Sources of students' difficulties in learning Chemistry

David Treagust,[1] Reinders Duit,[2] and Martina Nieswandt[3]

Abstract
Chemistry is a difficult subject to teach and to learn at both secondary and tertiary levels. Major learning difficulties are due to the particular views of chemistry phenomena that in many ways contradict intuitive and everyday views of the learners. As a result, major misunderstandings occur when students try to comprehend chemical explanations within the framework of their pre-instructional conceptions. This paper describes research findings on students' pre-instructional conceptions in the domain of chemistry and on attempts to guide students from their conceptions to the core ideas of chemistry. Rather than providing an overview of students' conceptions in various topics, we review learning difficulties from the perspectives of the challenge of multiple representations and the relation of chemistry to everyday experiences, including understanding the special language of chemistry. We believe that these perspectives contribute substantially to the limited success of teaching and learning chemistry.

Studies on understanding and learning chemistry

Understanding and learning core science concepts and principles, including those in chemistry, are difficult; many research studies have revealed major learning difficulties and identified key causes of these difficulties. A large number of intervention studies have attempted to address these difficulties by examining the role of students' preinstructional conceptions in the learning process. Further readings in this area are the bibliography by Pfundt and Duit (1998), general reviews of studies on learning science by Treagust, Duit and Fraser (1996) and by Duit and Treagust (1998), and a review on conceptual change approaches in science by Hewson, Beeth, & Thorley (1998).

[1]Science and Mathematics Education Centre, Curtin University of Technology, Perth, Australia.
[2]Institute for Science Education at the University of Kiel, Germany.
[3]University of Nevada, Las Vegas, USA.

There is overwhelming empirical evidence in the literature that what students already know is the key factor in learning. Usually students' preinstructional conceptions provide frameworks that are not in accordance with the science conceptions to be learned. From a constructivist perspective, which is the predominating contemporary view of learning in science education, every observation and every sensual input of any other kind has to be interpreted by the receiver (Steffe & Gale, 1995; Tobin, 1993). Students construct their own meanings of observations that they make when experiments are presented, pictures are shown, and explanations are given by the teacher or the textbook. The only interpretive frameworks that students possess are the conceptions gained in daily life or in science classes. As a result, in making sense of what is presented in science classes and in textbooks, sometimes students construct meanings that are in contrast to the expected chemistry view. Within this constructivist perpective, learning is not seen as the intake of knowledge that is delivered by the teacher and teaching is not viewed as transfer of knowledge from teacher or textbook to the head of the students. Rather, learning is viewed as an active construction process of the learner and teaching is designed to support and nurture this construction process. Accordingly, learning science can be a painstaking process of a sequence of gradual changes of students' preinstructional conceptions towards science conceptions (Vosniadou & Ioannides, 1998). The term conceptual change is usually employed to point to this process because it denotes that major changes of the initial conceptual frameworks are necessary when science concepts and principles are learned.

Most of the 3000 or so studies on learning difficulties in science reported by Pfundt and Duit (1998) have been carried out in the domain of physics (70%), with much less in biology (20%) and even less in chemistry (10%). Consequently, most general results on the role of preinstructional conceptions in the learning process and on the effect of conceptual change approaches to learning draw on findings from physics, although studies in biology and chemistry do contribute to these insights.

Studies on students' pre-instructional conceptions and learning processes in chemistry have examined major concepts and principles of chemistry in a number of topics. These topics include (a) views of chemical changes and reactions, (b) the particle view of atoms and molecules, (c) chemical equilibrium, (d) models and representations of chemical reactions, (e) acids and basis, (f) combustion, (g) electrochemistry and (h) the mole concept. In these topics, however, research findings are not as well established as in the case of physics, where, for instance, some hundreds of studies are available on Newtonian mechanics and electricity; at best, some 20 studies, for instance, are available on students' views of chemical changes. More research is necessary to better understand the learning difficulties in the major chemistry topics with a more diverse range of students and in an increasingly diverse range of settings as well as in additional topics such as organic chemistry.

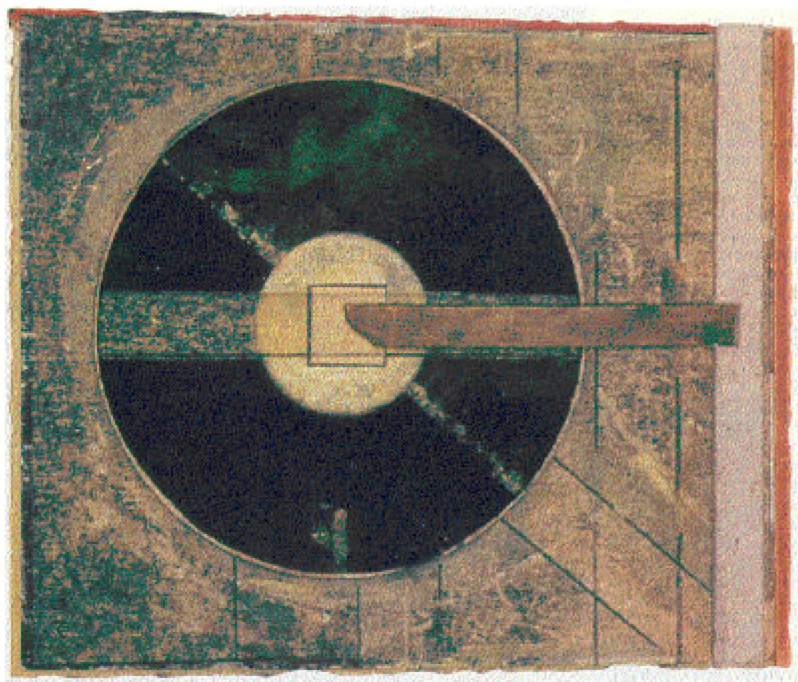
To date, several review articles have provided summaries of the results of studies on learning chemistry, each with different emphases. Andersson (1990) analyzed students' views of matter and its transformation within the framework of the four categories of disappearance, displacement, modification and transmutation. Nakhleh (1992) focused on the particulate nature of matter, molecules and intermolecular forces, phase changes, gases, chemical equations, chemical change and chemical equilibrium. Stavy (1995) primarily dealt with children's views of matter and its properties, including continuous versus particulate views and conceptions of the conservation of matter. The most recent and comprehensive review by Garnett, Garnett and Hackling (1995) summarized and discussed findings on (a) the particulate nature of matter, including the nature and characteristic of particles, the space between particles and the way particles are arranged, molecules in different phases, and changes of phase and the effects of temperature; (b) covalent bonding and intermolecular forces; (c) chemical equations; (d) chemical equilibrium, including characteristics of chemical equilibrium, constancy of the equilibrium constant and inappropriate use of Le Chatelier's principle; (e) acids and bases; (f) oxidation-reduction, and (g) electrochemistry.

Garnett et al. (1995) also provided an overview of theoretical frameworks in which research on students' learning difficulties is embedded. Implications from the research data available on teaching and learning include (a) the need to carefully examine the use of everyday language in a scientific context; (b) over-simplification of concepts and the use of unqualified, generalised statements; (c) the use of multiple definitions and models; (d) the rote application of concepts and algorithms; (e) students' preconceptions from prior world experiences; (f) overlapping of similar concepts; (g) endowing objects with human/animal characteristics; (h) inadequate prerequisite knowledge; and (i) students' inability to visualize the particulate/submicroscopic nature of matter.

Issues such as these need to be considered in the development of new curricula or courses in order to help students with their learning. This task is relatively difficult and few studies are reported that have incorporated these issues into a chemistry curriculum that has been systematically evaluated. Examples where such development and evaluation have occurred are the work of van Driel, De Vos, Verloop and Dekkers (1998) in chemical equilibrium and Acampo and De Jong (1994) in electrochemistry, both conducted in the Netherlands, and Stork (1995), in Germany.

Stork (1995) designed a course based on the literature of students' conceptions to introduce basic chemistry ideas to students of about 15 years of age. The study focused on the change of substances and students' view of the particle model and addressed, among others, students' conceptions that a change of substances is the same as change of characteristics of substances and that a substance is totally destroyed when it burns.

In the first instance, when copper is heated in air, in normal everyday conditions, a black layer forms which students describe as the copper becoming black; they think that the substance copper has been given a new characteristic, namely a black colour. In other words, students interpret their observations in terms of a change of characteristics of the substance which is a way of thinking that is usually successful in everyday situations. However, in chemistry, this change is conceptualized in a markedly different manner: Red copper does not exist any more, black copper-oxide comes into being. In the second instance, when zinc is burned, a white substance results which students believe is impossible to be returned to zinc. Even when an experiment showed that the metal zinc can be obtained from the ash, students were quite hesitant, but fascinated, to accept this result. These two examples show that chemistry views of change of substances are often



D. E. May, *Sin título*,1986. (Tomado de *The Sciences*, Sep./Oct. 1996, p. 21.)

strange to students; common sense thinking which is so successful in daily life no longer applies.

Although Stork's course focused on the traditional curricular content, there were marked differences from usual introductory courses in the sequence in which the content was presented and in the teaching approach used. The first three of the six units concentrated on topics for which concrete-operational thinking was adequate. Starting in unit four, phenomena were interpreted at the particle level requiring students to think increasingly in abstractions. Students' awareness was first enhanced by their own relevant everyday conceptions and then they were engaged in cognitive conflict triggered by a discrepant event (Fensham & Kass, 1988) in order to develop an understanding of the scientific concept.

During one school year, the course was taught and students' progress evaluated in four 9th grade classes at four different German Gymnasiums, selective upper secondary schools to which the top 30% of academically able secondary students attend (Nieswandt, in press). Students were given different tasks of transfer, the content of which belonged mostly to everyday problems. Results showed that students had different learning paths for their conceptions of change of substances and the particle model evaluated on five different occasions during one school year (Nieswandt, 1999). One third of the students realized that substances possess constant, recognizable properties, that a change in property indicated that a new substance has been created and they developed an increasingly differentiated knowledge about and deeper understanding of the scientific concepts. However, the majority of students required exposure to scientific concepts more than once, implying that learning is enhanced by re-teaching the chemical concept in different contexts and giving students different opportunities to practice the new concept for similar tasks and applying them to everyday phenomena. A small number of students preferred not to give an answer because they realized that their everyday conceptions were not useful for interpreting the scientific phenomena. Finally, a small proportion of students hold *hybrid conceptions* (Jung, 1993), a mixture of everyday descriptions and scientific explanations, and struggle with their scientific and everyday life knowledge. For these students, the new scientific concepts were not fully grasped and they did not realize in which context everyday conceptions are appropriate. The teacher's goal is to help students bring these two conceptions together so they can be used more appropriately.

The challenge of multiple representations

In chemistry, and in all sciences as well as in everyday life, analogies, metaphors and/or models are used to help explain a phenomenon that is not observable. However, the research literature on the use of models and analogies in science teaching and learning is ambivalent about whether or not the best way to learn concepts in science is by single or multiple analogies (Goswami, 1993; Zook, 1991). Studies investigating the role of multiple analogies or models in the teaching and learning of secondary chemistry by Garnett and Treagust (1992) showed that some students prefer not to be presented with more than one model at a time. Students who held more than one definition for oxidation/reduction experienced problems when trying to identify oxidation-reduction equations because they were uncertain as to which model to apply to given situations. However, in a study of the topic of organic chemistry, Harrison and Treagust (in press) observed that students who are exposed to, and who become skilled in the use of multiple analogies, develop a more scientific understanding of the science concept under investigation than do students who concentrated on one single well established analogy.

Learning chemistry, especially at senior high school and university level, emphasizes relationships, processes, abstract concepts and mental models. Relational thinking and scientific knowledge involve mental models which are a “special kind of mental representation, an analog representation, which individuals generate during cognitive functioning” (Vosniadou, 1994, p. 48). Mental models need not be technically accurate, but they must be functional and constantly evolve as individuals interact with their world (Johnson-Laird, 1983). How students develop their mental models is therefore a major challenge to both teachers in secondary schools and lecturers in universities.

Scientific models are normally used to represent the real world or as tools for connecting the real world with scientific and mathematical laws and theories (Hodgson, 1995). The boundaries between models as heuristic, explanatory and communicative devices are often blurred. This need not be a weakness because the heuristic effect of a model as it is being used to communicate ideas can help students in their understanding of the phenomena being investigated (Gilbert & Boulter, 1998). Models such as structural representations of organic and inorganic compounds, as used by chemists and found in all modern chemistry texts, are trademarks of science and are considered part of the chemical language (Hoffmann & Laszlo, 1991).

Chemistry texts are filled with a variety of drawings to represent molecules. These drawings can range from simple Lewis structures showing atom connectivity through to the highly abbreviated ‘line-bond’ structures. There are also many ways of representing three-dimensional molecules including ball & stick structures, space filling structures, Newman projections and Fisher projections. Each of these methods of representing molecules is used in almost all university chemistry texts to depict a particular aspect of the chemistry or structure of the molecule as required. None of these representations is universally applicable and the particular representation chosen for a given situation is dependent on the situation itself. Although, each representation has its particular advantages, they all depict the same molecule but neither textbooks nor lectures generally include descriptions of how one representation can be translated into another. Indeed, the process of explaining a phenomenon or problem solution through a different model often suggests new relationships and insights. This aspect is a major challenge for teachers and lecturers who want their students to functionally transfer between one model, structural representation or diagram, and another.

A recommendation for teaching at both secondary and tertiary levels is that early in chemical education it is essential for the teacher to emphasize students’ understanding that these symbols, formulae or models are *representations* of different properties of a molecule or substance and not a copy of anything. Such a teaching approach can work as is illustrated by the research reporting how a student named Alex used six different analogical models in his study of organic chemistry (Harrison and Treagust, in press). Alex viewed each of the ball-and-stick, space-filling, electron-dot, electron cloud/shell overlaps, 2-dimensional structural diagrams and the balloons model as a purpose-built model to describe the attributes of covalent organic molecules. His use of multiple mental models enabled him to have a fruitful conception of the nature of covalent-bonded molecules because different aspects of the six models represented different aspects of the molecules. Alex had developed close to an expert view of the use of these models in chemistry despite his relative inexperience in science (Grosslight, Unger, Jay & Smith, 1991).

The relationship of chemistry to everyday experiences

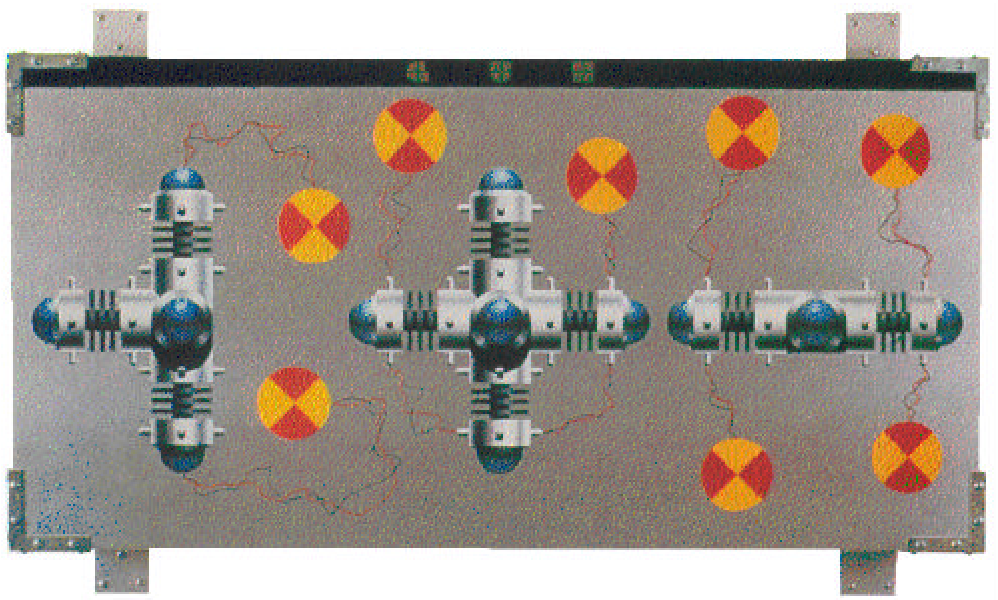
Teaching chemistry with an emphasis on the learners' everyday experiences and preconceived ideas is the basis of the constructivist perspective outlined earlier (Yager, 1991). The strategy of building on a core of familiar ideas requires the teacher to first identify the depth and breadth of a student's knowledge base. However, teachers often assume prior knowledge far beyond the students' comprehension and do not begin by examining the chemistry in the students' everyday life. In *Chemistry in the Market Place*, Selinger (1998, p. ix) expressed surprise how little 'added value' chemical educators give to their teaching examples.

Often no distinction is made between the scientific chemical meaning and the commonplace meanings of words in our vocabulary and, consequently, these words are used indiscriminately by students (Fensham, 1994). To complicate matters, even within the chemistry profession, there are several meanings for the same word (Selinger, 1998) and naturally enough, when students are confronted with the same words but with different meanings they become confused. For example, 'pure' can refer to the cleanliness of a substance, not its chemical nature; 'mixture' refers to something physically combined together, not, for example, the chemical nature of glass or blood or drinking water. Students' experience is mainly with mixtures; however, their perception is that these substances, for example, brass, lemonade, wine, tap water, are chemically pure. Words as different as dissolving and melting which are obvious to teachers are confused when used by students (Fensham, 1994). Students have insufficient background or experience with which to distinguish these terms and consequently the teacher's meaning is not communicated clearly.

As emphasized more than two decades ago by Gardner (1975), the language of science is difficult to learn. His analysis of science textbooks showed that students learning science have to learn not only new technical words about science, such as those described above, but also have to learn many linking words and phrases, such as 'then', 'so that', 'on the other hand', which tie the scientific propositions together in a logical argument. These linking words and phrases called 'logical connectives' create their own complexities and difficulties. To those familiar with the way in which science is taught in the first years of high school, this situation will not be surprising. Further, as students progress in their science studies, they encounter more special words to describe and explain scientific phenomena that differ in meaning between the everyday and scientific meanings, creating additional learning problems. In a scientific context, a word is frequently harder to understand because it has a more precise meaning and this extra precision requires more effort and thought (Cassels & Johnstone, 1983). For example, research in electrochemistry (Garnett, Garnett & Treagust, 1990) showed that students misinterpret the phrase ' the ions carry the charge' when referring, for example, to reactions between metals and acids in an electrochemical cell, as being in the same way that a suitcase is carried. They interpreted 'carry' to mean that the electron is picked up at one electrode, carried piggy-back fashion to the other electrode and then deposited or removed in the oxidation process.

The relevance, usefulness and applicability of chemistry to everyday life can influence students' attitudes towards learning chemistry, but unfortunately, many chemistry courses fail to do this. At the beginning of the chemistry course, students almost need blind faith in order to continue learning the symbols, valencies, and how to balance equations before they can apply any knowledge to see its relevance. Scientific nomenclature is like a foreign language and frustration can occur when trying to relate chemical names with everyday experiences.

To guard against pitching courses at too high a level and thus excluding a high percentage of the population, Selinger (1998) provides many examples of the use of chemistry in everyday life from the kitchen to industry. A number of chemistry courses have attempted to relate the content to students' everyday experiences; one such example, a laboratory course for university non-majors, adopted a practical approach where students made chemical products such as wine, soap, cheese, dyed fabric (Roberts, Selco & Wacks, 1996). This emphasis on extensive laboratory work dramatically improved the students' perceptions of chemistry–the use of familiar products was a significant factor in relating chemistry to the students. However, the assumption that this type of chemistry is only suited to non-chemistry students is not valid. In a course for chemistry majors (Doran, Chan & Tamir, 1998), experiments exposing scientific methods using everyday items such as baking soda, vinegar, shampoo and sugar in practical assessment tasks have been used to "reinforce the connection between science and the stu-



Ashley Bickerton, *GUH*,1986. (Tomado de *The Sciences*, Sep./Oct. 1996, p. 22.)

dents' out of school experience" (p. 131). In another chemistry program, the inclusion of environmental factors helped students to "see the influence of chemistry on daily life" when experiments were used to investigate environmental issues such as the presence of CFC's in household chemicals (Klemmer, Hutter, & Howard, 1996, p. 55).

The Salters Chemistry course developed in England during 1983-1987 started with the present interest and experiences of the students and built on this through active learning techniques such as discussions, experimental design, role-plays and decision making activities (Ramsden, 1992). Research studies on this course have indicated that students have responded favourably to the use of everyday references (Ramsden, 1994). In a typically content-driven curriculum, examples are provided to support the content, whereas the Salters curriculum is driven by everyday examples which is a fundamental change in the approach to presenting and explaining scientific phenomenon (Campbell et al., 1994). Examples of the units, Fire, Friend or Foe, Current Thinking, Sports Science, are interesting and different, and improve the image of the chemistry subject matter. Although the title does not make the students learn chemistry, it may improve their attitude to the subject and motivate them to learn. Campbell et al. (1994) reported that teachers felt there was an improvement in the climate of their science classrooms after using the Salters approach. Students' prior knowledge is an asset that can be accessed to link new concepts and students' preconceptions and misconceptions significantly influence the building of new knowledge. Strategies incorporating the use of familiar products and personal experiences can improve the linking of existing knowledge with new concepts.

Conclusions

Research has revealed that many difficulties in learning and understanding chemistry appear to be caused by a view of chemistry instruction that is oriented primarily to a view of chemistry that is academic and not related in any way to the chemistry of everyday life. Teaching and learning chemistry in a meaningful way needs a much broader perspective. Clearly, the nature of the chemistry content plays a significant part in the process of planning the teaching and learning processes. However, the clarification of subject matter structure has to be imbedded in considerations on the aims affiliated with teaching and learning that particular content and in reflections on student starting points. These student starting points include pre-instructional conceptions about the phenomena and concepts to be learned, views about chemistry and chemistry teaching, mental abilities, interests and motivations, as well as key features of daily life. Research has shown that learning for understanding needs an active, self-reflective and self-responsible learner whereby students construct their own knowledge. The teacher can only provide help in this construction process because knowledge cannot be transferred to the students' brain in a similar way as bytes are transferred in a computer's memory. Unfortunately, students engage in the painstaking construction process only if they see the need to learn and the process is only successful if students are carefully guided from their pre-instructional conceptions and views towards the chemistry concepts (Duit & Treagust, 1998). The findings of many more recent research studies where students' conceptions are taken into account and where contexts include issues of students' life world have proven promising (Wandersee, Mintzes & Novak, 1994).

When planning instruction in chemistry, for more effective learning, teachers need to take into consideration a much broader range of issues than the chemistry concepts themselves. These issues are to be aware of and take into consideration (*a*) students' prior knowledge, (*b*) the multiple ways in which chemistry phenomena can be represented, (*c*) the meanings of the same and similar terms used in chemistry and in everyday life, and (*d*) the chemistry of everyday life. When students become deeply engaged in their own learning, they frequently have a better understanding of chemistry and of the role of chemistry in their daily lives. Furthermore, the lessons are more pleasing experiences both for teacher and students.

References

Acampo, J. & De Jong. O. (1994). Chemistry teachers' learning processes: a study of teacher training and reflection on classroom activities. In H-J. Schmidt (ed.), *Problem-solving and misconceptions in chemistry and physics* (p. 229-237). Hong Kong: ICASE.

Andersson, B.R. (1990). Pupils' conceptions of matter and its transformations (age 12-16). *Studies in Science Education, 18*, 53-85.

Campbell B., Lazonby, J., Millar, R., Nicolson, P., Ramsden, J., & Waddington, D. (1994). Science: The Salters' approach—A case study of the process of large scale curriculum development. *Science Education, 78*, 415-447.

Cassels, J.R.L. & Johnstone, A.H. (1983). The meaning of words and the teaching of chemistry. In R.B. Bucat and P.J. Fensham (eds.), (1995). *Selected papers in chemical education research: Implications for the teaching of chemistry*. Delhi, India: The Committee on Teaching of Chemistry, International Union of Pure and Applied Chemistry.

Doran P.R., Chan, F. & Tamir, P. (1998). *Science educator's guide to assessment*. Arlington, VA: National Science Teachers Association.

Duit, R. & Treagust, D. (1998). Learning in science—From behaviourism towards social constructivism and beyond. In B. Fraser and K. Tobin, (eds.), *International handbook of science education* (p. 3-25). Dordrecht, The Netherlands: Kluwer.

Fensham, P.J. (1994). Beginning to teach chemistry. In P.J. Fensham, R.F. Gunstone, and R.T. White (eds.), (1994). *The content of science: A constructivist approach to its learning and teaching* (p. 14-28). London: Falmer Press.

Fensham, P.J. & Kass, H. (1988). Inconsistent or discrepant events in science instruction. *Studies in Science Education, 15*, 1-16.

Garnett, P.J., Garnett, P.J., & Hackling, M. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education, 25*, 69-95.

Gardner, P.L. (1975). Logical connectives in science: A preliminary report. *Research in Science Education, 5*, 161-176.

Garnett, P.J. & Treagust, D.F. (1992). Conceptual difficulties experienced by senior high school students of electric circuits and oxidation-reduction equations. *Journal of Research in Science Teaching, 29,* 121-142.

Gilbert, J.K., & Boulter, C.J. (1998). Learning science through models and modelling. In B.J. Fraser & K.G. Tobin (Eds.), *International handbook of science education* (p. 53-66). Dordrecht, The Netherlands: Kluwer.

Goswami, U. (1992). Analogical reasoning in children. Hove, U.K.: Lawrence Erlbaum.

Grosslight, L., Unger, C., Jay, E., & Smith, C. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*, 799-822.

Harrison, A.G. & Treagust, D.F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education, 80,* 509-534.

Harrison, A.G. & Treagust, D.F. (in press). Learning about atoms, molecules and chemical bonds; A case study of multiple model use in grade-11 chemistry. *Science Education.*

Hewson, P. W., Beeth, M. E. & Thorley, N. R. (1998). Teaching for conceptual change. In B.J. Fraser and K.G. Tobin (Eds.), *International handbook of science education* (p. 199-218). Dordrecht, The Netherlands: Kluwer.

Hodgson, T. (1995). Secondary mathematics modeling: Issues and challenges. *School Science and Mathematics, 95*, 351-358.

Hoffmann, R. & Laszlo, P. (1991). Representation in chemistry. *Angewandte Chemie, International Edition in English, 30,* 1-16.

Johnson-Laird, P.N. (1983). *Mental models.* Cambridge, MA: Cambridge University Press.

Jung, W. (1993). Hilft die Entwicklungspsychologie dem Naturwissen-schaftsdidaktiker? (Is developmental psychology of help for science educators?) In: Duit, R. & Gräber, W. (Eds.), *Kognitive Entwicklung und Lernen der Naturwissenschaften* (*Cognitive development and learning science*) (p. 86-109). Kiel: Institute for Science Education:.

Klemmer, G., Hutter, L. & Howard, E. (1996). Chemistry education and environmental awareness. *School Science Review*, 78 (280), 55-61.

Nakhleh, M.B. (1992). Why some students don't learn chemistry. *Journal of Chemical Education, 69,* 3, 191-196

Nieswandt, M. (in press). Problems and possibilities for learning in an introductory chemistry course from a conceptual change perspective. *Science Education.*

Nieswandt, M. (1999, March). *On the way to a scientific concept: Examples of students' learning paths in an introductory chemistry course.* Paper presented at the annual meeting of the National Asociation for Research in Science Teaching (NARST), Boston, USA.

Pfundt, H. & Duit, R. (1998). *Bibliography: Students' alternative frameworks and science education.* Kiel, Germany: Institute for Science Education at the University of Kiel (version August 1998; distributed electronically).

Ramsden, J. (1992). Going in through both ears and staying there: The Salters approach to science. *Australian Science Teachers Journal,* **38**[2], 13-18.

Ramsden, J. (1994, March). Context and activity based science in action. *School Science Review, 75* [272], 7-14.

Ramsden, J.M. (1992). If its enjoyable, is it science? *School Science Review, 73* [265], 65-71.

Roberts, J.L., Selco, J.I. & Wacks, D.B. (1996). Mother Earth Chemistry: A laboratory course for non-majors. *Journal of Chemical Education, 73*, 779-781.

Selinger, B. (1998). *Chemistry in the market place.* Melbourne: Harcourt Brace.

Stavy, R. (1995). Conceptual development of basic ideas in chemistry. In S.M. Glynn & R. Duit, (eds.), *Learning science in the schools: Research reforming practice* (p. 131-154). Mahwah, New Jersey: Lawrence Erlbaum.

Steffe, L.P. & Gale, J. [eds.] (1995). *Constructivism in education.* Hillsdale, New Jersey: Lawrence Erlbaum.

Stork, H. (1995). Was bedeuten die aktuellen Forderungen "Schülervorstellungen berücksichtigen, 'konstruktivistisch' lehren!" für den Chemieunterricht in der Sekundarstufe I? [Consequences of the actual demands to take students' conceptions into consideration and to teach 'constructively' for teaching chemistry in secondary level I]. *Zeitschrift für Didaktik der Naturwissenschaften, 1*, 15-28.

Tobin, K. (1993). *The practice of constructivism in science education.* Washington, DC: American Association for the Advancement of Science Press.

Treagust, D., Duit, R. & Fraser, B., eds. (1996). *Improving teaching and learning in science and mathematics.* New York: Teacher College Press.

Van J.H. Driel, De Vos, W., Verloop, N. & Dekkers, H. (1998). Developing secondary students conceptions of chemical reactions; the introduction of chemical equilibrium. *International Journal of Science Education,* **20**[4], 379-392.

Vosniadou, S. (1994). Capturing and modelling the process of conceptual change. *Learning and Instruction,* **4**, 45-69.

Vosniadou, S. & Ioannides, C. (1998). From conceptual change to science education: a psychological point of view. *International Journal of Science Education,* **20**, 1213-1230.

Wandersee, J.H., Mintzes, J.J., & Novak, J.D. (1994). Research on alternative conceptions in science. In D. Gabel (ed.), *Handbook of research on science teaching and learning* (p. 177-210, New York: Macmillan Publishing Company.

Yager, R.E. (1991). The constructivist learning model: towards real reform in science education. *The Science Teacher,* **58** [6], 52-57.

Zook, K.B. (1991). Effect of analogical processes on learning and misrepresentation. *Educational Psychology Review*, **3** [1], 41-72.