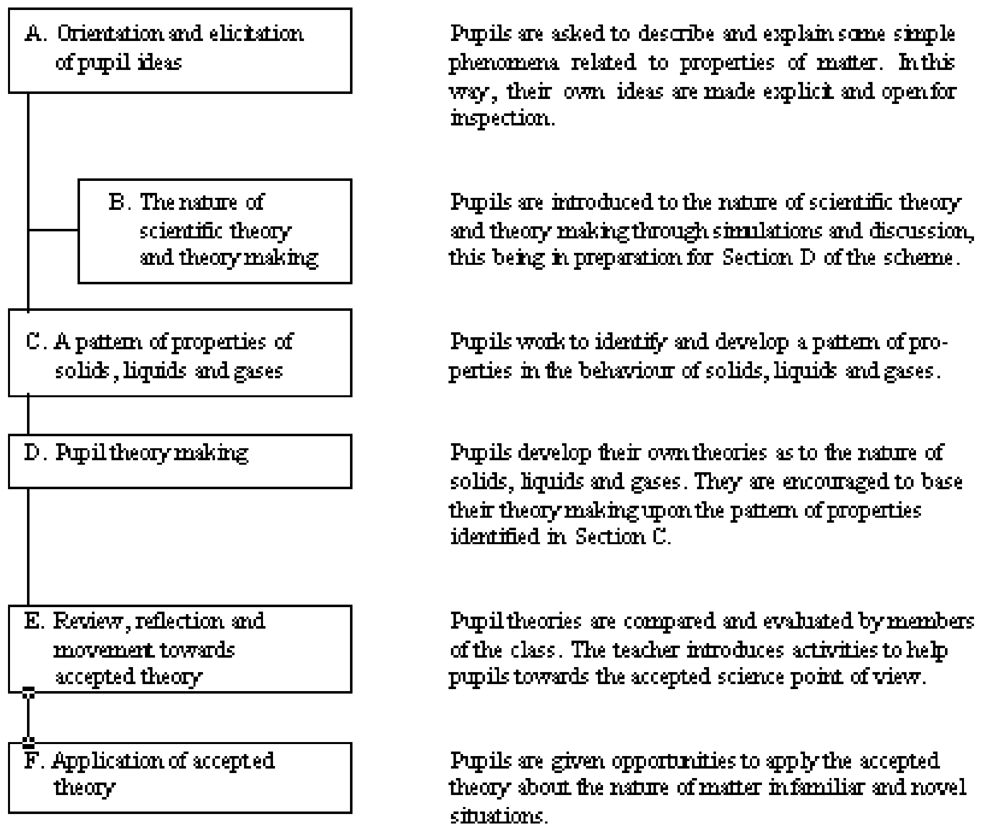

Figure 3: A constructivist scheme of teaching the particle model (from Scott, 1992, 205)

Analogies and conceptual change

Analogies and their relatives like metaphors play a significant role in conceptual change settings. Analogical reasoning is a key process in knowledge construction from a constructivist perspective (Duit, 1991). If understanding and learning is possible only on the basis of the already existing conceptions, the already available conceptions are scanned for similarities with the newly presented ones. Several studies on conceptual change employ analogies. But the success is varied. Whereas in some cases analogical reasoning has proven a potent facilitator of conceptual change in other studies this is not the case (for a review see Duit, 1991). A major reason for failures appears to be that analogical reasoning often cannot take place because the analogies presented to students are understood in a different way by the students than was intended (Duit & Glynn, 1992). Sometimes not even the analog domain, i.e., the domain that is the base of analogical reasoning is familiar to the students to the extent assumed by the presenters of the analogy.

The most influential approach of employing analogies in conceptual change settings has been the "bridging analogies" approach by Brown and Clement (1989). It falls into the category of continuous pathways (figure 1).

Two examples of "recipies" for addressing constructivist ideas in planning science instruction

There is a rising number of attempts to provide teachers with guidelines how to address constructivist ideas in planning science instruction. Two examples of "recepies" are presented in tables 3 and 4. The first example (table 3) is quite pragmatic in nature. It stems from an article in a science teachers' journal (Yager, 1991) and aims at making these teachers aware of key constructivist issues. The other example (table 4) has been worked out by the cognitive psychologist M. Wittrock (Wittrock, 1994) who has a long lasting interest in science education (Osborne & Wittrock, 1985). Here main issues of conceptual change and conceptual change supporting conditions are listed. The examples may serve the reader as tools to rethink the characteristics of constructivist science instruction outlined above in considering which characteristics are addressed there and which are not given sufficient attention.

Success of conceptual change approaches in science education

Providing evidence of success of constructivist approaches is a somewhat difficult matter (Duit & Confrey, in press). It is very difficult to condense the results reported into measures that allow comparisons with traditional approaches. The reason is the above outlined holistic character of many constructivist approaches towards conceptual change which usually include fundamental restructuring of traditional approaches in many respects. Do the categories for comparison have come from the traditional approaches or from the new ones? Both are quite different concerning their aims. It appears to be possible only to evaluate these approaches with regard to their own aims, i.e., to investigate whether these approaches achieve their aims or not.

Solomon (1994) in a recent review of advantages and problems of the contemporary use of constructivism in science education is rather reserved against constructivist teaching and learning approaches. With regard to the Children's Learning in Science project (Driver, 1989) she admits that much valuable work has been done but that a final judgment of the success of the teaching and learning methods employed is still not possible. In fact, there is reason for some reservations. Many studies on constructivist teaching and learning show only little success but there are also findings that appear to be most promising and that may indeed lead to the development of more successful approaches.

Invitation	Observe surroundings for points of curiosity Ask questions Consider possible responses to questions Note unespected phenomena Identify situations where sutdent perceptions vary
Exploration	Engage in focused play Brainstorm possible alternatives Look for information Experiment with materials Observe specific phenomena Design a model Collect and orngarize data Emply problem-solving strategies Select appropriate resources Discuss solutions with others Design and conduct experiments Evaluate choices Engage in debate Identify risks and consequences Define parameters of an investigation Analize data
Proposing explanations and solutions	Communicate information and ideas Construct and explain a model Construct a new explanation Review and critique solutions Utilize peer evaluation Assemble multiple answers/solutions Determine appropriate closure Integrate a solution with existing knowledge and experiences
Taking actionn:	Make decisions Apply knowledge and skills Transfer knowledge and skills Share information and ideas Ask new questions Develop products and promote ideas Use models and ideas to elicit discussions and acceptance by others

Table 3: Constructivist strategies for teaching (from Yager, 1991, 55)

Wandersee, Mintzes, & Novak (1993) in a recent review of research on students' conceptions in science have analyzed 103 intervention studies. They conclude that the wide range of modification studies show varying levels of success. This is true for intervention studies of the confrontation type (the discontinuous pathway type) and of studies that employ analogies alike. They also address limitations of the nature of the referring studies:

"A brief word of caution about the status of research on conceptual change seems in order. Much of this work is relatively recent in origin and, though promising, is probably best described as "exploratory" in nature. Many of the studies conducted to date have relied on small sample sizes, untested methods, anecdotal records, and relatively nonrigorous research designs lacking control group comparisons. Virtually none of the studies has been replicated. However, purely qualitative research continues to improve as research design keeps pace with advances in methods. So, even with the aforementioned caveats in mind, we remain impressed by the relative success some researchers have achieved to date." Wandersee, Mintzes, & Novak, 1993).

Knowledge, experience and conceptions

- Learn the students' conceptions and beliefs about science, beliefs about their own abilities to learn science, and beliefs about the meaning and usefulness of science in their daily lives.
- Learn the students' conceptions of what they must do to learn science.
- Teach the students that learning with understanding is a generative process. It is different from passively reading and remembering information.

Motivation

- Teach the students a distinctive type of motivation that involves:
(a) taking responsability for learning;
(b) believing that they can and will succeed at understanding science conceptions and through them gain a deeper understanding of complex everyday experience.
- Design instruction to enable sutdents to experience frequent success at understanding science through using generative learning procedures.

Attention

- Teach students to attend to the central problems of constructing meaning for science concepts. Teach them fo focus their attention on the problems of generating a structure of information and on the problems of relating science to other subjects and to everyday experience.

Generation

- After learning the students' models, beliefs and conceptions, teach a scientific model in relation to the sutdents' models. The primarily goal is not to "cover the subject matter" or to "present only the scientists' model" or to "show that the students' are wrong". Instead, the primary goal is to lead the students to generate a more scientific and more useful model thean they now have. That goal may not be attained quickly because it involves student generation of understanding. That generation of meaning requires student effort and thought that goes beyond learning from teacher reward and teacher punishment.
- Generate for them, initially at least, examples and applications of the two types of relations that facilitate comprehension: (i) relations among the concepts to be learned; and (ii) relations between these science concepts and student knowledge and experience.
- Lead students to generate these two types of relations, as a way to comprehend science.
- Design instruction to involve these two types of relations and to increase student ability to use the generative learning strategies that enhance comprehension through relation buinding.

Metacongnition

- Teach students to aware of and to consciously use their thought processes, including learning strategies, comprehension strategies, attention-directing strategies, attributions, plans, and monitoring strategies to comprehend, transfer, and apply science concepts to attain a greater understanding of their world and an enhanced ability to solve everyday problems.

Table 4: Practical plan for teaching science from the perspective of a model of generative teaching (from Wittrock, 1994, 35-40)

It appears that this statement adequately portrays the state of the art in the domain of conceptual change teaching and learning strategies in science education. It seems to be valid also on the basis of the other intervention studies available (the recent edition of the bibliography by Pfundt & Duit, 1994, lists about 600 intervention studies of many different kinds).

A meta-analysis of conceptual change approaches in science education (Guzetti & Glass, 1992) included 70 studies investigating intervention studies in science education and in reading education (the latter on science issues). The type of analysis the authors employed only allowed the incorporation of studies that compared a treatment group and a control group. Therefore, major constructivist approaches towards conceptual change, among them the leading ones like the Children's Learning in Science (CLIS) project in Leeds (Driver, 1989) were not regarded. Nevertheless, the findings show that there is a substantial amount of empirical evidence that challenging students' conceptions in some way usually results in significantly better outcomes than approaches that do not address students' conceptions explicitly. It appears that especially the theoretical assumptions of the theory of conceptual change (Posner, Strike, Hewson, & Gerzog, 1982), of the cognitive conflict strategies, and of the bridging analogies approach (Brown & Clement, 1989) are backed up by empirical findings on the basis of that meta-analysis:

"Based on the accumulated evidence from two disciplines [reading and science education is meant here], we have found that instructional interventions designed to offend the intuitive conception were effective in promoting conceptual change. The format of the strategy (e.g. refutational text, bridging analogies, augmented activation activities) seems irrelevant, providing the nature of the strategy includes cognitive conflict. Despite recent self-criticism of their earlier positions (Strike & Posner, 1992), the genre of instructional strategies described earlier by Strike and Posner (1985) that produces dissatisfaction with current conceptions and show the scientific conception as intelligible, plausible and applicable, has been effective." (Guzetti & Glass, 1992, 42).

There is therefore good reason for the optimistic view of Wandersee, Mintzes, and Novak (1993) as quoted above. Also further close cooperation of research in science education and cognitive science appears to be most promising in order to investigate both the fine structure of conceptual change processes and the impact of supporting conditions of conceptual change. Where analysis of the fine structure of conceptual change is concerned, there is an increasing number of interesting learning process studies in science education the past years (see the proceedings of a first conference on this issue by Duit, Goldberg, & Niedderer, 1992; see also Fischer & Aufschnaiter, 1993; Niedderer & Goldberg, 1993).

Teacher change -- constructivist approaches of pre - and inservice teacher education

Research has clearly shown that teachers are not usually ready to adopt constructivist teaching and learning approaches as sketched above without serious difficulties and distortions of the intentions of such approaches. Teachers' views of learning as well as their conceptions of science (i.e., their philosophy of science ideas) are limited basically in the same way as students' views and ideas of the same domains. Teachers usually hold a passive receiver view of learning, that neglects the active construction issue as addressed by constructivism, or at least mainly act in classroom practice as if they would be inclined to such a view (Baird & Mitchell, 1986; Baird & Northfield, 1992). Also, most teachers hold a naive realist and empiricist view of science that does not take into account the issue of science knowledge being tentative human construction as seen from the constructivist perspective. Further, a surprisingly large number of teachers, especially but not exclusively those who lack sufficient professional training, hold quite similar science conceptions on the content level as their students (see the referring section in the bibliography by Pfundt and Duit, 1994). Teacher change in various respects then is necessary if constructivist approaches of science instruction are to be more successful than traditional approaches. Many approaches of teacher inservice and preservice education have been developed and evaluated over the past decade (see the reports of the seminal PEEL project at Monash University in Melbourne by Baird & Mitchell, 1986, and Baird & Northfield, 1992; for overviews see the sections in recent volumes on constructivist science education in Tobin, 1993a, and in Treagust, Duit, & Fraser, in press).

The conceptual change model as developed by Posner, Strike, Hewson, & Gerzog (1982) has also proven to be a powerful theoretical framework for attempts to facilitate teacher change. As outlined above, the initial theory included four conditions of conceptual change, indicated by the labels dissatisfaction, intelligible, plausible, and fruitful. Gunstone and Northfield (1988) added a further condition, namely feasibility that points to the issue that teacher change may not occur although the new ideas are intelligible, plausible and fruitful because the teacher still places greater importance on the old ideas. Teacher change, as is also the case for student change, is a long lasting painstaking process (Gallagher, 1993), because changes fundamentally concern deep-rooted beliefs that have been a significant part of the teacher's personality. Models of teacher change, therefore, start from domains where teachers feel comfortable and where only few changes appear to be necessary. From there step by step the need for further rethinking of current practice is developed. Teaching and preaching constructivist ideas is rejected. Teachers are, of course, informed about basic principles of that view in seminar like sessions and are also given publications that provide easy access to key constructivist ideas. But main concern is coaching teachers in the process of self-generating constructivist ideas to become what Schon (1983) has called a "reflective practitioner".

Table 5 presents the constructivist model for teacher inservice developed by Hand & Treagust (in press). The table shows the five stages of the model, which kinds of changes are addressed and also in which way these changes fit the conditions of conceptual change. The step-wise strategy that is characteristic for constructivist models of teacher change is clearly to be identified. The change of teacher's role is a key issue. Here it is expressed in terms of change from a manager of classroom activities towards an empowerer, i.e., a person that actively supports students' construction processes by helping and encouraging them. Tobin (1993b) discusses the changes of teachers' role in his research program in terms of the change of teachers' metaphors. It is the basic assumption of this approach of teacher change that the beliefs and metaphors teacher hold about their role as teachers deeply influence their teaching behavior. Tobin (1993b, 217) provides, for instance, the case of the teacher Diana who holds three different metaphors:

"Diana used three metaphors to describe her teaching role in different contexts. Usually, she managed her class as a policewoman, in some circumstances she was a mother hen, and, on other occasions, she was an entertainer. Her mode of behavior (i.e., the metaphor she used to make sense of what she ought to do) depended on the context in which learning was to occur. And each conceptualization of her role as manager was associated with a discrete set of beliefs."

Stage of inservice and its focus	Teacher's knowledge base emphasised	Teacher's role characterised	Conceptual chage criteria addressed
Stage 1: Teacher's knowledge of classroom practice	Old pedagogical content knowledge	Manager	
Stage 2: Identification of students' knowledge	Student understandigs		Dissatisfaction
Stage 3: Teacher's knowledge of own pedagogy and science	Conceptual focus; New pedagogical knowledge	Technican	Intelligible Plausible
Stage 4: Application and linking of science concepts and pedagogical knowledge	Pedagogical concept knowledge	Facilitator	Fruitful Feasilble
Stage 5: Development of a constructivst teaching framework	Pedagogical Subject: Matter Knowledge	Empowerer	

Table 5: A constructivist model for teacher inservice (from Hand & Treagust, in press)

Tobin (1993b) describes a number of further metaphors and changes of them that empowered the teachers to take a role in constructivist instructional settings that supports students' change processes.

The constructivist view and science education for the 21st century

The present paper is presented at a conference on "Science and Mathematics Education for the 21st Century". Are the changes of more traditional approaches of science instruction towards the visions as provided by the constructivist view are suited for dealing with the challenges students will meet in the next century? There is, of course, no simple and short answer to that question. It very much depends on the visions of future societies different people may hold. If the aim is a responsible and reflective citizen, i.e., a person who is able to a certain extent to understand basic features of science concepts and ideas that will deeply influence also life in the 21st century (in desirable and also most fatal manners) then the deep understanding of science as underlying the constructivist view is a must so to speak. This understanding, namely, includes deep and applicable knowledge of science contents, insight into the role of science contents in technology and society (including issues of environmental concern) as well as comprehension of the nature of science knowledge (i.e., adequate philosophy of science views). There is another aspect of the vision the constructivist view provides that contributes to educating reflective and responsible citizens. Constructivist science education is humanistic in nature, it aims at supporting the development of the individual's personality. In that, I really think that the changes as proposed by the constructivist view have a lot to offer for the improvement of science education in order to empower students to deal with the challenges of their futures lives.

In order to avoid misunderstandings it has to be pointed out that more traditionally oriented approaches are not in stark contrast to all the visions as provided by the constructivist view. Interestingly, there appears to be some sort or irony in that more traditional approaches share at least some key aims with constructivist ones but try to address them with teaching and learning methodologies that have proven unsuitable for that purpose in numerous empirical studies. In fact, there is almost nothing in constructivism that is really new. There is a constructivist tradition (under different labels, of course) in pedagogy and also in science education that dates quite far back into history (Jung, 1993; Duit, in press). A number of teaching methods, for instance, employed by constructivist science instruction settings like the Socratic dialog and the cognitive conflict are surely not new at all. The contemporary constructivism is part of student centred pedagogy of science teaching and learning. What is new with this view is that it encourages development of approaches of a student centred science instruction in the above broad meaning in a rather consistent way. The body of research on students' and teachers' conceptions of various kinds, as well as research on student and teacher change provide a much more reliable basis for setting students centred science instruction in practice than ever before in the history of science education. In that I think there will be lasting effects of the constructivist view. The constructivist view will, without any doubt, be most influential in science education also after the term constructivism will have gone out of fashion.

A final note

The present paper is included in a series of other review type papers that I have written over the past years for different purposes and with different emphases. It is for this reason that there are several overlaps with issues addressed also in other papers. It appears that this primarily concerns the following ones: Duit, Treagust, & Fraser (in press); Duit & Confrey (in press); and Duit (1993a). From the paper Duit (1993b) I transferred the paragraphs on "conception and perception", "conception and action" and "conception may override empirical evidence" from the paper Duit (1994) the paragraphs on different pathways towards science conceptions and on the success of conceptual change approaches without major changes into the present paper.

References

Andersson, B.R. (1986). The experiental gestalt of causation: a common core to pupils preconceptions in science. European Journal of Science Education 2, 155-171.

Ausubel, D.P. (1968). Educational psychology: a cognitive view. New York: Holt, Rinehart and Winston.

Baird, J.R. & Mitchell, I., Eds. (1986). Improving the quality of teaching and learning - an Australian case study. Melbourne: The Monash University Press.

Baird, J.R. & Northfield, J.R. (1992). Learning from the PEEL experience. Melbourne, Australia: Monash University Printing Services.

Baird, J.R. & White, R.T. (in press). Metacognitive strategies in the classroom. In D. Treagust, R. Duit, & B. Fraser, Eds., Improving teaching and learning in science and mathematics. New York: Teacher College Press.

Brewer, W. & Lambert, B. (1993). The theory-ladenness of observation: Evidence from cognitive psychology. Proceedings of the Fifteenth Annual Conference of the Cognitive Science Society. June 18 to 21, 1993. Institute of Cognitive Science, University of Colorado-Boulder. Hillsdale, NJ: Lawrence Erlbaum, 254-259.

Brown, D.E. & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: Abstract transfer versus explanatory model construction. Instructional Science, 18, 237-261.

Brown, D.E. & Clement, J. (1992). Classroom teaching and experiments in mechanics. In R. Duit, F. Goldberg, & H. Niedderer, Eds., Research in physics learning: Theoretical issues and empirical studies. (pp. 380-397). Kiel, Germany: Institute for Science Education at the University of Kiel.

Brown, J.S., Collins, & Duguid, P. (1989). Situated cognition and the culture of learning. Educational Researcher, 18, 32-42.

Chinn, C.A. & Brewer, W.F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science education. Review of Educational Research, 63 (1), 1-49.

Chochran, K.F. (1991). Pedagogical content knowledge: Teachers' transformation of subject matter. NARST News, 33 (September), 7-9.

Confrey, J. (1990). The concept of exponential functions. In L. Steffe, Ed., Epistemological foundations of mathematical experience. (pp. 124-159). New York: Springer-Verlag.

Driver, R. (1989). Changing conceptions. In P. Adey, P., Ed., Adolescent development and school science. (pp. 79-99). London: Falmer Press.

Driver, R. & Erickson, G. (1983). Theories-in-action: Some theoretical and empirical issues in the study of students' conceptual frameworks in science. Studies in Science Education, 10, 37-60

Driver, R. & Scott, P. (in press). Curriculum development as research; A constructivist approach to science curriculum development and teaching. In D. Treagust, R. Duit & B. Fraser, Eds., Improving teaching and learning in science and mathematics. New York: Teacher College Press.

Duit, R. (1991). On the role of analogies, similes and metaphors in learning science. Science Education, 75, 1991, 649-672.

Duit, R. (1993a). Research on students' conceptions -- developments and trends. In J. Novak, Ed., Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics. Ithaca, NY: Cornell University (distributed electronically).

Duit, R. (1993b, November). Understanding understanding -- On interpreting discourse in interviews and classroom practice. Paper presented at the International Conference on Interpretive Research in Science Education, Taipei, Taiwan.

Duit, R. (1994, September). Conceptual change approaches in science education. Paper presented at the "Symposium on Conceptual Change". Friedrich-Schiller-University of Jena, Germany.

Duit, R. (in press). The constructivistic view, a both fashionable and fruitful paradigm for science education research and practice. In L. Steffe & J. Gale, Eds., Constructivism in education. Hillsdale, NJ: Lawrence Erlbaum.

Duit, R. & Confrey, J. (in press). Reorganizing the curriculum and teaching to improve learning in science and mathematics. In D. Treagust, R. Duit & B. Fraser, Eds., Improving teaching and learning in science and mathematics. New York: Teacher College Press.

Duit, R. & Glynn, S. (1992). Analogien und Metaphern, Brücken zum Verständnis im schülergerechten Physikunterricht. In P. Häußler, Ed., Physikunterricht und Menschenbildung. (pp. 223-250) Kiel, Germany: Institute for Science Education at the University of Kiel.

Duit, R. & Komorek, M. (1994). Constructivist informed research on students' understanding of basic ideas of chaos-theory. In H.J. Schmidt, Ed., Proceedings of the 12th Dortmund Summer Symposium "Problem Solving and Misconceptions in Chemistry and Physics". May 1994. Hongkong: ICASE (in press).

Duit, R., Goldberg, F., & Niedderer, H., Eds. (1992). Research in physics learning: Theoretical issues and empirical studies - Proceedings of an International Workshop held in Bremen, Germany, March 4-8. Kiel, Germany: Institute for Science Education at the University of Kiel.

Duit, R., Häußler, P., Lauterbach, R., Mikelskis, H., Westphal, W. (1992). Combining issues of "girl-suited" science teaching, STS and constructivism in a physics textbook. Research in Science Education 22, 106-113.

Duit, R., Treagust, D., & Fraser, B. (in press). Research on students' preinstructional conceptions. The driving force for improving teaching and learning in science and mathematics. In D. Treagust, R. Duit & B. Fraser, Eds. Improving teaching and learning in science and mathematics. New York: Teacher College Press.

Duit, R., Treagust, D., & Mansfield, H. (in press). Investigating student understanding as a prerequisite to improving teaching and learning of science and mathematics. In D. Treagust, R. Duit & B. Fraser, Eds. Improving teaching and learning in science and mathematics. New York: Teacher College Press.

Duschl, R. A. & Gitomer, D.H. (1991). Epistemological perspectives on conceptual change: Implications for Educational practice. Journal of Research in Science Teaching, 28, 839-858.

Dykstra, D. (1992). Studying conceptual change. In R. Duit, F. Goldberg, & H. Niedderer, Eds., Research in physics learning: Theoretical issues and empirical studies. (pp. 40-58). Kiel, Germany: Institute for Science Education at the University of Kiel.

Ernest, P. (1993). Constructivism, the psychology of learning, and the nature of mathematics: Some critical issues. Science & Education, 2, 87-93.

Fensham, P.F. (1986). 'Science for all'. Educational Leadership, 44, 18-23.

Fensham, P.F. (1991). Science and technology. In P.W. Jackson, Ed., Handbook for research on curriculum. (pp. 789-829). New York: Macmillan, AERA.

Fensham, P.F., Gunstone, R.F., & White, R.T., Eds. (1994). The content of science: A constructivist approach to its teaching and learning. London, UK: Falmer Press.

Festinger, L. (1962). A theory of cognitive dissonance. Stanford; CA: Stanford University Press.

Fischer, H.E. & Aufschnaiter, S. von (1993). Development of meaning during physics instruction: case studies in view of the paradigm of constructivism. Science Education, 77, 153-168.

Fischler, H. (1993). Von der Kluft zwischen Absicht und Handeln. In H. Behrendt, Ed., Zur Didaktik der Physik und Chemie. Probleme und Perspektiven. (pp. 226-228). Alsbach, Germany: Leuchtturm.

Gallagher, J.J. (1991). Prospective and practicing secondary school science teachers' knowledge and beliefs about philosophy of science. Science Education 75, 1, 121-133.

Gallagher, J.J. (1993). Secondary science teachers and constructivist practice. In: Tobin, K.: The practice of constructivism in science education. Washington, DC: AAAS Press, 181-191.

Glasersfeld, E. von (1989). Cognition, construction of knowledge and teaching. Synthese, 80, 121-140.

Glasersfeld, E. von (1992). A constructivist's view of learning and teaching. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), Research in physics learning: Theoretical issues and empirical studies. Kiel, Germany: IPN at the University of Kiel, 29-39.

Glasersfeld, E. von (in press). A constructivist approach to teaching. In L. Steffe (Ed.), Constructivism in education. Hillsdale, NJ: Lawrence Erlbaum.

Glasson, G.G. & Lalik, R.V. (1992). Social constructivism in science learning: Toward a mind-world synthesis. In S. Hills (Ed.), The history and philosophy of science in science education. Proceedings of the international conference on the history and philosophy of science and teaching science. Volume I. Kingston, Ontario: The Faculty of Education, Queens University, 399-404.

Goldberg, F. & Bendall (1992). Computer-video-based tutorials in geometrical optics. In R. Duit, F. Goldberg, & H. Niedderer, Eds., Research in physics learning: Theoretical issues and empirical studies. (pp. 356-379). Kiel, Germany: Institute for Science Education at the University of Kiel.

Goldin, G. (1991). Epistemology, constructivism, and discovery learning in mathematics. In R. Davis, C. Maher, & N. Noddings (Eds.), Constructivist views on the teaching and learning of mathematics. Reston, Virginia: National Council of Teachers of Mathematics.

Good, R., Wandersee, J., & Julien, J.St. (1993). Cautionary notes on the appeal of the new "Isms" (constructivisms) in science education. In K. Tobin, Ed., The practice of constructivism in science education. (pp. 71-87). Washington, DC: AAAS Press.

Grayson, D. (in press). Improving science and mathematics learning by concept substitution. In D. Treagust, R. Duit & B. Fraser, Eds. Improving teaching and learning in science and mathematics. New York: Teacher College Press.

Guzetti, B.J. & Glass, G.V. (1992, April). Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. Paper presented at the annual meeting of the American Educational Research Association, San Francisco.

Hand, B. & Treagust, D. (in press). Development and implementation of a constructivist model for teacher inservice.

Hanson, N.R. (1965). Patterns of discovery. Cambridge: The University of Cambridge Press.

Henessy, S., Twigger, D., Driver, R., O'Shea, T., O'Malley, C.E., Byard, M., Draper, S., Hartley, R., Mohamed, R., Scanlon, E. (1993). Changing learners' understanding using a computer-augmented curriculum for mechanics. In: Novak, J.: Proceedings of the Third International Seminar on Misconceptions and Educational Strategies in Science and Mathematics. Ithaca, New York: Cornell University (distributed electronically and via internet).

Hewson, P.W., & Hewson, M.G. (1992). The status of students' conceptions. In R. Duit, F. Goldberg, & H. Niedderer, Eds., Research in physics learning: Theoretical issues and empirical studies. (pp. 59-73). Kiel, Germany: Institute for Science Education at the University of Kiel.

Jung, W. (1986). Alltagsvorstellungen und das Lernen von Physik und Chemie. Naturwissenschaften im Unterricht - Physik/Chemie, 34 (April), 2-6.

Jung, W. (1989). Understanding students' understanding. The case of elementary optics. In J. Novak, Ed., Proceedings of the 2. Int. Seminar "Misconceptions and Educational Strategies in Science and Mathematics", Vol. III. (pp. 268-277). Ithaca, NY: Cornell University.

Jung, W. (1993). Uses of cognitive science to science education. Science & Education 2, 1, 31-56.

Karmiloff-Smith, A. & Inhelder, B. (1976). If you want to go ahead, get a theory. Cognition, 3, 195-212.

Kattmann, U. (1992). Originalarbeiten als Quelle didaktischer Rekonstruktion. Unterricht Biologie 16, Heft 174, 46-49.

Kelly, G.A. (1955). The psychology of personal constructs. Vol. 1,2. New York: W.W. Norton.

Kuhn, T. (1970). The structure of scientific revolutions. Chicago: University of Chicago Press.

Lawson, A.E. (1989). Research on advanced reasoning, concept acquisition and a theory of science instruction. In P. Adey, Ed., Adolescent development and school science. (pp. 11-36). London: Falmer Press.

Lawson, A.E., Abraham, M.R., & Renner,J.W. (1989). A theory of instruction: Using the learning cycle to teach science concepts and thinking skills. NARST Monograph Number One. National Association for Research in Science Teaching.

Lederman, N.G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. Journal of Research in Science Teaching, 29, 331-359.

Linn, M.C., Burbules, N.C. (1993). Construction of knowledge and group learning. In: Tobin, K.: The practice of constructivism in science education. Washington, DC: AAAS Press, 91-119.

Marton, F. & Neuman, D. (1989). Constructivism and constitutionalism. Some implications for elementary mathematics education. Scandinavian Journal of Educational Research 33, 1, 35-46.

Marton, F. (1981). Phenomenography -- describing conceptions of the world around us. Instructional Science, 10, 177-20.

Matthews, M.R. (1993). Constructivism and science education: some epistemological problems. Journal of Science Education and Technology, 1, 359-370.

McDermott, L.C. (1984). Research on conceptual understanding in mechanics. Physics Today, 37 (6), 24-32.

Niedderer, H., Goldberg, F.M. (1993, April). Qualitative interpretation of a learning process in electric circuits. Paper presented at the annual meeting of the National Association of Research in Science Teaching, Atlanta.

Nüse, R., Groeben, N., Freitag, B., & Schreiber, M. (1991). Über die Erfindung/en des radikalen Konstruktivismus. Kritische Gegenargumente aus psychologischer Sicht. Weinheim, Germany: Deutscher Studienverlag.

O'Loughlin, M. (1992). Rethinking science education: Beyond Piagetian constructivism toward a sociocultural model of teaching and learning. Journal of Research in Science Teaching 29, 8, 791-820

Ogborn, J., Mariani, C., Martins, I.P. (1994). Commonsense understanding of science - working paper 1 - the ontology of physical events. London: University of London, Institute of Education.

Osborne, R.J. & Wittrock, M.C. (1985). The generative learning model and its implication for science education. Studies in Science Education, 12, 59-87.

Pfundt, H. & Duit, R. (1994). Bibliography: Students' alternative frameworks and science education. 4th. edition. Kiel, Germany: Institute for Science Education at the University of Kiel.

Piaget, J. (1985). The equilibration of cognitive structures. Chicago: University of Chicago Press.

Pintrich, P.R., Marx, R.W., Boyle, R.A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. Review of Educational Research, 63 (2), 167-199.

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

Resnick, L.B. (1991). Shared cognition: Thinking as social practice. In L. Resnick, J. Levine, & S. Teasley, Eds., Perspectives on socially shared cognition. (pp. 1-19). Washington, DC: American Psychological Association.

Roth, W.-M. (1994). Experimenting in a constructivist high school physics laboratory. Journal of Research in Science Teaching 31, 197-223.

Roth, W.-M. (in press). Authentic school science. Dordrecht, The Netherlands: Kluwer.

Rowell, J.A. & Dawson, C.J. (1985). Equilibrium, conflict and instruction: A new class-oriented perspective. European Journal of Science Education, 5, 203-215.

Schecker, H. (1993). Learning physics by making models. Physics Education, 18, 102-106.

Schlichting, H.J. (1991). Zwischen common sense und physikalischer Theorie - wissenschaftstheoretische Probleme beim Physiklernen. Der mathematische und naturwissenschaftliche Unterricht, 44 (2), 74-80.

Schon, D.A. (1983). The reflective practitioner. New York: Basic Books.

Scott, P. (1992). Conceptual pathways in learning science: A case study of the development of one student's ideas relating to the structure of matter. In R. Duit, F. Goldberg, & H. Niedderer, Eds., Research in physics learning: Theoretical issues and empirical studies. (pp. 203-224). Kiel, Germany: Institute for Science Education at the University of Kiel.

Scott, P., Asoko, H., & Driver, R. (1992). Teaching for conceptual change: A review of strategies. In R. Duit, F. Goldberg, & H. Niedderer, Eds., Research in physics learning: Theoretical issues and empirical studies. (pp. 310-329). Kiel, Germany: Institute for Science Education at the University of Kiel.

Shulman, L.S. (1986). Those who understand: Knowledge growth in teaching. Educational Researcher, 15, 4-14.

Solomon, J. (1994). The rise and fall of constructivism. Studies in Science Education, 23, 1-19.

Steffe, L. & D'Ambrosio, B. (in press). Using teaching experiments to understand students' mathematics. In D. Treagust, R. Duit & B. Fraser, Eds., Improving teaching and learning in science and mathematics. New York: Teacher College Press.

Stinner, A. (1992). Science textbooks and science teaching: From logic to evidence. Science Education, 76, 1-16.

Strike, K., & Posner, G. (1992). A revisionist theory of conceptual change. In R. Duschl & R. Hamilton, Eds., Philosophy of science, cognitive psychology, and educational theory and practice (pp. 147-176). Albany, NY: SUNY.

Strike, K.A. & Posner, G.J. (1985). A conceptual change view of learning and understanding. In L. West & L. Pines, Eds., Cognitive structure and conceptual change. (pp. 211-231). Orlando: Academic Press.

Strike, K.A. (1987). Toward a coherent constructivism. In J. Novak (Ed.), Proceedings of the 2. Int. Seminar Misconceptions and Educational Strategies in Science and Mathematics, Vol.I. Ithaca, NY: Cornell University, 481-489.

Strube, P. (1989). The notion of style in physics textbooks. Journal of Research in Science Teaching, 26, 291-299.

Suchting, W.A. (1992). Constructivism deconstructed. Science & Education, 3, 223-254.

Sutton, C. (1989). Writing and reading science: The hidden message. In R. Millar, Ed., Doing science: Images of science in science education (pp. 137-159). London, UK: Falmer Press.

Taylor, P. (1993). Collaborating to reconstruct teaching: The influence of researcher beliefs. In K. Tobin, Ed., The practice of constructivism in science education. (pp. 267-297). Washington, DC: AAAS Press.

Taylor, P. & Fraser, B. (1991, April). Development of an instrument for assessing constructivist learning environments. Roundtable at the annual meeting of the American Educational Research Association, Chicago.

Tiberghien, A. (1980). Modes and conditions of learning - an example: the learning of some aspects of the concept of heat. In F. Archenhold, et al. Eds., Cognitive development. Research in Science and Mathematics. (pp. 288-309). Leeds, UK: University of Leeds.

Tobin, K. (1993b). Constructivist perspectives on teacher learning, In K. Tobin, Ed., The practice of constructivism in science education. (pp. 215-226). Washington, DC: AAAS Press.

Tobin, K., Ed. (1993a). The practice of constructivism in science education. Washington, DC: AAAS Press.

Treagust, D., Duit, R., & Fraser, B., Eds. (in press). Improving teaching and learning in science and mathematics. New York: Teacher College Press.

Wandersee, J.H., Mintzes, J.J., & Novak, J.D. (1993). Research on alternative conceptions in science. In D. Gabel, Ed., Handbook of research on science teaching and learning. (pp. xxx-xxx). New York: Macmillan Publ.

White, R.T. & Gunstone, R.F. (1992). Probing understanding. London, UK: Falmer Press.

Wiesner, H. (1994). Ein neuer Optikkurs für die Sekundarstufe I, der sich an Lernschwierigkeiten und Schülervorstellungen orientiert. Naturwissenschaften im Unterricht - Physik, 42 (Mai), 7-15.

Wittrock, M.C. (1994). Generative science teaching. In P.F. Fensham, R.F. Gunstone & R.T. White, Eds. (1994). The content of science: A constructivist approach to its teaching and learning. (pp. 29-38). London, UK: Falmer Press.

Wolf, D., Bixby, J., Glen III, J., & Gardner, H. (1991). To use their minds well: Investigating new forms of student assessment. In D. Grant, Ed., Review of research in education. (pp. 31-74). Washington, DC: American Educational Research Association.

Wolze, W. & Walgenbach, W. (1992). Naturwissenschaftliche Bildung als Systembildung. In P. Häußler, Ed., Physikunterricht und Menschenbildung. (pp. 163-186). Kiel, Germany: Institute for Science Education at the University of Kiel.

Yager, R.E. (1991). The constructivist learning model. The Science Teacher, 58 (6), 52-57.

Yager, R.E. (1993). Science-Technology-Society as reform. School Science and Mathematics, 93 (3), 145-151.

Zeki, S. (1992). The visual image in mind and brain. Scientific American, 267, September 1992, 43-50.

Appendix

Claims summarizing key findings of students conceptions research (from Wandersee, Mintzes, & Novak, 1993)

Claim 1: Learners come to formal science instruction with a diverse set of alternative conceptions concerning natural objects and events.

Claim 2: The alternative conceptions that learners bring to formal science instruction cut across age, ability, gender, and cultural boundaries.

Claim 3: Alternative conceptions are tenacious and resistant to extinction by conventional teaching strategies.

Claim 4: Alternative conceptions often parallel explanations of natural phenomena offered by previous generations of scientist and philosophers.

Claim 5: Alternative conceptions have their origins in a diverse set of personal experiences including direct observation and perception, peer culture and language, as well as in teachers' explanations and instructional materials.

Claim 6: Teacher often subscribe to the same alternative conceptions as their students.

Claim 7: Learners' prior knowledge interacts with knowledge presented in formal instruction, resulting in a diverse set of unintended learning outcomes.

Claim 8: Instructional approaches which facilitate conceptual change can be effective classroom tools.