J. Acampo

Teaching Electrochemical Cells

A study on teachers' conceptions and teaching problems in secondary education

TEACHING ELECTROCHEMICAL CELLS

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ONDERWIJZEN VAN ELEKTROCHEMISCHE CELLEN
Een onderzoek naar concepties van docenten en onderwijsproblemen
in het secundair onderwijs
(met een samenvatting in het Nederlands)

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Chapter 1

Introduction

This thesis deals with teachers' conceptions of teaching the topic of electrochemistry in secondary schools in the Netherlands. In this chapter, first the focus and the relevance of this study will be discussed (1.1). Subsequently, its nature (1.2) and design (1.3) will be outlined. A section on the contents will conclude this chapter (1.4).

1.1 Focus and relevance

Conceptions

At the end of the 1980s and the beginning of the 1990s, there was an increasing interest in the conceptions of science teachers, and the possible implications of these conceptions for their teaching (e.g. Hewson & Hewson, 1987; Baird et al., 1991; Bell & Gilbert, 1996; Treagust et al., 1996). However, this interest mainly focused on teachers' conceptions of a rather general nature. For example, research has been done into the conceptions which science teachers had of philosophy of science (Koulaidis & Ogborn, 1989; Gallagher, 1991), into differences in ways of reading science texts and science textbooks (Yore, 1991), into the history of science (King, 1991), and into the role of classroom experiments (Gramm & Koch, 1989, 1991). Consequently, little is known about conceptions of science teachers concerning the teaching of syllabus topics[1].

Because I received a university education in chemistry and my interest is the teaching of chemistry in secondary education, I chose to do some research into *the teaching of chemical syllabus topics*. More specifically, I chose the topic of *electrochemistry*. In taking the decision to look at this particular syllabus topic, my motives were, among

[1] In the Netherlands, the syllabus is an elaboration of the final exam programme. A syllabus is a list of topics for the different school years, complete with a concise explanation.

other things, the difficulty of the topic as perceived by both teachers and students and its importance as perceived by teachers.

Difficult and important topic

In the Netherlands, some research has already been done in order to determine which topics chemistry teachers consider problematic to teach (De Jong, 1982). The Dutch teachers in question ranked electrochemistry as one of the most difficult topics taught in secondary school chemistry. This opinion is echoed by teachers in several other countries (e.g. Bojczuk, 1982; Davies, 1991). Also, it appeared that Dutch students considered electrochemistry one of the most difficult topics (De Jong, 1982). In other countries, the same results were found (e.g. Davies, 1991; Griffiths, 1994). The topic of electrochemistry is not only considered as problematic, but also as important to teach (e.g. Finley et al., 1982; Butts & Smith, 1987b).
Already quite a lot is known about the nature of students' conceptual difficulties concerning electrochemistry (Allsop & George, 1982; Butts & Smith, 1987a; Sumfleth & Todtenhaupt, 1988; Acampo & De Jong, 1991, 1992, 1993a; Davies, 1991; Van de Berg & Van Driel, 1991; Barral et al., 1992; Garnett & Treagust, 1992a, 1992b; Ogude & Bradley, 1994). This is not the case for the nature of *teachers' conceptions of difficulties* in teaching electrochemistry. Consequently, research concerning teachers' conceptions would be a valuable addition to the subject. It seems possible to do such research in a more meaningful way with the help of the already acquired knowledge on students' conceptual difficulties.

Electrochemistry

As was mentioned above, electrochemistry is a topic which is part of Dutch secondary school chemistry. In this study, I shall focus on the so-called VWO level. VWO is the acronym for pre-university education (in the UK, the academic stream and in the USA, academic track). At VWO level, chemistry education starts in 3 VWO (students' age 15, 2 lessons a week), and goes on in 4 VWO (students' age 16, 3 lessons a week). I shall focus on the 5th form of the VWO which is the pre-final year. The average age of the students in 5 VWO is seventeen, and they generally have 4 chemistry lessons a week.
By the term of electrochemistry, a topic is indicated that is called 'Reductants and Oxidants' in the current Dutch final exam programme and syllabus for VWO (O&W, 1983, 1984). The subtopics mentioned under this heading are: 'redox reactions', 'electrochemical cells', 'Nernst's law', 'corrosion' and 'electrolysis'. In the greater part of the currently used 5 VWO textbooks, the subtopics have been reorganized, which reorganization results in two chapters, called: redox reactions and

electrochemical cells[2] (Smilde et al., 1985; Pieren et al., 1992; Reiding et al., 1986, 1993).

Electrochemistry in syllabi until 1984

The vast majority of teachers who teach in current secondary education were themselves taught within the framework of one of the *previous* syllabi. I will briefly go into the history of the topic of electrochemistry in these syllabi, because the previous syllabi may be connected to the teachers' *existing* conceptions.

In 1932, the first programme stating 'minimum demands' to be met at the final chemistry exams for higher-level secondary education (at that time HBS-B[3]) was published; before this those demands had not been publicly stated (Docters van Leeuwen, 1968). This programme was divided into three parts: a general part, an inorganic chemistry part, and an organic chemistry part. Concepts concerning electrochemistry came up in all three parts. In the general part, the ionic theory, electrolyses of a number of specified solutions and molten salts, and oxydimetry (without half reactions) were mentioned. In the inorganic part, oxidant and reductant strength (semi-quantitative) of specified elements and compounds were added, and finally, in the organic part, some examples were given of oxidation and reduction reactions.

As far as the topic of electrochemistry was concerned, this programme remained unchanged until 1964. It was only then that the term redox reactions was introduced, referring to reactions involving the transfer of electrons (Kruijtbosch & Richter, 1960, 1967).

In 1968, the syllabus was organized into (new) topics for the first time; one of those topics was electrochemistry. All the previously mentioned electrochemical concepts of former syllabi were retained in this syllabus. Concepts mentioned for the first time in this syllabus were: potential jump, normal potential, predicting the proceeding of redox reactions, and galvanic elements (O&W, 1979; this syllabus had previously been published in 1970 in the Staatscourant nr. 229). As far as redox reactions were concerned, in this syllabus both the extent of reactions as well as the direction of half reactions received more emphasis.

Like the previous one, the syllabus of 1977 was divided into topics (CMLS[4], 1978). Each topic was again divided into headers and subheaders. One alteration was the transposition of the concept of electrolysis from first to last header in the sequence. Furthermore, the concept of Nernst equation was mentioned for the first time. In addition, some suggestions for teaching were given, which had not been present in previous syllabi. For example, the header 'Nernst equation' had among its subheaders

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[2] Textbooks are written by authors, who, in most cases, are (former) teachers.

[3] Precursor of VWO.

[4] CMLS is the acronym for Commissie Modernisering Leerplan Scheikunde. My translation in English: Committee Modernization Syllabus Chemistry.

'measuring concentrations' and 'pH meter'. In the teaching suggestions, the influence of ion concentrations on electromotive force was mentioned. The header 'applications' had among its subheaders 'corrosion' and 'protection against corrosion'.

Electrochemical cells

I chose to look at the topic of *electrochemical cells*, because this topic includes all aspects of the other subtopics mentioned in the current syllabus, viz. 'redox reactions', 'Nernst's law', 'corrosion' and 'electrolysis'. Besides, my choice was inspired by previous research done in our research group (CSME[5]):

- De Vos (1985) studied the introduction of the concepts of chemical reaction and substance into chemistry education in relation to the development of corpuscular concepts[6]. He paid a lot of attention to the chemical event of reaction as the disappearing and arising of substances and to the location where that occurs. Also, the transport of mass was studied (see also De Vos & Verdonk, 1985a, 1985b, 1986, 1987a, 1987b).
- Van Driel (1990) studied the introduction of the concept of chemical equilibrium at a later stage in the educational programme[7]. The equilibrium concept requires a revision of some of the concepts taught before, namely concerning the extent and the direction of the reaction. He paid a lot of attention to two chemical events of reaction which are each other's opposite. Here, the time aspect of the occurrence of chemical events is introduced.

Their work was concerned with the *number of different chemical events*, with the *location* and with the *time*. Together, these three aspects form an educational concept, which I call the three-dimensionally unfolding of reactions.

These three aspects are also relevant for the topic of electrochemical cells. Because in a cell, *two different chemical events* of reaction occur which can be distinguished from each other but are connected with each other, at different *locations*, at the same *time*. In their turn, these distinguishable chemical events can be reversible. In my study, I want to pay attention to the corpuscular description of the three-dimensionally unfolding of reactions in electrochemical cells.

Relevance

A dissertation is a scholarly essay, and mainly addresses colleague-researchers. In that function, the present study is focused on increasing the knowledge of teachers' conceptions concerning teaching electrochemical cells.

[5] Centre for Science and Mathematics Education, Department of Chemical Education, Utrecht University.

[6] He did so in 3 VWO and 3 HAVO. HAVO means higher general education. Students get three years of chemical education.

[7] He did so in 4 VWO.

Educational research has also an important social function: results of research are meant to contribute to educational change. Such a change is necessary, because, as I argued before, there are problems in the current educational situation. Also Matuschek (1987) argues that contributing to educational change is a task of educational research:

> "The most important goal of educational research should be to start from problems on education and offer possible solutions connected to these problems."[8] (Matuschek, 1987, p.419)

If more knowledge of the educational situation is available, this can yield solutions to classroom problems, curriculum problems and the development of teacher courses, both pre and in-service. Explanations concerning the causes of difficulties which occur with students, teachers and interactions between them, will hopefully lead to improvements.
Educational change is a process which should be conducted by those who are involved in education: teachers, textbook authors, syllabus developers, test constructors and teacher educators. If you want to change education, you need to be credible to the people who care about and carry out this education.
In this dissertation, I will try to address them as much as possible in a plausible, intelligible and fruitful way.

1.2 Nature

Type of research
Because this study concerns descriptions of teachers' conceptions, *qualitative research* is very attractive. Maso and Smaling (1990) argue that qualitative research is meaningful when the objective is to describe beliefs and reasonings of people in their complex reality. Moreover, results of qualitative research can be recognizable in actual practice for people such as teachers.
The present study will also be *explorative of nature*. This means that I search for backgrounds to conceptual difficulties of both teachers and students. In search for these backgrounds, statements of teachers are interpreted as indicators of their conceptions. Knowledge about these conceptions contributes to clarifying backgrounds of difficulties concerning learning and teaching of electrochemical cells.
Finally, the study will also be *developmental in nature*. I agree with Treffers (1993) and Gravemeijer (1993) that the studying of conceptions needs to take place in real educational situations, e.g. the lessons in which new student course material is being executed and the teacher courses in which introduction to and evaluation of the use of this material takes place. Subsequently, this material should be evaluated and adjusted

[8] My translation of: "Grundsätzliches Ziel der Didaktik muß es sein, direkt von den Problemen des Unterrichts auszugehen und daran anknüpfend konkrete Lösungsmöglichkeiten anzubieten."

on the basis of the experiences in the real educational situation. If the whole process is done in cycles, it can be called developmental research.

Type of teacher education

I chose to study chemistry teachers' conceptions and their development within the framework of an in-service course. Experience of how to execute in-service courses has been gained in our research group (CSME).

De Vos (1985) reported about new student course material on the introduction to corpuscular theory in a chemical context. At first, only he and a colleague worked with the student material. They exchanged their experiences with the material in their respective classes, and used these experiences for the evaluation and adjustment of the material. His study is mainly developmental in nature as far as the student course material is concerned.

In addition, De Jong (1990) studied teachers' conceptions of teaching the topic of chemical calculations. A number of meetings were held, which were partly dedicated to discussions of draft versions of the student course material, partly to the exchange of opinions about and experiences with the final versions, and partly to teachers' reflections. He audiorecorded classroom discourses and teacher meetings. The meetings also served a research goal: collecting data about teachers' conceptions of education which posed problems in chemical calculations. His study is explorative of nature.

Van Driel (1990) did something similar, but he also confronted teachers with recorded discourses of groups of students in the classroom. In his research on the teaching of chemical equilibrium, he chose a design in which the posing of (educational) problems and teachers' discussions concerning these occupied an important place. The posing of problems refers to the fact that he confronted teachers with authentic written answers of groups of students and with transcribed classroom discourses. Teachers were invited to reflect on their own educational experiences and educational opinions. With this approach, he wanted to prepare teachers for the use of student course material in classes. This study is also explorative of nature.

The three above-mentioned courses principally focused on the conceptual development of students concerning particular syllabus topics. Therefore, teachers needed to know how to work with new student course material. In addition, in my study, mainly *teachers' conceptions* in connection with conceptual development of students are focused upon, and the student course material is thus more a means to an end than a goal in itself.

In conclusion, two differences arise between the in-service course reported on in the present study and the three courses mentioned before.

First, I mainly study teachers' conceptions in the framework of an in-service course, whereas the main concern of the three courses mentioned before consisted of students' conceptions only.
Second, I also focus on new teacher course material, whereas the researchers mentioned before focused only on new student course material.

Two educational structures
I feel that it is important to study *both* teaching and learning in connection. Verdonk (1986) also argues that these two should be studied in connection with one another, but in his statement he still mainly focuses on student course material:

> "By studying learning and teaching in connection with each other as well as with learning contents and educational tools in the micro situation, a possibility is created to improve the development of learning programmes, exams and student course material ("bottom up" research). It is precisely this coherence which makes possible the development of matching structures for learning and teaching, which should be expressed in student course material and examinations."[9] (Verdonk, 1986, p.47-48)

In the present study, I focus on the conceptions of teachers in view of their learning in the teacher course as well as in their teaching in the classroom.
On the basis of educational research executed in such a way, so-called *educational structures* can be obtained. In such structures, the choice and the sequence of concepts is established on the basis of their learnability and teachability. In learnability and teachability, contexts play large roles: it is within contexts that concepts acquire meaning. Also existing conceptions of learners are of importance.

I call such a structure concerning the topic of electrochemical cells: *an educational structure of electrochemical cells.* In order to obtain such a structure, the search for relevant concepts concerning the topic of electrochemical cells demands attention.
Learning and teaching will be studied in coherence and in connection with the educational content. Not only criteria for the choice and the sequence of chemical concepts are developed, but also criteria for different parts of the educational situation, such as teaching activities. The educational structure concerning learning conditions which is thus developed, I call: *an educational structure of creating conditions for learning electrochemical cells.* I expect that this structure shall be developed from the results of both the student and the teacher course.

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[9] My translation of: "Door leren en onderwijzen in samenhang met elkaar en met leerinhoud en leermiddel in de micrositatie te onderzoeken, creëert men een mogelijkheid om de ontwikkeling van leerplannen, examens en onderwijsmateriaal te verbeteren ("bottom up" onderzoek). Juist deze samenhang maakt de ontwikkeling mogelijk van op elkaar passende structuren voor leren en onderwijzen, tot uiting komend in leermiddel en in toetsing."

Both structures will be based on empirical research as well as on accompanying reflection on the educational content of both existing and new courses, for teachers as well as for students.
This study took place within the limiting conditions of the current educational situation. These conditions, such as limitations which follow from syllabi and exam programmes, are not merely accepted, but also become object of investigation.

1.3 Design

Research issue
In section 1.1, it was mentioned that there were difficulties concerning the learning and teaching of the topic of electrochemical cells. It became clear that as far as chemistry teachers are concerned, not much research has been done concerning the nature of their difficulties, and insight into the backgrounds of their conceptual difficulties is lacking so far. The already existing teachers' conceptions influence both the development of chemistry students' conceptions and the creating of learning conditions by the teachers.
Because I want to design the two previously mentioned educational structures, new courses for students as well as for teachers are necessary. However, few criteria for designing these courses are available. For that reason, the research issue of my study can be formulated as follows: *what is missing is an educational structure of electrochemical cells, both for a teacher and a student course. Also, an educational structure of creating conditions for learning electrochemical cells is missing.*

Two parts
The study comprises two parts: a part which concerns *current teaching* of electrochemical cells, and another part which concerns cycles of a *new* teacher course. Two cycles of teacher course were executed.
In the first part of the study, current educational situations concerning teaching and learning of the topic of electrochemical cells were studied. In this case study, some teachers were observed in their own classroom while teaching the topic of electrochemical cells. Lessons were audiorecorded and the recordings were transcribed. Subsequently, these transcripts were analysed in order to describe *existing teachers' conceptions* in relation to those of the students. They were also used to create a list of electrochemical key concepts.
Also on the basis of the results of the first part of the study, the first courses both for students as well as for teachers were developed. A number of teachers took part in the teacher course and executed the student course in their own classrooms. Audiorecordings were made of teacher course meetings and of lessons taught by these teachers. These recordings were transcribed and both kinds of transcripts were

analysed. The analysis of the first cycle mainly focused on *teachers' conceptions concerning key concepts.*
Also on the basis of the results of the first cycle, the second versions of the courses were developed. A number of other teachers took part in the second teacher course, and executed the second student course in their own classrooms. Again, audiorecordings were made and transcribed, and the transcripts were analysed. The analysis of the second cycle mainly focused on *teachers' conceptions concerning creating conditions for learning key concepts.*

1.4 Contents

In chapter 2, I will focus on selecting concepts which are important in the development of understanding electrochemical cells. Subsequently, I will consider the selected concepts in three environments: the scientific history, the tertiary education and the current secondary education. I will pay attention to the contexts in texts in which the selected concepts are developed and described.

Subsequently in chapter 3, I will describe research results concerning current teaching of electrochemical cells. I will pursue this matter further while discussing teaching problems in current education and teachers' conceptions of these from the context perspective of chapter 2. Lastly, I will discuss possible backgrounds of the teaching problems described from two other perspectives.

Then in chapter 4, I will describe concepts which are important for this study. As such, I will examine the meaning of conceptions, and their development. Also, I will go into a model of learning conditions. In doing so, I will give my criteria concerning the design of a teacher and a student course.

In chapter 5, the design of the two cycles of teacher course will be described. In this chapter, the central research questions will receive attention, as well as the method of research. Subsequently, both versions of the teacher course are described. These descriptions include both versions of the student course material.

In the chapters 6 up to and including 8, detailed descriptions of empirical research results will be given obtained from the new teacher and student course. The chapters are titled:
* teaching the concepts of electron transfer and transport (chapter 6);
* teaching the concept of ion transport (chapter 7);
* teaching the concept of potential difference (chapter 8).

The results concern teachers' conceptions and teaching problems. The results concerning the teaching of the four concepts will be presented in the same sequence as the concepts have come up in the student course material.

The report will be wound up with a chapter in which a summary is given of this thesis. Also, an educational structure of electrochemical cells is outlined and suggestions for an educational structure of creating learning conditions for learning electrochemical cells are given. Finally, this study is evaluated and suggestions for further research are mentioned (chapter 9).

Chapter 2

Electrochemical cells: concepts and contexts in texts

As this study discusses the conceptions which teachers have concerning the teaching of electrochemical cells, this chapter will provide an overall description of what I mean by this topic.
I will start by selecting some electrochemical concepts, describing the concept of context, and selecting three environments (2.1). Subsequently, I will describe the development of the selected chemical concepts in the scientific historical environment in which different contexts are named (2.2). These contexts are evaluated as instruments for describing the concepts in tertiary educational textbooks (2.3). Within the secondary educational environment, relevant documents are studied concerning the use of contexts in describing the selected concepts (2.4). The chapter will be concluded by a discussion of the meanings of the selected concepts and the named contexts (2.5).

2.1 Contexts in different environments

Four selected concepts
Teachers derive the meaning of the concepts which they teach to a considerable extent from the university textbooks which they used during their preparatory training.
Descriptions of the topic of electrochemical cells can be found, for instance, in physical chemistry textbooks. A well-known and frequently used physical chemistry textbook describes an electrochemical cell as follows:

> "The basic apparatus is an electrochemical cell (...) A cell consists of **two electrodes, or metallic conductors**, in contact with **an electrolyte, an ionic conductor** (which may be a solution, a liquid, or a solid). An electrode and its electrolyte comprise an

> electrode compartment. The two electrodes may share the same compartment. If the electrolytes are different, the two compartments may be joined by a salt bridge, which is a concentrated electrolyte solution in agar jelly that completes the electrical circuit and enables the cell to function. (...) A galvanic cell is an electrochemical cell that produces electricity as a result of the spontaneous reaction occurring inside it. (...) A **redox reaction is a reaction in which there is a transfer of electrons from one species to another.** The reducing agent (or 'reductant') is the electron donor and the oxidizing agent (or 'oxidant') is the electron acceptor. (...) In an electrochemical cell the reduction and oxidation processes responsible for **the overall reaction are separated in space: one half-reaction takes place in one electrode compartment and the other takes place in the other** (...). As the reaction proceeds, the electrons released in the half-reaction (...) travel through the external circuit and re-enter the cell through the other electrode. (...) The work that **a given transfer of electrons can accomplish depends on the potential difference between the two electrodes.**"[1] (Atkins, 1994, p.324, 326, 330, 331)

I have analysed this extract from the point of view of the educational concept of the three-dimensionally unfolding of reactions (section 1.1). For that reason, I opted for a number of particular concepts. In doing so, I was also inspired by the results of the analysis of the current teaching. The following concepts were selected by me:
* *Electrolyte*, which indicates an ionic conductor in the previous quotation.
* *Electrode*, which indicates a metallic conductor in the previous quotation.
* *Electrode reaction*. In the quotation, this concept arises in terms of a half reaction separated in space from another half reaction. Although I realize that the term electrode reaction is not used in this quotation, I still want to use it. I feel that the term half reaction is unsatisfactory because this term is also used to describe a direct redox reaction which is not separated in space, in an analytical way on paper. Because of the importance of the location criterion, I prefer to use the term electrode reaction.
* *Potential difference*, which refers to the work potentially done by a transfer of electrons in the previous quotation.
I will focus on these four concepts for the remainder of this thesis.

Different contexts
The knowledge which teachers and students have of these four concepts is influenced by the contexts in which they give meaning to these concepts. I agree with Van Keulen (1995), who describes his meaning of concepts in context as follows:

> "The meaning of knowledge thus does not come from the things in themselves, but from the context in which things are experienced. *A context is a whole of entities that give meaning to each other*, in the widest sense." (Van Keulen, 1995, p.42).

In view of the interest of this coherence, I shall also have to indicate contexts, and give a justification for using them in the new courses. For the purpose of indicating these

[1] (...) means that a fragment has been left out by me. Bold print in this quotation is mine. Both kinds of representation apply also to the other quotations in this chapter.

contexts, I will study the meaning of the selected concepts in three different environments: the scientific historical, the tertiary educational and the secondary educational environment.
The four concepts were originally developed in a scientific environment, before they were taken over in education. However, in this process a change in meaning has taken place, during the process from development of a concept in a scientific environment to the adoption of that concept in an educational environment (e.g. Joling et al., 1990).

Three environments
As mentioned before, I will distinguish between three environments: the scientific historical, the tertiary educational and the secondary educational environment.
First, I will describe the four concepts in the contexts in which they receive meaning in the scientific historical environment, and I will describe as well as name these contexts. I will also describe the sequence of the contexts.
For the second environment, the tertiary education, I will see whether the concepts in tertiary texts can be described in a systematic way by means of the named contexts. In this environment, existing teachers' conceptions can become visible.
For the third environment, the secondary education, relevant documents will be studied concerning the use of contexts in the descriptions of the four concepts. In this environment, existing conceptions of students as well as teachers may become apparent.
The concepts could have another meaning when the three environments are compared. Also, the sequence of the contexts in concept development could differ for each environment, which is interesting for course development.

2.2 Scientific historical environment

The historical facts which are important for the understanding of the meaning(s) of the four concepts are mainly taken from publications of Ihde (1984), Brock (1992), Knight (1992) and Nye (1993). The interpretations of these facts are my own.
I describe the meaning of the four concepts starting from the beginning of the nineteenth century, because during that period much research was done, mainly by Faraday, Davy, Von Grotthuss and Berzelius. Before that, of course, there were others who were important, like Galvani and Volta.

The concept of electrolyte
Faraday devised a number of terms, one of which was the term of electrolyte in 1833. With this term he indicated certain current conducting substances (viz. substances

which decompose when electrical current is passed)[2]. During a period of cold weather, Faraday observed that the flow of electricity stopped when a film of ice had formed on the electrode, and he concluded that ice is a non-conductor. Extending this observation, he found that substances like lead chloride, though non-conductors in the solid state, became conductors when melted. Using copper and platinum electrodes, a current was produced when the electrodes were immersed in molten salts. Faraday proved that pure water was a very poor conductor, and that the capacity of water for conducting immediately increased when soluble salts were added.
Hittorf studied the electrolysis of salts in solution in the 1850s and he interpreted that the current was presumably carried through the solution by ions[3] which moved towards the electrodes at a different speed (Botsch, 1993). Kohlrausch showed in 1874 that every ion has a characteristic mobility regardless of whatever ion it was associated with in the original salt.
Arrhenius studied the behaviour of salts, acids and bases in connection with electrochemistry. He postulated that salt molecules dissociate when they dissolve in water. He used the term ions for this kind of sub-molecular particles. Arrhenius not only professed a belief in the existence of ions, but also suggested that they were formed when the salt dissolved in water. Thus, he disagreed with Faraday, Hittorf, Kohlrausch and others who believed that ions were produced only at the moment that current began to flow. The ionic theory of Arrhenius was published in 1884[4]. It was thanks to Ostwald that the dissociation theory of Arrhenius was accepted so fast. His dilution law makes up a large part of the ionic theory. In 1923, Debije and Hückel developed a corpuscular theory about the relation between activity coefficients and ion strengths.

In my opinion, the concept of electrolyte is initially mainly developed in a phenomenological context. I call a context a *phenomenological context* when phenomena are interpreted in terms of properties (cf. Faraday). The concept of electrolyte finally mainly acquires meaning in a corpuscular context. I call a context a *corpuscular context* when phenomena are interpreted in terms of corpuscula (cf. Arrhenius, Debije and Hückel).

The concepts of electrode and electrode reaction

Faraday's research into electrolysis led him to suspect that there was a quantitative relationship between the amount of substance decomposed and the quantity of current

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[2] Faraday introduced the term electrolyte together with Whewell (Ihde, 1984, p.136).

[3] Here Hittorf used the term which Faraday had introduced for the particles discharged at the electrodes *during* electrolysis.

[4] Ion transport was apparently described earlier on particle level than electron transport. The electron was not discovered until 1897 (Stock, 1995).

that passed through the solution[5]. His work proceeded smoothly after he developed the coulometer, as it has commonly been known since 1902. The oxyhydrogen coulometer was simply an electrolytic cell, designed in such a way that the gases which evolved during decomposition of water could be collected separately or mixed. In this way, the quantity of electricity which caused the liberation of 1 gram of hydrogen could be studied in relation to the ability of that quantity of electricity to cause decomposition in cells placed in series with the coulometer. Faraday proved that the size and the number of plates in the cells made no difference, nor did the dimensions of the electrodes or the distance between them. He was able to demonstrate that the quantity of electricity which liberated 1 gram of hydrogen, liberated other substances in an amount equal to the chemical equivalents of those substances[6]. Due to the stoichiometry, this discovery had a more immediate impact on chemistry than on physics.

In 1805, Von Grotthuss developed a popular explanation for current passage, which was based on alternating decomposition and recombination of *particles* in the electrolyte. For example, with the electrolysis of water the negative pole attracts a hydrogen particle from a nearby water particle. Subsequently, the isolated oxygen particle deprives the next water particle of its hydrogen and so on, until the last oxygen particle is released at the positive pole.

In 1812, Berzelius also came up with an explanation of current passage, the so-called dualistic theory. He postulated *electrical links* between atoms, which would mean that atoms which are alike must repel each other and combine only with opposite atoms, making molecules like O_2 impossible. In his theory, Berzelius assumed that chemical and electrical attraction are identical. He assumed that atoms were electrically charged because compounds decomposed as a result of electrical current, and that the elements freed in this manner were formed at one of the poles. Also, he assumed that atoms showed polarity, with positive or negative polarity dominating in different atoms. He took oxygen to be the most electronegative element. Metals he usually considered electropositive. Chemical combination he saw as the result of mutual neutralization of

---

5 "Faraday's own words are: "The chemical power of a current of electricity is in direct proportion to the absolute quantity of electricity which passes." (Faraday's Experimental Researches in Electricity, Everyman's Library.) At that time (1833) the distinction between quantity of electricity and electrical energy was not clearly drawn. As a result Faraday's law was severely criticized by some of his contemporaries, especially by Berzelius, who could not believe that the same quantity of electricity would separate the constituents of different compounds having different amounts of energy associated with their formation. However, as will be seen later in this book, the energy changes associated with different electrochemical reactions can have very different magnitudes, even though the same *quantity* of electricity is involved, since the electrical energy depends on the potential difference as well as on the quantity of electricity." (MacInnes, 1961, p.24)

6 The discovery that a given quantity of electricity liberates elements from their compounds in amounts that are proportional to their equivalent weights, was made independently by the Italian Matteucci (Ihde, 1984, p.138).

opposite charges. The formed compound need not be neutral because the opposite charges are not always the same. Also, because the atoms show polarity they can be negative with respect to one element and positive with respect to another.

In 1833, Faraday devised the term of electrode[7]. By this, he meant an object at which reactions occur. He was never convinced that the electrodes attracted any portion of the electrolyte. In order to avoid a term which implied polarity or attraction, he replaced pole with electrode.

Von Helmholtz also held certain ideas about the way in which electrode reactions occur. He associated himself with a theory of electrical "particles" which stated that the ions produced in electrolysis carry discrete and indivisible "atoms of electricity" which are independent of the elementary substance with which they combine. In the 1890s, electrolysis and solution theory were also Nernst's point of entry into ionic and electronic theories in chemistry. Nernst took up Von Helmholtz's conception, and used the word "electron" for Von Helmholtz's "atom of electricity". However, the difference between them was that Von Helmholtz was concerned with amounts of substances, whereas Nernst was concerned with concentrations.

In my opinion, the concepts of electrode and electrode reaction are initially mainly developed in a measure context. I call a context a *measure context* when properties are interpreted in terms of quantities (cf. Von Helmholtz). I consider a measure context to be part of a phenomenological context. Finally, both concepts mainly acquire significance in a corpuscular context which is initially connected with an electrostatic context. I call a context an *electrostatic corpuscular context* when phenomena are interpreted in terms of charged corpuscula which attract and repel each other (cf. Berzelius).

The concept of potential difference

In his lecture "Über die Erhaltung der Kraft"[8], published in 1847, Von Helmholtz emphasized the equivalence between the electromotive force and reaction enthalpy. Unfortunately, the theory corresponded only within certain limits to the measured values in the experiments he subsequently executed. Because of this, Von Helmholtz and Gibbs introduced Gibbs free energy, which they called 'free reaction enthalpy'.

Nernst completed this theory around 1890. Von Helmholtz had measured the electromotive force of concentration series, and from this Nernst calculated the dependence of the electrode potential on the concerned concentrations. In his theoretical interpretation, Nernst assumed that an equilibrium was established between the solution pressure of the electrode material and the osmotic pressure value of

[7] Faraday devised the term *electrode* together with Whewell (Ihde, 1984).

[8] My translation in English: "On the Conservation of Energy".

relevant ions in the solution. The Nernst equation represents the dependence of the electrode potential of concentrations[9]. Nowadays, the Nernst equation can be derived by means of the change in the thermodynamic potential and the amount of charge transfer, but then it is a relation between (voltaic) potential and activities.

In my opinion, the concept of potential difference is initially mainly developed in a measure context and has finally become part of a thermodynamic context. I call a context a *chemical thermodynamic context* when phenomena of reaction and phase transition are interpreted in terms of changes in state quantities.

Conclusion

I have been able to distinguish several contexts in the development of the four concepts in the scientific historical environment. Descriptions and names of these contexts were given in the previous parts of the section. In my analysis, all four concepts were developed in at least two successive contexts (see table 2.1).

The *context sequence* of the development of the concepts of *electrolyte, electrode and electrode reaction* is from an initially mainly *phenomenological* context to a *corpuscular* context. The *context sequence* of the development of the concept of *potential difference* is from an initially mainly *measure* context to a *chemical thermodynamic* context. In these context sequences, the development of the natural sciences is being reflected.

Table 2.1
Development of concepts in contexts in the scientific history[10]

	Concept * Electrolyte	* Electrode	* Electrode reaction	* Potential difference
Context				
- Phenomenol.	+	+	+	
	↓	↓	↓	
- Measure	+	+	+	+
	↓	↓	↓	↓
- Electr. Corp.	+	+	+	
	↓	↓	↓	↓
- Corpuscular	+	+	+	+
				↓
- Chem. Therm.				+

[9] Nernst was also the person who proposed to take the hydrogen electrode as a reference, equating it with the value zero (Botsch, 1993).

[10] A "+" indicates that the context could be pointed out. An arrow indicates the main sequence of the contexts.

It is interesting to study whether the named contexts can be used for describing the four concepts in educational texts in a systematic way. I will do so first for the tertiary education (2.3), and then for secondary education (2.4).

2.3 Tertiary educational environment

Document choice

In this section, I will report on the analysis of some relevant documents concerning tertiary chemistry education. In order to be able to do so, I analysed two kinds of textbooks which are relevant to this topic: electrochemistry and physical chemistry textbooks. The electrochemistry textbook which I looked at, is a textbook by Bard and Faulkner (1980)[11]. The physical chemistry textbook is by Atkins (1994).

The concept of electrolyte

In both textbooks, the concept of electrolyte is described as follows:

> "We are constantly concerned with the processes and factors affecting the transport of charge across interfaces between chemical phases. Almost always, one of the two phases contributing to interface of interest to us will be an ***electrolyte***, which is merely **a phase through which charge is carried by the movement of ions. Electrolytes** may be **liquid solutions, or fused** salts, or they may be **ionically conducting solids**, such as **sodium β-alumina, which has mobile sodium ions.** (...) Since the **ionic strength** affects the **activity coefficients**, $E^{o'}$ will vary from medium to medium." (Bard & Faulkner, 1980, p.1, 2, 52)
> "For dilute solutions of non-electrolytes (...) it is generally safe to make the approximation that **solute activities can be replaced by their molalities** (...) However in **ionic solutions, the interactions between ions are so strong** that this approximation is valid only in very dilute solutions (...) and, in precise work, **activities themselves must be used** (...) **an electrolyte, an ionic conductor (which may be a solution, a liquid, or a solid).** An electrode and its electrolyte comprise an electrode compartment. (...) If the electrolytes are different, the two compartments may be joined by a **salt bridge**, which is **a concentrated electrolyte solution in agar jelly** that completes the electrical circuit and enables the cell to function." (Atkins, 1994, p.319, 324)

In my opinion, in both textbooks, the concept of electrolyte is described in a phenomenological context (e.g. liquid solutions). This context is *mixed* with a corpuscular context (e.g. movement of ions). Also, the concept of electrolyte is described in a chemical thermodynamic context, because 'activities' are taken into account.

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[11] This edition of the textbook of Bard and Faulkner (1980) is still in use at Utrecht University; no new edition has been published so far.

The concept of electrode

In the two textbooks, the concept of electrode is described as follows:

> "The second phase at the boundary might be another electrolyte, or it might be an ***electrode***, which is a phase **through which charge is carried by electronic movement. Electrodes** can be **metals or semiconductors**, and they can be **solid or liquid.** (...) For a pure phase at **unit activity** (e.g., solid Zn (...)." (Bard & Faulkner, 1980, p.2, 60)
>
> "A cell consists of **two electrodes, or metallic conductors** (...) An electrode and its electrolyte comprise an electrode compartment. The two electrodes may share the same compartment. (...) In each case we have used the fact that **the pure metal (...) has unit activity** (...) As the reaction proceeds, **the electrons** released in the half-reaction (...) **travel through the external circuit and re-enter the cell through the other electrode.**" (Atkins, 1994, p.324, 325, 326)

In my opinion, in these textbooks, the concept of electrode is described in a phenomenological context (e.g. metals). Again, this context is *mixed* with a corpuscular context (e.g. electronic movement). Also, the concept of electrode is described in a chemical thermodynamic context (e.g. pure metal (...) has unit activity).

The concept of electrode reaction

In both textbooks, the concept of electrode reaction is described as follows:

> "Two types of processes occur at electrodes. One kind comprises those just discussed, in which **charges (e.g. electrons) are transferred** across the metal-solution interface. This electron transfer causes oxidation or reduction to occur. Since these reactions are governed by Faraday's law (i.e., **the amount of chemical reaction caused by the flow of current is proportional to the amount of electricity passed**), they are called *faradaic* processes. (...) Assume also that the extent of the reaction is so small that **the activities** of all species remain unchanged **during the experiment.**" (Bard & Faulkner, 1980, p.6, 47)
>
> " We shall often find it useful to express the composition of an electrode compartment in terms of **the reaction quotient Q for the half-reaction.** (...) In this final chapter of the text we examine one more example of chemical change, that of the **transfer of electrons at electrodes**" (Atkins, 1994, p.325, 1007)

I think that here the concept of electrode reaction is described in a corpuscular context (e.g. electrons are transferred). In the electrochemistry textbook, a measure context can be indicated (e.g. the amount of chemical reaction caused by the flow of current is proportional to the amount of electricity passed). Also, the concept of electrode reaction is described in a chemical thermodynamic context in the two textbooks (e.g. the reaction quotient Q for the half-reaction).

The concept of potential difference
In the textbooks, the concept of potential difference is described as follows:

> "In general, there is a **measurable difference in potential between the two electrodes** whether the cell is passing a current or not. (...) Thus the **measurement and control of *cell potentials*** (the difference in potential across the electrodes of a cell) is one of the most important aspects of experimental electrochemistry. (...) Our goal is to understand how potential differences are established and what kind of chemical information can be obtained from them. At first, these questions will be **approached through thermodynamics.** That attack will show that **potential differences are related to free energy changes** involved in processes that may occur in an electrochemical system" (Bard & Faulkner, 1980, p.2, 44)
> "The bulk of the chapter is concerned with the **description of the thermodynamic properties of reactions** that take place in electrochemical cells, in which, as the reaction proceeds, it drives electrons through an external circuit. We shall see that **thermodynamic arguments can be used to derive an expression for the electric potential of such cells and that the potential can be related to their composition.**" (Atkins, 1994, p.311)

In my view, it is only in the electrochemistry textbook that the concept of potential difference is described in a measure context (e.g. the measurement and control of cell potentials). This context is *mixed* with a chemical thermodynamic context (e.g. potential differences are related to free energy changes). In the physical chemistry textbook, the concept is described mainly in a chemical thermodynamic context, but with a possibility for a measure context (e.g. thermodynamic arguments can be used to describe an expression for the electric potential and composition measurements are mentioned).

Conclusion
From the analysis, it appears that it is possible to use the named contexts. The electrostatic corpuscular context, indicated in the scientific historical environment, is not mentioned in the two textbooks. The remaining contexts are used to describe the four concepts in a systematic way in two tertiary educational texts (see table 2.2).

According to my analysis, *context mixing* can be pointed out in both texts.
For the concepts of electrolyte and electrode, there is a mix of the phenomenological context and the corpuscular context. For the concept of electrode reaction the *context sequence* has changed when compared with the sequence in the previous scientific environment: in the textbooks, the sequence is from a corpuscular context to a measure context instead of the other way around. For the concept of potential difference, the books use a mix of the measure context and the chemical thermodynamic context.

Table 2.2
Description of concepts in contexts in the tertiary education[12]

	Concept * Electrolyte	* Electrode	* Electrode reaction	* Potential difference
Context				
- Phenomenol.	+	+		
	↕	↕		
- Corpuscular	+	+	+	
			↓	
- Measure			+	+
				↕
- Chem. Therm.	+	+	+	+

The question is whether and how the contexts are used in the description of the four concepts in relevant documents concerning secondary education. It is also interesting to see whether changes in the relations between the contexts can be indicated, and whether contexts appear or disappear.

2.4 Secondary educational environment

Document choice

Three kinds of documents are important for secondary education: exam programmes, syllabi and textbooks (see section 1.1). In this section, syllabi and textbooks are considered, because I want to look at *concepts in relation with contexts*. In exam programmes, it is almost impossible to indicate contexts.

I will look at the chemistry syllabus for VWO which is in use at this moment (O&W, 1984). Also, I will look at the most common textbooks for the Netherlands. A textbook can be considered as a syllabus which is made operational. During the period the research was executed (1991-1995), two chemistry textbooks were most often used for 5 VWO. These are entitled: 'Chemie' (Smilde et al., 1985) and 'Chemie Overal' (Reiding et al., 1986)[13].

[12] A "+" indicates that the context could be pointed out. An arrow indicates the sequence of the contexts. An arrow with two directions indicates a mix of contexts. The represented sequence of the contexts differs from those in table 2.1. Finally, the electrostatic corpuscular context has disappeared when compared with table 2.1.

[13] During this research, from both textbooks a revised edition has been published. For 'Chemie': Pieren et al., 1992, and for 'Chemie Overal': Reiding et al., 1993. There are not many relevant differences between the subsequent editions for the topic of electrochemical cells. Most teachers used the editions mentioned in the text during the period of this research.

The generally used syllabus

The syllabus for 5 VWO (O&W, 1984) contains among other things the topic of 'Reductants and Oxidants' which is subdivided as follows (see table 2.3).

Table 2.3
Topic sequence in the current syllabus under the header 'Reductants and Oxidants' (O&W, 1984)[14]

a. Redox reactions
*predicting and verifying with the help of a table of oxidant and reductant strengths, formulating of reaction equations, applications such as preparing lead
b. Electrochemical cells
*connecting reductant and oxidant via an electrolyte, standard potentials, cell notation, calculating the electromotive force with the help of standard potentials, applications such as building a lead accu
c. The law of Nernst
*measuring concentrations, ion selective electrode, applications such as influence of ion concentrations on electromotive force
d. Corrosion
*protection methods, applications such as galvanizing
e. Electrolysis
*electrode reactions, charge transport, inert and non inert electrodes, applications such as energy use in the production of aluminium

From this table, I conclude the following concerning the four concepts.
The concept of electrolyte is mentioned once: in the topic of electrochemical cells as a connection between reductant and oxidant. The concept of electrode comes up twice: in the topic of Nernst's law as ion selective electrode, and in the topic of electrolysis as inert and non-inert electrodes. The concept of electrode reaction comes up once: in the topic of electrolysis. The concept of potential difference is not mentioned as such. But the electromotive force is mentioned once: in the topic of electrochemical cells as a means of calculating the electromotive force with the help of standard potentials.
Compared with the previous syllabi (see section 1.1), the current syllabus is more specific, and also gives more directions for teaching. Besides, the topic sequence has changed and so has the context sequence. For example, in previous syllabi, the topic of electrolysis was mainly connected with the aspect of preparing substances, actually in a phenomenological context, and after this in a mainly corpuscular context. In previous syllabi, the topic of electrolysis was always mentioned at the start. In the current syllabus, the topic of electrolysis is mentioned last. Moreover, from the terms behind the asterisk concerning this topic (in table 2.3) it can be seen that the context sequence has changed. In the current syllabus, *the sequence is from a corpuscular context* (e.g. electrode reactions, charge transport) *to a phenomenological context* (e.g. aluminium production).

[14] This document includes some more terms, but I did not consider them relevant for my analysis.

The analysis of the interviews which took place during the period of teaching of the lesson series is related to how teachers described their motives and activities.
The analysis of the interviews which took place after the period of teaching of the lesson series is related to teachers' conceptions of the indicated teaching problems.

3.2 Teaching problems and use of contexts

Before I give the results concerning teaching problems and teachers' conceptions of them, I want to remark that both teachers used more or less the same method of teaching. They introduced new concepts and procedures by discussing illustrative examples, executing (demonstration) experiments which were mostly of an illustrative kind or delivering monologues about these. The examples and experiments were taken from their textbook. In addition, the teachers asked their students questions about the subject that came up. Besides, students had to answer a lot of questions from the textbook, individually or in small groups. At the end of each lesson series about one topic, a test was executed. In this test, students were to solve some problems of which the vast majority did not deviate much from the earlier exercises.
This observed method of teaching can be characterized as daily routine, both for students and teachers. The teachers stuck closely to their textbooks, both in contents and in sequence of topics. The teachers chose and decided which examples, experiments, assignments and exercises were done.

From the analysis results, it appeared that there were a number of teaching problems. For the orientation of the reader, I give my specification of the topics connected with these problems in table 3.2.

Table 3.2
Topics which are connected with teaching problems

* Electron transfer on distance
* Ion transport, salt bridge
* Corrosion
* Nernst equation, calculating the electromotive force

After this, I will present teaching problems with the above mentioned topics and illustrate them with transcripts of lesson fragments. I only describe teaching problems which came up more than once and with both teachers. Each presentation of a particular teaching problem will be closed off by comments of the teachers which I relate to that teaching problem. Hereafter follows a description of three important teaching problems:

After pretesting this method of recording, the lesson series on electrochemical cells taught by the two teachers was observed by me. All lessons were audiorecorded and I sat in on them and took notes. My interest was to observe what happened during the lesson (*observation notes*). The observations included copying everything which was written on the blackboard (*blackboard schemes*).

In view of answering the second question, I conducted some interviews with both teachers (table 3.1). The interviews were held individually, at the teacher's school, and consisted mainly of open questions. One kind of interviews took place during the period of teaching of the lesson series on electrochemical cells; the other right after that period.

At the interviews during the lesson series, questions were asked about preceding parts of lessons which, in my opinion, were unclear as to the objective the teacher had in teaching them. These questions were, for example, questions which asked for the teacher's motives for particular activities such as the skipping of particular exercises or experiments.

At the interviews right after the series, questions were asked about teaching problems which were indicated by me. For these, fragments of transcripts were used. My indication of teaching problems was based on the preceding analysis of transcripts of the lesson series.

The interviews were audiotaped and written out into *interview transcripts*.

Analysis

The lesson transcripts were analysed in view of their indication of teaching problems, for which observation notes and blackboard schemes were used as a support. All transcripts were read and analysed by two researchers, independently of each other.

The first step in the analysis was the acquisition of research material in which conceptual difficulties of students could be indicated.

The second step in the analysis was to relate as much as possible the indicated students' difficulties to teaching activities.

The final step in the analysis was to classify these activities in categories connected with the use of contexts.

The results of these first individual analyses were compared and discussed by the two interpreters. If a difference of meaning arose, a discussion took place until consensus was reached.

The interview transcripts were analysed in view of how teachers described their own motives and teaching activities and their conceptions of the teaching problems indicated by me. Also all interview transcripts were analysed by two researchers independently of each other.

In question 1, the term teaching problems is mentioned. Teaching problems are defined by me as teachers' use of contexts which, according to interpretations of the transcripts, causes difficulties for students in understanding concepts. I will now describe teaching problems by means of contexts, because they were useful for describing concepts in texts (chapter 2). Question 2 is asked for teachers' confirmation of the indicated teaching problems. In this question, the term conceptions is used. As indicators of their conceptions of the teaching problems I will take the teachers' comment(s) on these problems under consideration.

Design

In view of answering the first research question, I decided to study current teaching. With reference to this kind of teaching, I considered it most useful to audiotape lessons. Subsequently, I transcribed these into *lesson transcripts*. Because of the expected extent of the series of lessons, namely approximately 15-20 lessons for the topic of electrochemical cells, and the labour intensiveness of the method of transcript analysis, I decided to conduct this part of the study with the help of a limited number of experienced teachers, viz. two, of different schools[2] (table 3.1). These teachers each taught from a different, representative, textbook for 5 VWO, namely 'Chemie' (Smilde et al., 1985) and 'Chemie Overal' (Reiding et al., 1986). Together these textbooks are used by a large majority of the teachers in the Netherlands, approximately 70% (Kuiper & Alting, 1990)[3].

Table 3.1
Data concerning the two teachers

Teacher	***Textbook***	***Years in 5 VWO***	***Number of lessons on cells***	***Number of interviews***
T1	Chemie	12	19	3
T2	Chemie Overal	5	15	2

Because the objective was to record statements of teachers and dialogues of teachers and students, an audiorecorder with two microphones was placed on the teacher's table. One microphone was directed towards the classroom and the other towards the blackboard[4]. I chose this method on the basis of what I saw in current teaching and what I call 'frontal' teaching, i.e. the teacher explains things to the class as a whole and enters into discourse with individual students.

[2] The Christelijk Lyceum Dr. Visser 't Hooft (Leiden) and the Rijnlands Lyceum (Oegstgeest).
[3] Respectively 'Chemie' 49% and 'Chemie Overal' 22%.
[4] This method of making audiorecordings was pretested with a teacher who conducted a short series of lessons about redox reactions at the Revius Lyceum (Doorn).

Chapter 3

Problems and contexts in current teaching

I will start this chapter by describing the research questions and the design of this study of *current* teaching of electrochemical cells (3.1). Because of teachers' use of contexts, this part of the study was executed in real educational situations. Audiorecordings were made of lessons in current teaching as well as of interviews with teachers. These recordings were written out into transcripts and the transcripts were analysed. I will report on the analysis which resulted in descriptions of use of contexts and teaching problems (3.2). Furthermore, backgrounds of the teaching problems indicated will be discussed (3.3). Finally, I will go into the consequences for the further course of the research (3.4).

3.1 Research questions and design

Research questions

This part of the study, conducted in 1992, concentrated on problems concerning current teaching of electrochemical cells[1]. This part of the study centres around the following questions:

(1) What teaching problems can be indicated in current teaching of electrochemical cells?
(2) What conceptions of chemistry teachers can be described, when they are confronted with the indicated teaching problems after teaching?

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[1] On the nature of the teaching problems which teachers have with the topic of redox reactions is published elsewhere (De Jong & Acampo, 1994; De Jong et al., 1995).

The most commonly used textbooks

In this part of the section, I will describe and analyse the four concepts in relation to contexts in the relevant chapters in both 5 VWO textbooks. The sections which arise in the chapters of 'Chemie' and 'Chemie Overal' are mentioned in table 2.4.

Table 2.4
Sections in the chapters on electrochemical cells in the two textbooks

Chemie (Smilde et al., 1985)	***Chemie Overal (Reiding et al., 1986)***
1. Redox reactions on distance *salt bridge, electrochemical cell, half cell, ion current, electron current, electrolyte, electrode, voltage *2. Determination and calculation of electromotive forces* *potential diagram, reference electrode, standard electrode potential, cell diagram *3. Changes in the electromotive force* *Nernst equation *4. Electrical concentration determinations* *applications *5. Well-known electrical cells* *applications *6. Corrosion* *applications *7. Electrolysis* *voltage of electrolysis, applications	*1. Introduction and objectives* *2. Electrochemical cells* *half cell, salt bridge, emf, cell diagram, connecting electrolyte, standard electrode potential *3.Changes in the electrode potential* *Nernst equation, equilibrium constant *4. Electrochemical concentration determinations* *applications *5. Current sources* *applications *6. Corrosion* *applications, ion transport *7. Electrolysis* *counter voltage, applications *8. The production of aluminium* *applications

The concept of electrolyte

In 'Chemie', the concept of electrolyte is mentioned in the first section, and is described as a conducting substance, in most cases a salt solution, located between the oxidant and the reductant. Before this, a demonstration experiment concerning a galvanic cell is outlined. Subsequently, the equations for the occurring reactions in this cell are explained. Also, ion transport is pictured with the help of positive and negative ions and the directions in which they move. After this, a salt bridge is described.

In 'Chemie Overal', in the first section, a demonstration experiment concerning a galvanic cell is described. Although the electrode reactions are not represented in equations, in the accompanying descriptions the phenomena concerning these reactions are given. In a figure given in this description, the direction of the movements of only the positive ions in solution is indicated by arrows. After this, a description of a salt bridge is given in which the term electrolyte comes up for the first time.

In both textbooks, the concept of electrolyte is described as follows:

> "**The magnesium goes into solution. Mg^{2+} (aq) ions arise,** while at the same time electrons flow away through the magnesium ribbon and the connecting wire to the

> other electrode. In the tap water are now $Mg^{2+}(aq)$ ions without any negative ions as their opposites. That is of course not possible. These negative ions have to be supplied or the positive ions have to be removed. This **ion flow takes place via the salt bridge.** (...) a conducting substance in between, mostly a salt solution; **such a solution is called an electrolyte.**" (Smilde et al., 1985, p.118, 119)
> "Because the salt bridge is filled with a **(current conducting) salt solution,** it is indicated by the term of **'connecting electrolyte'.**" (Reiding et al., 1986, p.176)

The concept of electrolyte is introduced in a corpuscular context in the two textbooks (e.g. ion flow takes place; the indicated arrows in the figure). The direction of the ions is indicated in both textbooks, but what kind of ions they are comes up more explicitly in 'Chemie'. The corpuscular context is *mixed* with a phenomenological context, because the textbooks describe what phenomena take place (e.g. the magnesium goes into solution[15]; current conducting).

The concept of electrode

In 'Chemie', the concept of electrode is mentioned in the first section right after the description of the first demonstration experiment.
In 'Chemie Overal', a description of the concept of electrode is given in the first demonstration experiment.
In the two textbooks, the concept of electrode is described as follows:

> "**two bars** which can be connected with a connecting wire; mostly **carbon bars or platinum plates** are used, **so-called electrodes** (...) from the half reactions we see that **the electrode of zinc gives electrons to the connecting wire.** (...) The electrons reach the copper electrode via the connecting wire, where $Cu^{2+}(aq)$ from the solution accept them." (Smilde et al., 1985, p.119, 120)
> "A Daniel cell is built with the help of a copper strip in a beaker with 0,1 M $CuSO_4$ solution and a zinc strip in a beaker with 0,1 M $ZnSO_4$ solution. (...) During current delivery of the cell, **the zinc strip is going into solution** and **copper precipitates on the copper strip.** Argue in **what direction the electron flow moves.** (...) Which of **the two electrodes is the positive one, Zn or Cu?**" (Reiding et al., 1986, p.175, 176)

The concept of electrode is described in a phenomenological context (e.g. two bars; the zinc strip is going into solution[15]). This phenomenological context is *mixed* with the corpuscular context (e.g. the electrode of zinc gives electrons to the connecting wire; argue in what direction the electron flow moves (...) Which of the two electrodes is the positive one, Zn or Cu?).

The concept of electrode reaction

In both textbooks, the term of electrode reaction is not mentioned as such. The authors write about half reactions at the electrodes, in which a half reaction is considered as a process involving electron transfer. The concept of half reaction has already been

[15] This statement could be critisized: from a chemical point of view the metal reacts.

introduced in both textbooks in the previous chapters about direct redox reactions. There, a half reaction is used as a tool in order to balance redox reaction equations. In the two textbooks, the concept of electrode reaction is described as follows:

> "The reaction which occurs in this experiment is:
> **$2H^+(aq) + Mg(s)$ -> $H_2(g) + Mg^{2+}(aq)$**
> The reaction can be written as two half reactions:
> Mg -> $Mg^{2+} + 2e^-$
> $2e^- + 2H^+$ -> H_2" (Smilde et al., 1985, p.118)
> "This leads to the following half equations:
> $Br_2 + 2e^-$ -> $2Br^-$
> $2I^-$ -> $I_2 + 2e^-$
> **$Br_2(aq) + 2I^-(aq)$ -> $I_2(aq) + 2Br^-(aq)$**" (Reiding et al., 1986, p.147)

The concept of electrode reaction is described in a *corpuscular context* in both textbooks.

The concept of potential difference

The two textbooks jumble up the terms of electromotive force, voltage and potential difference. In the following description, I will use the term potential difference.

In 'Chemie', the concept of potential difference of an electrochemical cell is mentioned in the first section. In the second section, experiments concerning the measuring and calculating of potential differences are described. Below the descriptions of the experiments, the intended results and conclusions are given, viz. different combinations of half cells result in different values of potential difference. In the third section, a quantitative relation between potential difference and concentration is mentioned: the Nernst equation. After this, an experiment is described concerning the influence of ion concentrations on the potential difference, in which measured values and calculated values of potential differences are to be compared. These values can be calculated with the help of a table including half reactions and their thermodynamically obtained values of standard potentials (Binas, 1992).

In 'Chemie Overal', the concept of potential difference is defined after a description of two demonstration experiments concerning the measuring of potential differences. After these experiments, a quantitative relation between potential difference and concentration is mentioned: the Nernst equation. Then a lot of exercises follow which involve calculating values of potential differences with the help of the Nernst equation and the values of concentrations, and vice versa.

In both textbooks, the concept of potential difference is described as follows:

> "When a voltmeter is placed in the current circuit you **measure a voltage. The voltage which a voltmeter indicates** when a cell does not deliver current, is called the electromotive force of that cell." (Smilde et al., 1985, p.120)
> "**Both metal strips are connected via a voltmeter. The potential difference is read off**; this is the electromotive force of the cell. (...) The electromotive force of an

electrochemical cell is the potential difference between the electrode of the half cell with the strongest oxidant and the electrode of the half cell with the strongest reductant." (Reiding et al., 1986, p.175, 177)

The concept of potential difference is described in a measure context in the two textbooks (e.g. measure a voltage; the potential difference is read off). The measure context is *mixed* with a calculate context (e.g. exercises concerning calculating values of potential differences with the help of values of concentrations and the Nernst equation and vice versa). I call a context an *electrochemical calculate context* when calculations are done, based on measured values or tabulated values.

Conclusion

From the analysis, it appears possible to use the named contexts. Just like in the tertiary educational environment, it was not possible to indicate the electrostatic corpuscular context. Moreover, the chemical thermodynamic context could not be explicitly pointed out either, instead of this it is a matter of an electrochemical calculate context. The remaining contexts are used in order to describe the four concepts in the secondary educational environment in a systematic way (see table 2.5).

Again, it is possible to indicate *context mixing* in the texts.
The concepts of electrolyte and electrode are described in a mix of a corpuscular context and a phenomenological context.
In contrast with the other concepts, a mix is absent in the description of the concept of electrode reaction. This concept is mainly described in a corpuscular context.
The concept of potential difference is described in a mix of a measure context and an electrochemical calculate context.
Finally, no *context sequence* can be indicated in the secondary educational environment, because there is either a mix of contexts or only one context in which a concept is being described.

Table 2.5
Description of concepts in contexts in the secondary education[16]

	Concept * Electrolyte	* Electrode	* Electrode reaction	* Potential difference
Context				
- Phenomenol.	+	+		
	↕	↕		
- Corpuscular	+	+	+	
- Measure				+
				↕
- Electr. Calc.				+

2.5 Concepts in contexts

Contexts in texts

In the last two sections of this chapter, educational textbooks have been analysed. Other educational researchers consider textbooks important for teaching, just like myself (Gallagher, 1984; Hashweh, 1987; Yore, 1991; Gottfried & Kyle, 1992; Stinner, 1992). A vast majority of teachers use a textbook most of the time; hence the textbook becomes an outline of the students' course, its framework, the parameters for students' experience in testing and a world view on science (Yager, 1983). About the textbooks themselves, Stinner (1992) writes that most modern textbooks attempt to provide links between what is considered an "established scientific fact" of a topic and the concrete level of evidential and experiential support. But the finished product of "scientific fact" and mathematical formulation is emphasized in science teaching. Here, in my view, Stinner shows a lack of attention for a phenomenological context and emphasizes the attention for the calculate context with formulas. In textbooks, many topics are being practised with the use of exercise problems. Against that background, the correct solution of problems posed in exercises provides evidence to the teacher of the success of his teaching, and it gives the student a sense of confirmation of mastery and understanding of the subject matter, and these two confirm each other. Stinner (1995) pleads for incorporating contexts into teaching

[16] A "+" indicates that the context could be pointed out. An arrow with two points indicates a mix of contexts. The represented sequence of the contexts differs from those in table 2.1. Two contexts, viz. the electrostatic corpuscular and the chemical thermodynamic, have disappeared when compared with table 2.1. One new context, the electrochemical calculate context, has appeared when compared with table 2.1.

practice. If I interpreted his words correctly, he pleads for *development of student texts in which more explicitly attention is paid to contexts.* This is already taking place, but I aim for contexts to be *functional* contexts as to their learnability and their teachability.

Context sequence and context mixing

The four selected concepts are described and analysed by means of contexts. In doing so, the use of contexts can be indicated, viz. the context sequence and context mixing.
In the historical development, the concepts of electrolyte, electrode and electrode reaction initially acquired meaning in a mainly phenomenological context and finally in a mainly corpuscular context, and the concept of potential difference initially acquired mainly meaning in a measure context and finally mainly in a chemical thermodynamic context.
In the selected texts for the current tertiary educational environment, the context sequences, e.g. from a phenomenological context to a corpuscular context, become context mixes. This holds true for the indicated sequences for the concepts of electrolyte, electrode and potential difference. For the concept of electrode reaction, the sequence has been turned around, it is now from a corpuscular context to a measure context.
Context mixing can also be indicated in textbooks for the secondary educational environment, except for the concept of electrode reaction which is described in only one context, viz. the corpuscular context.
The change in meaning which according to Joling et al. (1990) takes place during the process from the development of a concept in a scientific environment to the taking over of that concept in an educational environment, is clearly visible. For example, for the concept of electrode reaction, the development in a context sequence of a phenomenological context to a corpuscular context changes in describing it in only one context, viz. the corpuscular context.

The use of contexts *in texts* may cause problems for the understanding of particular concepts by students. For example, mixing the corpuscular context and the phenomenological context may create difficulties for students in learning electrochemical concepts.
Also *teachers'* use of contexts can bring about problems for students. The next chapter is dedicated to descriptions of use of contexts in current teaching.

- emphasizing a particular context,
- mixing contexts,
- constructing contexts themselves.

The teaching problem of emphasizing a particular context

A teaching activity that caused students' non-understanding of a concept, can be formulated as the emphasis a teacher places on the meaning of a concept in one particular context, while ignoring the meaning of that concept in another context.
For example, both teachers emphasized the importance of the use of the Nernst equation in a calculate context. After presenting the Nernst equation, the teachers gave a number of calculation examples. Subsequently, they asked their students to solve a large number of arithmetical problems, in which the Nernst equation was to be applied. Finally, they discussed a number of analytical and societal applications of the Nernst equation (for example, some electrochemical concentration measurements). First doing calculations involving the Nernst equation as description of an electrochemical cell, and only afterwards talking of some applications of this equation appeared to cause problems for the students: the meaning of the Nernst equation in a measure context did not become clear. For this, see the next transcript:

Transcript 3.1:
The teacher puts the next equation on the blackboard: $Zn \rightleftarrows Zn^{2+} + 2e^-$. He asks what is going to happen when the concentration of Zn^{2+}-ions decreases. Subsequently, he says that a formula exists for calculating the potential.

01 T: *In the book you see logarithm oxidant concentration divided by ... in general we had better write down ... that the V is equal to the V_0 plus 0,059 divided by n, logarithm and does anyone get an idea when you see those two like this, Peter maybe ... what does it remind you of?*
02 S1: *Equilibrium*
(Subsequently, the Nernst equation is filled out for another reaction equation)
03 T: *Is there any question left? Hendrieke*
04 S2: *Yes, I do understand it, but I do not really understand it ... no I do not really know what it is you are calculating*
05 T: *Well look, what we calculate is ... or rather what you can calculate is the voltage of a half cell in which the concentrations are not one molar ... because as the concentrations are one molar you get the logarithm of 1 time 1 to the eightst divided by 1 ... with all before this, is logarithm of 1 and a logarithm of 1 is*
06 S2: *Zero*
07 T: *Zero, so that whole part can be dropped ... and then the V is equal to the V_0 which is in the table*
08 S2: *But what's the use of it?*
09 T: *What the use of it is is that you can now calculate for every other concentration than one molar what the voltage will be then ...*
10 S2: *Okay*
(end of discourse)

This lesson transcript[5] shows that a student runs into difficulties (stats. 04 and 08)[6], because she does not understand the concept of the Nernst equation. The teacher emphasizes the concept in only one context, namely the calculate context in which, in this case, voltages are being calculated. Although the student clearly wants an explanation in another context (stat. 04), the teacher continues to talk in the calculate context. He does not connect this context to the measure context.
Because teachers strongly emphasize the meaning of a new concept in a particular context, and ignore the meaning of that concept in another context, students experience difficulties understanding that concept.

Another teaching activity that caused difficulties for students is one in which there is insufficient paying attention to relevant meanings of a concept in different contexts.
For example, the teachers talked a lot about salt bridges in an electrochemical cell. In doing so they paid most attention to the meaning of closing the current circuit in a phenomenological context. However, the corpuscular context does not come into the closing of the current circuit: much less attention was paid to other meanings, for example to the fact that a salt bridge compensates differences in charge in half cells caused by electrode reactions. Although the teachers did mention that a salt bridge closes the current circuit (phenomenological context), they did not explain how a salt bridge does this (corpuscular context). An alternative for the salt bridge proposed by the students, a metal wire, was declared unsuitable by the teachers. The teachers did not explain why they thought a metal wire unsuitable instead of a salt bridge, although students did ask for this explanation. Because of the teachers insufficient paying attention to meanings of a salt bridge in other contexts, it became difficult for students to comprehend other meanings of this concept. The following transcript shows that the teacher talks continually about one meaning of a salt bridge, and that students are still left with questions.

Transcript 3.2:
During the first lesson about cells, the teacher executes the introductory experiment. He builds the following cell: $Mg(s)|H_2O(l)||H_2SO_4$ solution$|C(s)$, as described in the textbook. In first instance (in the first part of this transcript) without a salt bridge.
01 T: *So we have to make a current circuit (...) so what we have to do is to make a connection between these ... and we do so with a so-called salt bridge ...*
Nine lessons later the salt bridge comes up again.
02 T: *Between the one half cell and the other half cell there is always a salt bridge represented by these two thin lines, instead of a salt bridge you can have a porous septum*
03 S: *But also another wire?*[7]
The teacher does not answer this question. (end of discourse)

[5] An explication of the notation of the transcripts is given in Appendix A.
[6] Stat. means statement and stats. means statements, see also Appendix A.
[7] The term "another" refers, in my opinion, to the 'external' wire between the electrodes.

In this transcript, the teacher ignores the question of a student whether a metal wire can be used. The teacher could have answered that a metal wire is suitable to serve as a connection as to make current passage possible, but that there will be side-effects: electron transfer will occur at the metal-electrolyte surface when current passage takes place and this may be unwished for[8]. This would have been an answer in a corpuscular context. The teacher does not explicate his point of view to his students and does not present any arguments.

From a point of view of current passage, both the salt bridge as well as the metal wire can function. However, from a point of view of measuring potential difference or preparing, the metal wire is not acceptable as connection. Because of potential jumps or contaminations respectively. The teacher probably considers the matter from the point of view of measuring potential differences, and therefore he does not give the answer from the point of view of current passage.

One consequence of insufficient paying attention to the corpuscular context of a salt bridge could be that students do not grasp this meaning of current passage. The following transcript illustrates this conceptual difficulty of students:

Transcript 3.3:
The students try to solve a part of an exercise about an electrochemical cell. This part concerns the direction of the electron transport in the wire.
01 S1: *But isn't it possible along the bottom*
02 T: *Along the bottom?*
03 S1: *Yes instead of via that voltmeter ... yes I do understand that electrons always go from minus to plus, but they can also go via all those beakers, can't they?*
04 T: *In a beaker an electron cannot move ... in a beaker only ions move*
In the next lesson, the teacher returns to the topic of salt bridge.
05 T: *Martine, what is the function of the salt bridge?*
06 S2: *Transfer of electrons*
07 T: *The salt bridge doesn't have transfer of electrons*
08 S2: *Mmm ... ions*
The schoolbell rings and the lesson ends. (end of transcript fragment)

The student in the previous transcript imagines electron transport via the electrolyte, which is considered by the teacher in his definition of electrochemical cell an incorrect assumption in a corpuscular context. Probably, the student has an electrostatic corpuscular context: negative electrons are attracted by a positive electrode.

Summarizing, students experience difficulties in understanding the concept of the closing of a current circuit in an electrochemical cell. Probably, because the teacher describes the closing of the current circuit in a phenomenological context, and insufficiently pays attention to the corpuscular way in which this is being effected.

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[8] A metal wire closes the current circuit by means of electron transport and electron transfer. A salt bridge closes the current circuit by means of ion transport. At a salt bridge no half reactions will occur. However, a sequential direct reaction can take place if the salt in the salt bridge is not well chosen, e.g. KCl in a salt bridge and an electrode reaction where Ag^+ arises.

Because teachers do not sufficiently pay attention to relevant meanings of new concepts, students are not stimulated to think of the meaning of concepts in other relevant contexts.

The teachers had some comments on the indicated teaching problem of emphasizing a particular context. Concerning this problem, they said that the time available for teaching the topic of electrochemical cells was very short. Moreover, they said that as a consequence they emphasized new concepts only within that context which students were required to be familiar with at their final examinations. This is reflected for the electrochemical cell content in the following interview transcript:

> Transcript 3.4:
> During the interview the teacher was asked why he had skipped an exercise about the so-called 'air pollution detector'.
> 01 T: *I do not think this part is that important, it distracts from what is really important here, and that is working with Nernst's law in order to calculate these concentrations, and I enjoy exercising with solubility products*
> The answer was finished, another question was asked. (end of transcript fragment)

This teaching problem could also be indicated for other topics. See, for example, the next transcript in which the concept of corrosion is discussed:

> Transcript 3.5:
> During the interview the teacher was asked why he had said to his students that the textbook section on corrosion was a section they could read for general information, but did not need to learn.
> 01 T: *Such a part here, which is an application, well they may just read it as far as I'm concerned (...) but I believe it distracts too much at that point (...) look, and there is a part on applications at the end and there it would fit in, I think it is annoying at this moment ... I have the feeling you just have to stay in this substantial part and not digress again*
> The answer was finished, another question was asked. (end of transcript fragment)

Both teachers remarked that it might be better to try to deal with *more meanings of a concept, also in other relevant contexts.*
The teaching problem of emphasizing a particular context may also cause a weak relationship between meanings of a concept in education and in society.

The teaching problem of the mixing of contexts
A teaching activity which caused a lot of confusion for students concerning the understanding of a concept is the teachers' use of shortened terms and expressions when they talked about concepts[9].

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[9] See, for example, also the discussion on the use of terms, e.g. anode and cathode, in education by Haack (1976), Hondebrink (1976), Gerhartl (1976), Feis (1976), Kerbusch and Biezeveld (1976), Feis (1977) and Gerhartl (1977).

Most use was made of these kinds of terms and expressions when the teachers described substances or (charged) particles. They jumble up 'substance-terms' and 'particle-terms'. This is illustrated by the next transcript:

Transcript 3.6:
The teacher explains how the Daniel cell works with the help of the concepts of oxidant and reductant: Cu^{2+}-ions accept electrons, Zn-atoms give electrons away.
01 T: *It appears that copper arises and that the zinc goes into solution ... what now is the oxidant, Mark?*
02 S: *Receives them*
03 T: *Receives, so?*
04 S: *So ... zinc ... copper ...*
05 T: *Copper is the oxidant ... and so zinc is the*
06 S: *Reductant (...) but why, why, why is copper here the oxidant ... and not the other way around*
07 T: *(...) Zinc is glad to give away his electrons, copper appears not to do so, copper appears rather to take electrons on, here is ... mmm ... zinc the reductant, is a stronger reductant then the copper here, otherwise the reaction would be the other way around ...*
(end of discourse)

In the preceding transcript, the teacher jumbles up substance-terms and particle-terms while talking about zinc and copper.
When talking about zinc: in statements 01 and 05, it is unclear whether he talks in a corpuscular context or in a phenomenological context. In statement 07, he talks about zinc in a corpuscular context.
When talking about copper, the same occurs. First, he mentions copper in a phenomenological context (stat. 01), then in mixed contexts (stat. 05), and finally in a corpuscular context (stat. 07). Moreover, in statements 05 and 07, he uses an incorrect designation, he should have said copper two plus ions.
These kinds of teachers' descriptions caused a lot of difficulties for students. In statement 05, the teacher does not make clear whether he means copper or copper two plus ions. In statement 06, the student does not know why it is that the copper is the oxidant.

The teachers' comments on the indicated problems related to context mixing can be summarized as follows: some teaching activities have developed over the years into routines about which they do not think very often. See the next interview transcript:

Transcript 3.7:
During the interview, the use of shortened expressions in lessons is mentioned. The teacher was asked whether he thinks something should be done about this:
01 T: *I think we do not realize often enough that that is important, and we do not get confronted with this often enough ... maybe partly laziness*
Some remarks about students were made before going on with the next question. (end of transcript fragment)

Concerning their use of shortened terminology, teachers remarked that describing concepts and procedures in a shortened way was daily routine for them. *At the same time, they said that as teachers they should use adequate terminology for students.*

The teaching problem of teachers constructing contexts themselves

Two kinds of teaching activities which hampered students in constructing contexts themselves are elucidated in this part of the section.

A kind of teaching activity which did not help students to learn was the fact that teachers offered a lot of observations and interpretations themselves (Acampo & De Jong, 1993c). Teachers tended to make observations themselves, attribute colour changes and gas bubbles to particular substances participating in reactions, or give interpretations in corpuscular terms. See, for example, the next transcript:

Transcript 3.8:
The teacher demonstrates the electrolysis of an aqueous copper sulphate solution between graphite electrodes.

01 T: *Copper sulphate blue ... if everything is okay the copper two plus ions have to accept electrons at the minus pole ... and you see also something red arise ... that takes a while ... but now there is a faint film on it, so that is copper, that's at the minus pole, yes ... and at the plus pole again the water that reacts ... yes*

02 Ss: *Yes* (in a resigned tone)

(end of discourse)

Students are not stimulated to make their own observations and to give their own descriptions and explanations. In other words, constructing the phenomenological context by means of observations and constructing the corpuscular context by means of interpretations. Not being able to construct their own contexts does not motivate students (stat. 02). It appears that this approach of the teachers of expressing their own observations and interpretations, and giving students no opportunity to construct contexts, does not contribute to giving meaning to new concepts by students.

A second teaching activity which hampered students' learning is that teachers ignored students' reasonable alternatives for the meaning of a concept. Teachers tended to neglect student alternatives, for example concerning the descriptions and explanations of phenomena. Implicitly, the teachers selected information brought up by students, because they took notice of some alternatives and they dismissed others.

In the next transcript, a teacher introduces his meaning of a concept, at the expense of the student's alternative. The concept in this case is the concept of cell diagram or cell notation. A cell notation is a representation of a cell in a corpuscular context[10]. It is a somewhat reduced description, because not all kinds of particles are mentioned.

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[10] An example of such a cell notation is: $Zn(s)/Zn^{2+}(aq)//Cu^{2+}(aq)/Cu(s)$.

Transcript 3.9:
The following transcript is taken from the first lesson about electrochemical cells. The teacher is explaining what a cell diagram is with the help of the Daniel cell.

01 T: *Cell diagram of a Daniel cell looks as follows, first a zinc electrode (...) then a bar to show what, which ions are in the solution, these are* Zn^{2+} *ions (...) then we get the salt bridge (...) represented by a double bar ... then come the ions which are important in the solution of the second part of that cell, that is ... copper and then the material of which the electrode is made, so first again a bar and then copper solid, this is the so-called cell diagram of the Daniel cell ... yes*

02 S: *But why not first the copper solid, then the* Cu^{2+} *and then ...*

03 T: *Because I start from a situation like this one and then I look, from the negative electrode I go to the positive electrode, thus first here zinc, then the solution, then the salt bridge, then the solution and then ... yes*

(end of discourse)

This transcript shows that the student wants to describe parts of the cell in another sequence in the cell diagram than the teacher (see also Acampo & De Jong, 1993a). The student wants to know whether the sequence can be the other way around, with other words does it matter with which electrode the cell diagram is started. The teacher wants to start with the negative electrode and to finish with the positive electrode[11]. The teacher erroneously rejects the student's alternative. The teacher states that only his own method is acceptable, but he does not say why (stat. 03). The student is not given a reason why his alternative is being rejected. The teacher does not think this necessary, probably because he is the expert, and thus he is the one to decide.
The approach of teachers to reject alternatives from students which are reasonable in students' view, without giving arguments for this rejection, does not stimulate students to develop alternative ideas and suggestions. New concepts, in this case the cell diagram, do not become meaningful for students in this way.

Teachers' comments on the indicated teaching problems which are related to the construction of contexts by teachers themselves, reflected two kinds of arguments.
Concerning the activity of formulating observations and explanations by teachers, they remarked that it had become a habit to offer students their own observations and explanations. They connected this habit to the amount of time available. See the next interview transcript:

Transcript 3.10:
During the interview, the teacher was asked why he did not give his students the opportunity to make observations and interpretations themselves.

01 T: *Why I don't let my students interpret the observations themselves ... I think that this is an aspect of my own style ... moreover VWO5 is generally not*

[11] According to the International Union of Pure and Applied Chemistry: "Thus a cell diagram may be drawn either way round, and correspondingly the electric potential difference appropriate to the diagram may be either positive or negative." (IUPAC, 1988, p.45).

thinking along that much ... in that respect they are lazy consumers, and to that I adjust my story (...) the point is ... it is a large group, and a large group you teach more frontal than a smaller group (...) and a large class already causes loss of speed ...

The next question was asked after a pause. (end of transcript fragment)

Besides, according to the teachers, this teaching activity prevents students from developing concepts deviating from the teachers' intended concepts. *According to the teachers, these deviating concepts can cause a lot of confusion.* This is reflected in the next interview transcript:

Transcript 3.11:

During the interview, the teacher was asked why he executed an experiment as a demonstration, while in the textbook it was indicated as a student experiment.

01 T: *I have done this as a demonstration, because I think in experiment number 1 a lot of different results arise and that is confusing ... and when you do it yourself, you can put things right at that moment*

The teacher gives an example which concerns the measured values of potential differences. Then the next question is asked. (end of transcript fragment)

Concerning the ignoring of students' reasonable alternatives, the teachers said this was caused by a shortage of time. They had not enough time to go into every serious proposal of students. *Subsequently, the teachers remarked that if they had the time it would be preferable to pay attention to serious proposals of students.*

Above, three important teaching problems have been described. Below, in table 3.3, I will give a summary of these problems, in which the relation between the use of contexts and the teaching activities is described.

Table 3.3
Summary of problems concerning teaching electrochemical cells

Teachers' use of contexts	***Teaching activities***
Emphasizing a particular context	* Emphasizing only one meaning of concepts * Insufficient paying attention to relevant meanings of concepts
Mixing of contexts	* Using shortened terminology
Constructing contexts themselves	* Expressing observations and explanations themselves * Ignoring students' reasonable alternatives

3.3 Backgrounds to teaching problems

In this section, backgrounds to teaching problems as described in the previous section will be discussed. I want to discuss the indicated teaching problems from two perspectives:

- *An expert-novice perspective*, in which the role of the participants is of importance. The role of the teacher is the expert role, and the student's role is the novice;
- *A top-down teaching perspective*, in which the method of teaching is of importance. A teaching method in which the teacher gives information and the student receives it.

Expert-novice perspective

In my opinion, an important background to teaching problems can be described from the expert-novice perspective. The indicated teaching activity of *using shortened terminology* which hampers students' learning can be related to this perspective.
I think that using shortened terminology is not intended as such by the teachers. Teachers do not realize that they use expert terminology. The advanced and often abstract nature of the topics which come up may make this terminology appear new, foreign, and bewildering to students (e.g Moje, 1995).
It is difficult for teachers to know when to adjust their terminology and when to be very precise. In teachers' language a lot of expert theory is implicit. Experts see other connections than beginners, as argued by Bromme (1992). When experts talk to each other in a shortened way, this is not a problem because they have enough knowledge to know what the other expert is talking about. No (repeated) explanation of used concepts is required, imprecise usage does not have a confusing effect, parts of sentences are understood as if they conveyed a complete message. Students, of course, will imitate the teacher's discourse which includes using his shortened terminology (Stinner, 1995). However, the students will not know the complete message. Other imitation-language takes place from the textbooks. For example, students often use equations from the textbook without really knowing what they mean. Other educational researchers have the same opinion as I:

> "Students are able to use formulas in equations and even balance equations correctly without understanding the meaning of the formula in terms of particles that the symbols represent." (Gabel et al., 1987, p.695)

This imitating of language can cause conceptual difficulties, because for students this kind of terminology is meaningless.

Top-down teaching perspective

In my opinion, other important backgrounds of teaching problems can be described from the top-down teaching perspective. The indicated *expressing of observations and*

interpretations by teachers themselves and of *ignoring students' reasonable alternatives*, which both hamper students' learning can be related to this perspective. First, the teaching activity of teachers expressing observations and interpretations themselves. Teachers who express observations themselves, do not understand that these observations are often not the observations which students themselves would have made. Observations and interpretations are guided by theoretical frameworks. Students' theoretical frameworks are often not the same as those of the teachers. Consequently, the problem arises that students often do not know what to pay attention to when an experiment is being executed. Understanding that inquiry is guided by particular ideas and questions, and that experiments are tests of ideas, can be achieved by engaging students in reflecting upon the relationship between ideas and the activities of science, by differentiating ideas from the evidence that supports those ideas (Carey et al., 1989). In my opinion, teachers often do not pay enough attention to students' theoretical frameworks (for example, the idea that a metal wire can be used in an electrochemical cell instead of a salt bridge). Here, the teaching activity of ignoring students' reasonable alternatives can be related to the top-down teaching perspective, because teachers ignore students' theoretical frameworks.
Edwards and Mercer (1987) claim that student conceptions of the nature and meaning of their own observations and interpretations are strongly governed by the 'judgements' offered to them by the teacher. These 'judgements' concern a variety of communicative devices ranging from gestures and silences to the uses of implication and verbal descriptions. Which means no active learning for students and still teachers deciding which observations and interpretations are worthwhile.

A mix of the two perspectives

I believe that the teaching activities of *emphasizing only one meaning of a new concept* and *insufficient paying attention to relevant meanings of a new concept* can both be described from a mix of the expert-novice and the top-down teaching perspective. Teachers who are experts in particular syllabus topics (expert-novice perspective) need not be experts in teaching (top-down teaching perspective). Emphasizing only one meaning of a concept or insufficient paying attention to relevant meanings of a concept, can be expert behaviour in an expert-novice perspective, but these experts are in my view not aware of the student difficulties they evoke when doing so. In a top-down teaching perspective, the expert would have thought about students' learning.
In my opinion, both activities have to do with the aspect of not relating old 'facts' with new ones. I believe teachers do not pay enough attention to students' prior knowledge. The following opinion illustrates that others also believe that mobilizing prior knowledge is important:

> "When we come to cognitive learning tasks, however, it is quite clear that maturational effects in themselves are insufficient to explain readiness, so that we must also take into account *prior learning*. Prior learning, as for example of a particular kind of

> subject matter, has two main effects. On the one hand, it determines the child's specific readiness for other *particular* kinds of subject-matter learning, that is, contributes to his *subject-matter* readiness. On the other hand, it also contributes to *general* changes in cognitive readiness, that are, at least in part, independent of the kind of subject matter studied. (...) In other words, prior learning of specific subject matter influences both specific matter learning and *developmental* readiness." (Ausubel & Robinson, 1969, p.176)

I feel that this attention for prior knowledge is of importance because ignoring the already existing conceptions of students can have serious consequences for the cognitive development of students. Take for example the concept of electrolyte. Teachers could specifically take into account that students have knowledge of the ionic theory from the previous grade, but not in the sense of transport and electrical neutrality. They often do not take this into account and this causes teaching problems.

3.4 Discussion and conclusion

The present chapter reported on a case study in which two teachers were involved who taught in the current teaching. Indicated conceptual difficulties of students were related to teaching activities. These teaching activities are categorized in terms of teachers' use of contexts which are called teaching problems.

The first research question of this part of the study concerned what teaching problems could be indicated. This question is answered in section 3.2. A number of teaching problems could be indicated and have been described by means of teachers' use of contexts, viz. *emphasizing a particular context, mixing of contexts* and *constructing contexts themselves*.
The second research question, which concerned which teachers' conceptions of the indicated problems could be described, is answered in the parts in section 3.2, in which the teachers commented on the teaching problems indicated by me.
It is remarkable that not every teaching problem is experienced as a problem by the teachers. For example, they are not aware of the problems concerning their formulating of observations and explanations themselves.
As far as the teachers became aware of a teaching problem, they described a number of causes. The teachers attribute few problems to internal causes, like teachers' use of contexts. Their explanations contained a lot of external causes, such as lack of time and direction towards the final examination.

In current teaching, most contexts which are named and described in chapter 2 can be indicated. Secondly, also the problem of mixed contexts can be indicated in current teaching. But more problems become visible in terms of use of contexts. Namely, the fact that teachers constructed contexts themselves and emphasized one particular context. Important backgrounds to teaching problems can be described from the expert-novice perspective, the top-down teaching perspective and a mix of these perspectives.

Some of the teaching problems say something about the relation between education and science. For example, because the Nernst equation is described mainly in an electrochemical calculate context, the measure context is insufficiently discussed.
Other teaching problems say something about the relation between education and society. For example, instead of explaining the concept of corrosion as an important example of electrochemical cells, it is reduced to a reading section.
Combining the results of this chapter with the results of the previous one, it has become clear that the relation between *electrochemical cell education and science as well as society could be improved, and that education has its own way of reasoning.*

Because this part of the study is a case study, there are probably more teaching problems, than the ones indicated and described in this chapter. However, I expect that these three kinds of teaching problems will provide a reasonable starting point for development of new student and teacher course material. I expect this because these kinds of problems have also been described in other studies (Barral et al., 1992; Garnett & Treagust, 1992a, 1992b). Also in studies concerning other syllabus topics, these kinds of problems have been described (e.g. Gabel, 1994; Griffiths, 1994).

In general, external causes, such as exam programme and syllabus, cannot be changed immediately by the teachers, these are beyond their reach. One factor which determines teacher activities and which can be changed is the textbook (section 2.5). *Thus if I want to change education, the only factor I can change is the textbook. Therefore new student course material in relation with new teacher course material will be developed.*

Key concepts
After this analysis, I conclude that there are at least four concepts which are connected to the indicated teaching problems. Thus, they are, in my opinion, difficult for students to learn and problematic for teachers to teach. These concepts I call *key concepts.*
These concepts concern the four concepts selected in section 2.1: the concept of electrolyte, the concept of electrode, the concept of electrode reaction, and the concept of potential difference. However, I wish to make an explicit distinction between the phenomenological context and the corpuscular context. Therefore, in a corpuscular context, I will rename the first three concepts into: *the concept of ion transport, the concept of electron transport, and the concept of electron transfer.* The names which they had before were derived from a mix between the phenomenological and the corpuscular context.

For the fourth concept, the concept of potential difference, I wish to make an explicit distinction between the measure context and the calculate context. However, there is till now no other name available for this concept in the calculate context. Therefore, I do not rename *the concept of potential difference* now.

Consequences for teacher course and student course

The teaching problems described in section 3.2 should take up an important position in the teacher course, because it has become clear that *use of contexts* is of importance. I feel teachers should discuss their teaching with the help of transcripts from the first part of the study, while keeping in mind their uses of contexts.
Also the student course has to be based on the results of the first part of the study. This means that in a different way than in current teaching, attention has to be paid to the *key concepts*. In *designing the student course material, contexts will be used.*

Chapter 4

Contexts, conceptions and conditions

In this chapter, I will analyse more precisely concepts like the concepts of conception and teaching problems used up till now, in order to achieve criteria for the design of a new teacher and student course. I will start by making some remarks about the coherence between the use of language, concepts and contexts (4.1). Next, I will go into the development of conceptions (4.2). After this, the mentioned concepts and the described coherence will be used in the description of two frames of student course and two frames of teacher course (4.3). For describing these courses themselves, a model of learning conditions will be described (4.4). The chapter will be rounded off by a section containing the criteria which in my opinion should be met by the student and teacher courses (4.5).

4.1 Conceptions

Knowledge manifests itself as the assigning of meaning to words. People give meaning to the world around them, as well as to themselves, by communication. Stenhouse (1986) describes this process for education as follows:

> "(...) to return to the question of the meaning of words or concepts. (...) the meaning of a word is its use in the language. (...) that "understanding a concept" is to be equated with "knowing the rules for the use of word (or symbol)" (...) "knowing the rules" does not mean "stating an exhaustive list of them": it means being able to use the word/symbol correctly in the appropriate language-game. (...) We judge whether or not a student understands a concept by whether or not he or she can correctly use the words (or symbols) relating to that concept." (Stenhouse, 1986, p.416-417)

In this quotation, Stenhouse brings up the notion of conceptions. Partly on the basis of the previous quotation, *I describe a conception as the whole of meanings and the* *accompanying use of language which a person practises about concepts.* I consider concepts to be content-related words, like the concept of 'corrosion' for students and the concept of 'correctly', as used in the quotation, for teachers. Concepts only have meaning in context(s), as I have argued in section 2.1. I use the context dependence of concepts to describe learning. Linder (1993) describes learning as follows:

> "(...) conceptual change depiction of learning should be extended to include conceptual fitting based upon context. (...) So instead of depicting meaningful learning in terms of conceptual *change* we should consider depicting it in terms of conceptual *appreciation* - an appreciation that is *delimited by context.*" (Linder, 1993, p.293-295)

I agree with Linder and I describe learning as *the development of conceptions through which content is understood.* In my opinion, development of conceptions by students must be connected to use of contexts by teachers.

4.2 Development of conceptions

Constructivist perspective

For the last two decades, a lot of research has been done into conceptions of learners. This research is strongly influenced by the constructivist perspective on the development of conceptions (e.g. Bodner, 1986; Driver & Bell, 1986). On the one hand, the constructivist perspective can be seen as a reaction to the authoritarian, teacher-dominated, transmission model of science instruction. On the other hand, it can be contrasted with discovery learning, which was part of the curriculum reforms in the 1960s (Matthews, 1994). The constructivist theory is by no means a uniform theory (Duit & Komorek, 1994). Although the constructivist view has become one of the leading ideas in science education research on students' understanding, this is certainly not the case for science education research on teachers' understanding. In this study, I choose to look at both from a constructivist perspective.

Existing conceptions

The core of constructivism is the claim that every process of interpretation is determined by the conceptions of the interpreter: *existing conceptions* are very important. A lot of research has been done into learners' conceptions (Wittrock, 1986; Houston, 1990; Gabel, 1994; Galton & Moon, 1994; Griffiths, 1994). However, these are mainly studies into students' conceptions. Moreover, the students' conceptions under consideration are mostly related to syllabus topics. In contrast with this, the research which has been done into science teachers' conceptions mostly concerns conceptions of a rather general nature, which are not related to specific syllabus topics.

Because research has been done into students' conceptions related to syllabus topics, some general characteristics of these conceptions are known. In the first part of this study, I came across the following characteristics (section 3.2).
* Existing conceptions can originate from everyday life experience. This can cause conceptual difficulties because students have problems in using different objects for the same purpose. For example, in everyday life, metal wires are used to close a current circuit, but in lessons on electrochemical cells, a salt bridge is usually used for that purpose. For students, the use of a salt bridge is not always a straightforward choice (Acampo & De Jong, 1994a).
* Existing conceptions can also originate from previous use of models in other school subjects. This can cause conceptual difficulties for students because models can have different meanings in different school subjects. For example, for the topic of electrochemical cells, the use of models from the school subject physics may cause difficulties. From the model of current passage used in physics, students think that electrons see to all charge transport in an electrochemical cell. In this model only electron transport receives meaning, whereas electron transfer and ion transport are left out (Acampo, 1995).
* Existing conceptions can also be equivalent to ideas which were held by important scientists in the past (e.g. chapter 2, footnote 5). These conceptions can cause conceptual difficulties for students. For example, students often argue in an electrostatic corpuscular context: a positive ion cannot be attracted by a positive electrode. This kind of arguing can cause problems for students because the term *positive ion* comes from one context, viz. the corpuscular context, and the term *positive electrode* from another context, viz. the phenomenological context. Therefore, for interpretations in which both terms come up in connection, the electrostatic corpuscular context is not applicable.

Existing conceptions may interfere in the way of observing. When a student is asked by the teacher to give his observations of phenomena occurring in a particular experiment, the observations he makes can differ from those intended by the teacher and their communication can be fruitless. Differences in observations may be caused by differences in existing conceptions: what students and teachers pay attention to, depends on what is considered relevant and interesting by them (e.g. Hewson & Hewson, 1988; Joling et al., 1988; Galili et al., 1993). This could cause teaching problems (see section 3.2).
So, I agree with Driver (1988) who argues that if learning of science involves development of students' conceptions, then educators need to appreciate these existing conceptions, and, moreover, they need to take them into account in the design of learning programmes. Thus in my study, I shall pay attention to existing conceptions, of both students and teachers.

Active process
The development of conceptions seen from a constructivist perspective stresses the role of *physical and social experiences* (Bodner, 1986; Driver et al., 1994). Physical experiences can be gained by, for example, executing experiments. Social experiences can be gained by interactions between teacher and students and between fellow students. These experiences are acquired by the learner in an *active process*. For students, an active process may mean, among other things, executing experiments, doing assignments and having discussions together. For teachers, an active process means the same thing, both with students in the classroom and with colleagues in the teacher course. Moreover, for teachers it can also mean executing new material in the classroom, which, in their case, can be described as educational experiments.
Physical and social experiences are therefore important parts of learning for students and teachers, as well as of teaching for teachers. Physical and social experiences should link up with each other, both in learning and in teaching.

Teachers' existing conceptions
Teachers' existing conceptions mainly come from prior life experiences, from teacher education experiences and from classroom experiences and they are considered important for classroom practice (Lantz & Kass, 1987; Cornett et al., 1990). Teachers' conceptions of teaching are strongly influenced by the way in which they themselves have learned the subject matter (Huibregtse et al., 1994). Thus, existing conceptions are also determined by their tertiary textbooks (section 2.3). Teachers have all had their share of traditional teaching. Most teachers imitate the way they were taught in their own way of teaching. Huibregtse et al. (1994) call this the 'didactic teaching-learning-teaching cycle' and write that it is necessary to break this cycle in order to change educational practices. This is possible if teachers are willing to change. In other words: for the development of conceptions, it is necessary that a teacher himself has change as his goal. Teachers find it difficult to give up well-established conceptions, because they are productive in their education (e.g. Wallace & Louden, 1992; McDevitt et al., 1993; Hewson et al., 1995). Because it is difficult to teach teachers to teach differently from what they are used to, it is useful to explore the conditions under which teachers are prepared to rethink and change their established beliefs and ideas (Johnston, 1991). In order to change the conceptions that teachers have, it is necessary to have knowledge of existing conceptions and their productivity for the teachers.
According to Wubbels (1992), there is a lack of integration between theories presented in teacher education and existing conceptions of teachers. Although his article is about student teachers, I assume that this also holds true for in-service education for experienced teachers. In order to develop teachers' conceptions, existing conceptions concerning electrochemical cells, theories concerning conceptual development and use of contexts should be integrated within teacher courses.

In my view, teachers' conceptions can be related to a number of categories of knowledge described by Shulman (1987)[1]:
(a) content knowledge;
(b) general pedagogical knowledge;
(c) curriculum knowledge;
(d) pedagogical content knowledge;
(e) knowledge of learners and their characteristics;
(f) knowledge of educational contexts ranging from the characteristics of groups (...) to the character of communities and cultures;
(g) knowledge of educational ends, purposes, and values, and their philosophical and historical grounds.

Because my starting points are concepts within contexts, teaching problems in connection with use of contexts (see chapters 2 and 3), and existing conceptions and their development (see previous parts of this section), I have decided to study:
- *content knowledge (a)*: knowledge of the four key concepts and the use of contexts of electrochemical cells in texts (chapters 2 and 3),
- *pedagogical content knowledge (d)*: knowledge concerning the creation of learning conditions and teachers' use of contexts of electrochemical cells,
- *knowledge of learners and their characteristics (e)*: knowledge concerning both existing students' conceptions concerning electrochemical cells and the development of their conceptions.

The four other categories of knowledge mentioned by Shulman are not used, because they are, in my view, not specific for teaching electrochemical cells and thus too general for my objective. I explicate this for the category of curriculum knowledge (c). The curriculum is an important factor in teaching, because the curriculum determines the content of syllabi and textbooks. De Vos and Verdonk (1984a, 1984b) argue that a curriculum does not follow from learning theories alone. Learning theories may indicate *how* something should be taught, but *what* and how *much* should be taught, and to *whom* follow from different or additional considerations. Among these are judgements of social needs, personal needs, the relevance of different domains of content and experience, and finally political decision-making. Constructivists and other learning theorists frequently ignore, or implicitly assume, such considerations in extrapolating from learning theory to curriculum matters, and to educational theory more generally (Matthews, 1994).

In the field of science education, several studies have been conducted which relate Shulman's categories of teachers' knowledge to classroom practice. Various research

[1] Shulman's categories are not exclusively for science teachers.

methods were used: for example, some studies were conducted in actual classroom settings (e.g. Roth, 1984; Lantz & Kass, 1987; Johnston, 1988); in some studies, interviews with teachers were held (e.g. Brickhouse, 1990; Berg & Brouwer, 1991); and some studies were based on literature study (e.g. Beasley, 1992; De Jong et al., 1997).
All these kinds of studies come up with similar results: there are four categories of teachers' knowledge which influence classroom practice: content knowledge, pedagogical content knowledge, knowledge of learners and their characteristics and knowledge of educational contexts. For all of these studies, the nature of the influences is not made explicit.

In this study, I choose to study three kinds of teachers' conceptions, all related to electrochemical cells: conceptions related to content knowledge, pedagogical content knowledge and knowledge of learners and their characteristics.

Development of conceptions from a social constructivist perspective
From a constructivist perspective, two major aspects can be described in explaining the process of learning: personal and social constructivism. I feel that sharing experiences and conceptions with each other can help learners developing their conceptions and therefore I will choose social contructivism. The social constructivist perspective implies that learning takes place in, for example: *speaking/listening, writing/reading and observing/interpreting phenomena together.*
Learning science means learning to *talk* science and to use that language in *reading* and *writing*, in *reasoning*, and in *practical action* in laboratories and in daily life (Bruner, 1966; Barnes, 1975; Lemke, 1990). *Listening* to other people's verbal expressions helps the learners evaluate their previous ideas and evaluate what was useful for making sense. I think that *writing* is important because writing allows learners to express their current ideas about scientific topics in a form that they can look at and think about. Written statements provide cues for expressing ideas verbally to others (e.g. Fellows, 1994). *Observing* together can contribute to constructing a phenomenological or a measure context. Consequently, *interpreting* can contribute to constructing contexts such as a corpuscular context. For observing as well as interpreting, learners have to put their conceptions into words, have to defend and adjust them. *In teaching, there should be attention for speaking/listening (S/L), writing/reading (W/R) and observing/interpreting (O/I) of learners together.*

4.3 Creating conditions for learning

If learning is considered to be the development of conceptions, then *teaching is considered as the creation of conditions for the development of conceptions.*

I want to distinguish between two partly overlapping forms of teaching: *teaching within a transmitting frame* and *teaching within a guiding frame*. In this section, I will describe some properties of both forms. I will first describe the frames for teaching in a student course setting, and subsequently those for teaching in a teacher course setting. I will use brackets for references to use of contexts (chapter 3) and to the constructivist perspective (section 4.2).

Two frames in a student course setting

In the current teaching of the topic of electrochemical cells, I observed a particular kind of teaching, which I call teaching within a transmitting frame. The main characteristics of the observed kind of teaching follow hereafter.

S/L: * group teaching; in general the teacher speaks and the students listen (teachers constructing contexts themselves),
* teachers decide which conceptions and contexts are talked about (emphasizing a particular context),

W/R: * students formulate few own (written) observations and interpretations (insufficient exercising of the use of language),
* students read generalizations in textbooks which are premature for them (textbooks construct contexts),

O/I: * dominance of demonstration experiments (insufficient opportunity for physical and social experiences),
* experiments are by nature meant to be verifying and illustrating for students (context sequence is, for example, from a corpuscular to a phenomenological context).

In previous parts of this chapter, for example in the section about social constructivism, I considered some aspects of another kind of teaching. This I call teaching within a guiding frame. The main characteristics of this kind of teaching follow hereafter.

S/L: * group work; students work together in small groups on experiments and assignments (students construct contexts themselves),
* students talk on the basis of experiences with experiments and assignments (physical and social experiences),

W/R: * students write texts in which they formulate their own observations and interpretations (practising the use of language),
* students read their own texts, and with the help of these they formulate generalizations (constructing contexts themselves),

O/I: * dominance of student experiments (physical and social experiences),
* the experiments are meant to be constructing as to a theoretical framework and exploring of nature for students (the context sequence is, for example, from a phenomenological context to a corpuscular context).

Evaluation of the two frames in student course setting
As far as speaking/listening is concerned, there are few opportunities for students to speak to each other or to the teacher within the transmitting frame (few social experiences and little opportunity for use of language and development of conceptions), whereas within the guiding frame, they are stimulated to speak a lot to each other and to the teacher (and thus can have a lot of social experiences).
As for writing/reading, the most important difference between the two frames is *who* writes the texts and *who* makes the generalizations with the help of those texts. I believe that if a learner does not make his own generalizations, like in the transmitting frame, these generalizations cannot become very meaningful to him.
As for observing/interpreting, the major difference between the two frames is *who* directs the development of the conceptions. From a constructivist perspective, I feel that experimenting in a transmitting frame does not really stimulate learners in their development of conceptions.

In my view, the role of the science teacher has to be changed to become more than a transmitter of information. If teaching within a guiding frame means providing situations that may help students to develop conceptions, teacher comprehension in this frame may be even more critical than it is for teaching within a transmitting frame. Some main teacher's activities which encourage students' active participation in the lesson can be question-asking and discussion. In a transmitting frame, questions have often been used to check students' attention and to assess rote learning. Within a guiding frame, questions are vital to stimulate students thought and discourse.

Teacher education can be described in the same terms that I used to describe teaching in classrooms: a *teacher course within a transmitting frame* and a *teacher course within a guiding frame*. The descriptions of the two frames in a teacher course setting which follow hereafter should be considered as a provisional description in order to develop a teacher course.

Two frames in a teacher course setting
Some main characteristics of teacher education within a transmitting frame are:
S/L: * lectures; the educator speaks and the teachers listen (educator constructs contexts himself),
* educator decides which conceptions and which contexts come up (emphasizing a particular context),
W/R: * teachers write and read few own texts (insufficient opportunity for use of language),
* teachers read about theories prematurely (texts construct contexts),
O/I: * few physical and social experiences, only during the course.

Some main characteristics of teacher education within a guiding frame are:

S/L: * groupwork; teachers work together in small groups on experiments and assignments (teachers construct contexts themselves),
* teachers talk on the basis of experiences with (classroom) experiments, observations and interpretations (physical and social experiences),

W/R: * teachers write about own (classroom) observations and interpretations (practising use of language),
* teachers read their texts and generalize about these (teachers construct contexts themselves),

O/I: * physical and social experiences in classroom and course (learning and teaching as phenomena).

Evaluation of the two frames in teacher course setting

As far as the importance of speaking/listening, writing/reading and observing/interpreting is concerned, similar arguments hold true to those for the evaluation of the two frames in a student course setting.

In the following part of the section, some kinds of teacher courses are described by means of the two frames mentioned above.
Some courses are taught within a transmitting frame. This kind of teacher courses is not very useful to change classroom practice. Only listening to the course leader does not change a thing in the classroom (Fullan, 1982). During a teacher course, teachers can say that they are going to focus on particular teaching activities, but they may focus on other teaching activities when they are back in the classroom. These differences should receive attention.
Other courses are a mix of aspects of courses within a transmitting frame and within a guiding frame. Many teacher courses come under this heading. For example, Baird et al. (1991) describe a study in which was examined in an in-service course whether evaluation of own teaching could enhance the teaching and learning of science. The evaluation was practised both individually and in groups, and involved the evaluation of practice in the classroom and of the nature of science teaching and learning. For teachers, both types of evaluation acted to improve their conceptions, their awareness and their control of themselves as well as their classroom practice.
Some courses are taught within a guiding frame. For example, Bucat and Fensham (1995) describe a study in which the teachers agreed to commit themselves to improving the quality of student learning by sharing with each other their ideas and classroom experiences. My aims are similar, but more far-reaching because I want to connect students' and teachers' learning.

An important point is, in my opinion, that evaluation of classroom practice which teachers execute in the transmitting frame is often different from evaluation in a

guiding frame. It is common to use evaluation as a means of helping teachers to explore and improve aspects of their practice. My intention is to teach teachers why and how to observe and describe classroom behaviour in order to improve their teaching and evaluation. Therefore, an alternation of teacher course and classroom experiences is necessary. I call this an *in-service course within a guiding frame.* Teachers need time to evaluate their practices, assign language to their actions and develop new knowledge which they can again use to make sense of the changes in their practice (Briscoe, 1991).
During the process of becoming a teacher who teaches from a constructivist perspective, teachers must get involved in developing conceptions of science, of science teaching and of learning (Aguirre et al., 1990; De Jong & Acampo, 1993; Louden & Wallace, 1994). This may be possible in a teacher course within a guiding frame.

In my view, in order to learn, teachers have to share experiences with fellow teachers and bring their own conceptions up for discussion. In order to make this possible, there should be an alternation of teacher course meetings and classroom practice in order to evaluate the creation of the conditions for learning in terms of use of contexts and both frames for education.

4.4 A model of learning conditions

If learning conditions for students and teachers have to be described, including the relationship between them, an instrument of description has to be chosen. For both courses, the same instrument was chosen. This instrument offers the teacher possibilities to describe his teaching and the evaluation of that teaching (see also Smith et al., 1993) as well as the teacher educator criteria for the design of the student and teacher course and the evaluation of these designs.

Posner's model

Posner et al. (1982) have developed a model of learning conditions in connection with conceptual development[2]. In Posner's model, a concept is either *assimilated or accommodated*[3]. The authors of the model consider assimilating a new concept to mean using existing conceptions in order to explain and interpret new phenomena. Furthermore, accommodating a new concept is considered by them as reorganizing existing conceptions in order to explain and interpret new phenomena.

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[2] Hereafter in short: Posner's model.
[3] In Posner's model the terms concept and conception are used indiscriminately. This is contrary to the use of these terms in this study: as was already mentioned in section 4.1, I distinguish between conception and concept.

The four conditions under which the process of accommodation takes place are represented below. Of the conditions as stated below, only the last three are needed for the process of assimilation.

> "*There must be dissatisfaction with existing conceptions.* Scientists and students are unlikely to make major changes in their concepts until they believe that less radical changes will not work. (...)
> *A new conception must be intelligible.* The individual must be able to grasp how experience can be structured by a new concept sufficiently to explore the possibilities inherent in it. (...)
> *A new conception must appear initially plausible.* Any new concept adopted must at least appear to have the capacity to solve the problems generated by its predecessors. Otherwise it will not appear a plausible choice. Plausibility is also a result of consistency of the concept with other knowledge. (...)
> *A new conception should suggest the possibility of a fruitful research program.* It should have the potential to be extended, to open up new areas of inquiry." (Posner et al., 1982, p.214)

Posner et al. (1982) describe their four learning conditions in very general terms for constructing education. In order to describe construction of education, I combine Posner's model with a phase model for structuring education. This model was presented by Van Dormolen (1981), and consists of three phases: *orientation, development* and *application*. Between the different phases there are no distinct boundaries. Moreover, an activity in one particular phase, like application of a concept, can have meaning for another phase, like orientation on a new concept. The four learning conditions are also combined with the use of contexts.

The *orientation phase* is about the *introduction of contexts*, and about getting familiar with the appropriate terms. This phase can be connected with the *learning condition of necessity*, which is also a term used by Posner et al. (1982) (in the above-mentioned quotation they use the term dissatisfaction for this condition). The necessity can be created by offering new contexts. The existing conceptions do not explain or predict enough for the learner, so he needs a new concept in order to be able to handle a phenomenon. The creation of this condition can be enhanced when a cognitive conflict arises. Constructivists argue that experiences which challenge prior knowledge and beliefs prove very helpful in developing new understanding.

> "One model for promoting conceptual change which has received considerable attention by science educators is that of generating cognitive conflict. This model (...) proposes that learners, when confronted with discrepant or conflicting information, will attempt to adjust the way they conceptualize the problem in order to resolve the conflict." (Driver, 1988, p.177-178)

Such a cognitive conflict is a situation in which (physical and social) experiences arise which learners do not expect and cannot explain on the basis of their already existing

conceptions. A cognitive conflict can arise for students while learning electrochemical cells, but also for teachers while teaching it.
In my view, the learning condition of necessity has two aspects: a theoretical aspect and a practical aspect. The theoretical aspect comprises the need to make a line of reasoning coherent. For example, if a student knows that electron transfer takes place at an electrode, and electron transport in an electrode and wire, then he probably will want to know how to describe the electrolyte in order to make the whole line of reasoning concerning current passage coherent. The practical aspect concerns the need to get an answer to a question about an application. For example, students will want to know something about the way batteries function.

In the *development phase* special attention is paid to a further acquaintance with contexts, in the form of *context elaboration* and *context coupling*. This phase can be connected with the *learning condition of intelligibility* and the *learning condition of plausibility*.
The intelligibility can be created by offering context elaboration and coupling. I believe intelligibility means that the learner ought to know what the new concept means, the parts of the picture of the concept should fit together for the learner, the learner ought to be capable of finding a way to present the concept and to discover the possibilities of that concept. The intelligibility of a concept concerns its meaning.
The plausibility can also be created by offering context coupling and elaboration. I think this means that the learner ought to believe the concept is true, it is consistent and compatible with other concepts accepted by the learner and that the concept is logical for the learner. The plausibility of a concept concerns the learner's beliefs.

The *application phase* is a matter of using a concept, connected to the *application of contexts*. This phase can be connected to the *learning condition of fruitfulness*. I believe this means that the concept ought to have value for the learner, the concept should solve, until now insolvable, problems for the learner, the concept should suggest new possibilities, directions and ideas for the learner.

Usefulness of Posner's model for this study
In Posner's model, learning is seen as a process of conceptual development. In this model, it is not mentioned whether this process is of a personal or social nature. Also, little is said about the realization of the learning conditions and what to do in the classroom; only the use of anomalies, analogies and metaphors is referred to. In this part of the section, I shall go into some comments on Posner's model, but only as far as the comments are useful for my *key concept and context related use* of the model.

Posner's model has often been used for the development of new course material. Hewson and Thorley (1989)[4] describe, on the basis of a literature study, that although the model is used as a rationale for the design of new course material, the specific relevance of the model to such a design is often not clear. I agree with them, because often no details are given, and therefore the role of the learning conditions in such designs is difficult to establish. Two of the authors of the 1982-article, Strike and Posner himself (1992), restate some aspects of the model. The most important revision is the additional description of the learner's conceptual ecology in terms of, for example, existing conceptions. I approve of this addition, as I think that when the learner's starting situation is described in more detail, the influence of learning conditions on education will come out more clearly. *In the design of both courses, I will explicitly elaborate on the learning conditions connected to the use of contexts, the key concepts and the existing conceptions of the learners.*

Some of the four learning conditions get much more attention than others. For example, White and Gunstone (1989) and Gunstone et al. (1992) write that the efforts of teachers, and the attention of the learning theorists of the recent past, was concentrated for the greater part on the learning condition of intelligibility. According to them, this is because the popular teaching method of teacher-question and student-answer, the use of convergent tests of knowledge of propositions and the ability to follow algorithms are well developed, highly practised, and well suited to promote the intelligibility.
According to both studies, it is common for the learning condition of intelligibility to get much attention. I want to pay attention to *all four* learning conditions in relation to the use of contexts and key concepts.

Posner's model has been used to design new courses for students. It could also be used to design *teacher courses*. In their article, Thorley and Stofflett (1996) explore the application of this model for the learning and teaching of science. According to them, an analysis of conceptions and their connection to different parts of the model are valuable to both science teachers and teacher educators. Also, according to them, describing students' work and interpreting classroom discourse and connecting this to the model is important. I fully agree with them, *therefore, in addition to the contexts, Posner's model should be part of the content of the teacher course.*

I think that the above shows clearly that the use of the model is patchy and not very consequent. The model is mostly used to design student courses, but not very often to design teacher courses. As far as I know, the model has not been used in the interlinked development of both a teacher and a student course. *In this study, the*

[4] Hewson is a co-author of Posner's original article.

objective is to design a teacher and student course in connection with each other, and using Posner's model.

4.5 Criteria for course design

I shall develop a teacher course, a part of which is a student course. In this section, I will state my choices of point of view concerning both courses. I will start by describing the student course, because I use this in the elaboration on the teacher course.

The new student course

The choice for the social constructivist development of conceptions follows from the section on the development of conceptions (section 4.2). This means a choice for group work, because group work can be connected with students' use of language and social and physical experiences in an active process. In the new student course, students are to execute experiments with accompanying assignments about which they can talk, listen, write, read, observe and interpret. In my opinion, it is essential for students' learning that they acquire their own experiences with experiments and talk about them with their fellow students. Of course, the experiments and assignments should be designed in such a way that they can act as a basis for further discourse and that through them students are able to put conceptions into words. Within this set-up, existing conceptions should be taken into account. *Thus, attention must be paid to existing conceptions and to physical and social experiences in the student course.*

From the current teaching, it appeared that some teachers' use of contexts can hamper students' learning (section 3.2). I think that other uses of contexts can enhance learning, which I have connected with the learning conditions of Posner's model in Van Dormolen's three phases (section 4.4). Consequently, in the student course, attention must be paid to use of contexts, viz. *sequence, introduction, elaboration, coupling and application*, together with the learning conditions of *necessity, intelligibility, plausibility and fruitfulness*, in the educational phases of *orientation, development and application.*

The new teacher course

Three kinds of teachers' conceptions are selected by me to feature in the teacher course (section 4.2). These conceptions are related to: *content knowledge, pedagogical content knowledge* and *knowledge of learners.*

Concerning content knowledge: in the new teacher course, attention needs to be paid to the *electrochemical key concepts*, which should be developed with the help of *use of contexts.* For the key concept of ion transport, for example, I feel that the sequence

should be from a phenomenological context to a corpuscular context. And for the key concept of potential difference, from a measure context to a calculate context.
Concerning pedagogical content knowledge: in the new teacher course, *Posner's model* as well as the teachers' *use of contexts* should emerge.
Concerning knowledge of learners: *existing students' conceptions* as well as *existing teachers' conceptions* will need to be taken into account.

Because people's learning can be seen as the development of conceptions, in student and teacher courses, assignments (social experiences) and experiments (physical experiences) should be offered to enhance doing together. I want to create discourse possibilities for teachers in the teacher course and for students in the student course. Teachers are expected to talk in small groups on the basis of experiments and assignments. They are also expected to participate in an active way and be confronted with methods and ways of reasoning of their students more intensely than they usually are. *I opt for an in-service course within a guiding frame because of the alternation of classroom experiences and discussing them in the teacher course. This concerns the learning of as well as the creation of conditions for learning of the topic of electrochemical cells.*

Chapter 5

Design of the research cycles

After explorative research into current texts and teaching concerning electrochemical key concepts (chapters 2 and 3), and development of criteria for an in-service teacher course concerning these key concepts (chapter 4), I will now give concrete form to the developmental nature of this qualitative research in the design of the research cycles. I will start by formulating the research questions (5.1). Subsequently, I will report on the research method (5.2 and 5.3). In order to answer the research questions, two versions of an in-service teacher course including a student course were developed and their design will be described in (5.4 and 5.5).

5.1 Research questions

In this study, chemistry teachers will be involved in the teacher course. During this period, teachers are working with the student course material as part of the course. The research questions were formulated as follows:

(1) What conceptions of chemistry teachers can be described when they take part in the in-service course including new student course material on electrochemical cells?
(2) What teaching problems can be indicated in teaching with this material?

The teachers' conceptions I want to look at are related to content knowledge (the four key concepts and use of contexts), pedagogical content knowledge (learning conditions and teachers' use of contexts) and knowledge of students (existing students' conceptions and development of their conceptions) (section 4.2).
Analysis results of both questions can be used to contribute to two educational structures which I want to develop: an *educational structure of electrochemical cells*

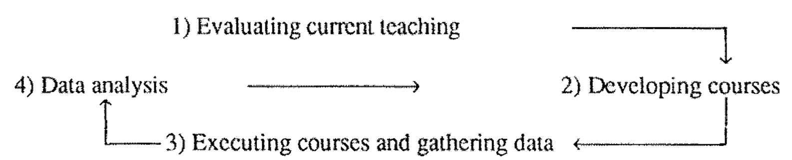
and an *educational structure of creating conditions for learning electrochemical cells* (section 1.2).

5.2 The cyclical method

In order to answer the research questions, I have opted for a method which is called the cyclical method. I will elaborate on this method which comprises four stages:
- evaluating previous teaching,
- developing an in-service teacher course including a student course,
- executing the new courses and gathering data,
- data analysis.

The results of the data analysis are used to develop a second version of the course material. Subsequently, execution of this version will take place and data will again be gathered and data analysis will take place. So, the last three stages are repeated in a second cycle. Therefore, the method as a whole is called *the cyclical method* (e.g. Verdonk & Lijnse, 1993). This method is represented in figure 5.1.

Figure 5.1
The cyclical method



The first cycle

The stage of *evaluating the previous teaching* is a starting stage. At this stage, for the first cycle, a close look is taken at the current teaching. This has already mainly been described in chapter 3.

After this, the stage of *developing an in-service teacher course including a student course* will take place. The nature of these courses will partly be influenced by the results of the analysis of the current teaching. New material will also be based on literature of key concepts, of existing students' conceptions and of use of contexts.

Subsequently, *the executing of the courses and gathering of data* will take place. In order to gather data which provide information on what happens in educational situations, I choose to execute the material in real classrooms and in an actual in-service teacher course. The research data collected in the classroom include audiotapes of lessons, observation notes of lessons, and completed evaluation forms about the student course. The research data collected in the teacher course include audiotapes of teacher course meetings and written answers to the assignments of the teacher course. In the stage of *data analysis*, I will use the method of transcript analysis. After this, the second cycle can be embarked upon.

The second cycle

The second version of the courses will be adapted according to the results of the first cycle. Some stages of the first cycle, viz. executing the first courses, gathering data and data analysis, are part of the (first) stage of *evaluating the previous teaching* of the second cycle.

The second cycle will continue with the stage of *developing the second versions of the courses*.

Subsequently, the stage of *executing the second version of the courses and gathering data* will take place.

Finally, *data analysis* will take place in the same way as in the first cycle.

In the next section, I will elaborate on the chosen method of data-analysis, viz. transcript analysis.

5.3 Transcript analysis

Transcript analysis as a method

There are difficulties concerning the manner of studying conceptions, which result from the inability of observing learners' conceptions directly. However, indirectly this can be done by listening to what learners say and observing how they act. In section 4.1, I have described that a major aspect of conceptions is the use of language, both in teaching as well as in written text. According to Lemke (1990), a close look at language is needed because language is not just vocabulary and grammar, but a system of resources for making meanings. However, there are some problems. Edwards and Mercer (1987) point out that where collection and interpretation of linguistic data are concerned, the transparency of the manner in which language carries meaning is of importance. Transcript analysis focuses on what people say to each other, what they talk about, what understandings they convey, and on the difficulties which are encountered in following the way in which these understandings come about and are built upon as the discourse proceeds.

I studied conceptions of teachers by analysing transcripts. My interest is in teachers' statements which can be considered as indicators of conceptions related to content knowledge, pedagogical content knowledge and knowledge of students.

Kinds of results of transcript analysis
The results of transcript analysis can be divided into three types of results which concern 'roles' of persons, viz. the researcher, the course developer and the teacher educator.
One type of results concerns the researcher: by paying attention to statements of teachers and students, transcript analysis can contribute to a better understanding of the development of conceptions of both of them. According to Carter (1990), learners' knowledge is directly related to their classroom performance. Besides, it is possible to investigate teachers' and students' conceptions in connection with each other. So, it is important to study whether there are differences between students' and teachers' conceptions, because these may cause teaching problems.
A second type of results concerns the course developer: transcript analysis can be used to improve science education courses, because it can contribute to the development of criteria for constructing such courses.
A final type of results concerns the teacher educator: he can use the transcripts as a tool for the education of science teachers. In that case, teachers may be invited to analyse given transcripts or transcripts produced by themselves by audiotaping their own classroom practices. The results of the analyses can be discussed with colleagues. According to Gunstone et al. (1993), such discussions can contribute to sharing experiences and providing support for colleagues, which is crucial in teaching. In this way, teachers appear to be stimulated to evaluate their own teaching conceptions as well as their classroom activities.

Comments and implications of transcript analysis
A first comment is that collecting audiorecordings, transcribing them and analysing transcripts are very time consuming activities. I tried to reduce the time involved by making a selection of the audiorecordings which I transcribed.

Another drawback of this method is that the information laid down in transcripts is a strongly reduced version of the educational reality. For example, about students or teachers who say nothing, nothing can be said. Also, people in classrooms do not speak in standardized ways, so as to produce the regularities found by analysts. They speak to get things done (Heap, 1985). The gap between real discourse and a transcribed version can be very big. Knowledge of intonation and non-verbal behaviour is sometimes of great importance in the interpretation of a statement in a transcript. Observing lessons, sitting in the back of the classroom, taking notes and copying blackboard schemes can be of help in the interpretation. I observed each teacher once during teaching in his classroom. Observing all lessons, which was even better, was not possible for the one available observer, because of the number of teachers and consequently of the number of lessons involved.

Also videorecordings could be of use concerning the non-verbal behaviour, because they contain more information than audiorecordings about this behaviour. However, because the conceptions I study are connected to use of language, I have not used video.

A final comment on transcript analysis is that the analysis of transcripts is influenced by the expectations of the researcher, which form his analysis context and can lead to a biased expectation. Even co-operation with other analysts may lead to problems: it may lead to a less critical attitude of the analysts towards each other.
Therefore instead of only giving interpretations, I decided to represent in this dissertation a number of transcripts, connected with student material, teacher course material and my expectations on teachers' conceptions. Then the reader gets the opportunity to make his own interpretations. I will analyse the transcripts by comparing transcript statements with my expectations, and the reader can do this himself. According to Wester (1987), the representation of transcripts, student and teacher course material and expectations, may contribute to the plausibility of the interpretation, because the reader of a report of a study himself can contradict the offered descriptions, declare them invalid or refuse to accept them as he considers them not applicable to a particular situation. This is sometimes termed analytic generalization: the reader of the analysis decides whether he recognizes the situation and knows similar situations. The possibility to generalize from the given material is up to the reader. Of course, it is important in this case to give detailed information of the contexts (ecological validity). Wester (1987) claims that credibility can also be enhanced by trying to make them fit in with analysis results published in literature. I agree with him, and therefore I will check the appropriate literature.

Production of transcripts

The quality of transcripts may be influenced by several factors. The quality of a transcript may again influence the quality of the results of this analysis.
One of the most important steps for producing transcripts involves the audiotaping of statements. This requires the presence of one or more taperecorders. Whether the teacher carries the taperecorder or whether it is positioned somewhere in the room, in each case it is important that the presence of the recorders does not influence the behaviour of students and teachers. Only then is it possible to record ordinary discourses. Of course, the same is true when the recorder is used in the teacher course. It is the experience of the CSME[1], that students and teachers quickly accept the presence of recorders and, after a short period of time ignore the equipment entirely. Of course, how soon they will ignore the equipment also has to do with its visibility. The less visible, the sooner they will ignore it.

[1] Centre for Science and Mathematics Education, Utrecht University.

In this study, the teachers were volunteers, who were willing to record their discourses during the teacher course and their lessons, and to allow a researcher to visit their classrooms in order to observe them teaching with the new student course material. Since I was interested in teacher statements, either or not in connection with student statements, each of the teachers got a small taperecorder with a microphone to wear on their person. In this way, all lessons taught with the new student course material were recorded by the teachers. In the teacher course, the tape recorder was on the table recording a general discussion or discussions of small groups of teachers.

Transcripts as 'measure instrument'

In order to produce transcripts from audiorecordings, several methods are possible. One method consists of transcribing all recorded statements. Although this approach takes a lot of time, all statements end up in written form to be used at some point or other. Another method consists of selecting and transcribing a number of episodes, after a first scanning of the discourses on tape with a specific question in mind. The selection should be based on the assumption that the considered episodes could be relevant in answering the formulated research question(s). Although this approach is rather efficient, there is a risk of missing out on important information, because in subsequent parts of a study, the researcher's conceptions become more specific. In my experience, the most productive method is in between the two. In this method, the outcomes of the analysis of the first selection of episodes determine the need of an additional selection.

In my study, all audiotapes were listened to, and parts were written out into transcripts. These transcripts were analysed several times, the analyses ranging from general and tentative to more specific and definite. After this, an additional selection of other transcripts could take place.

Another important step in transcript analysis involves the type of notation used for the transcripts. In my study, each transcript is a verbatim representation of the discourse: parts of sentences, partially pronounced words, pauses, and so on, are also written down. Because often only later on, during the analysis, it is possible to determine the value of this kind of information. For purposes of analysis, I numbered all statements (see also Appendix A).

Procedure of the analysis

In order to analyse the transcripts of the two kinds of discourses, viz. in the classroom and in the teacher course, the procedure as stated below was followed.

All transcripts were read and analysed tentatively by two researchers, independently of each other. These analysts had knowledge of the setting involved, such as knowledge of classroom practices, textbooks being used, and so on. Part of the analysts' knowledge was gained by (previous) classroom observations.

At the start of the analysis, the analysts developed and used, separately, provisional categories of conceptions to interpret the transcript contents. The categories had been generated by the research question(s) in combination with a first reflection on the transcript content. If necessary, supportive data material[2] was used. After ample discussion of their experiences, the analysts further refined the categories to make them more suitable. Subsequently, they used the revised categories, independently of each other. If necessary, the steps of revising and applying categories were repeated.
Finally, the results of their analysis were compared and discussed by the researchers. In this way the analysis results got an interpersonal status. However, there is a risk involved of less critical attitudes being displayed towards a fellow analyst. If there was a difference of opinion, the discussion and repeated analyses went on until consensus about the interpretation was reached. By including both the transcript and its interpretation in this thesis, readers can judge for themselves and either agree or suggest another interpretation.

5.4 The first teacher course

The teacher course on the teaching of electrochemical cells within a guiding frame is divided into three stages of teaching (Acampo & De Jong, 1994b; Acampo, 1995). Because of its in-service character concerning learning to teach electrochemical cells with the help of the new student course material, I use new terminology:
- the introduction stage,
- the realization stage,
- the evaluation stage.

These stages refer to kinds of teachers' activities in the teacher course. The course comprises four institute meetings and a number of lessons taught with the new student course material. The first two meetings were planned to take place prior to the lessons, the third one during the period of teaching, and the fourth after the series of lessons had been rounded off.
The introduction and the evaluation stage take place during institute meetings. The realization stage takes place in the teacher's own classroom. I expect that during all three stages, teachers will make statements which I can interpret as conceptions related to content knowledge, pedagogical content knowledge and knowledge of students.

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[2] Supportive material concerns: written teachers' answers on in-service course assignments, standard evaluation forms completed by the teachers, and observation notes made by me.

During the first teacher course, conducted in 1993, eleven teachers[3] were involved who used the new student course material in their classroom. Because of insufficient number of equipment, audiotapes were made of lessons by the teachers in nine of the classrooms. Apart from audiotaping his lessons, each teacher was to fill in an evaluation form at the end of each lesson[4].

In the next part of the section, both the student as well as the teacher course will be described. I will start by describing the student course, because I will use this description in the description of the teacher course.

First student course material

In designing the student course material, I used the criteria elaborated on in previous chapters: concepts in contexts (2.5), use of contexts (3.2), key concepts (3.4), active learning (4.2), social constructivism (4.2), Posner's learning conditions (4.4) and the three phases of Van Dormolen (4.4).

The student course material comprises two main parts (see Appendix C):

* The concept of current passage emerges in a phenomenological context, and subsequently, through interpretation of a certain number of cell phenomena, in a corpuscular context (§1-§6);
* The concept of potential difference emerges in a measure context, and subsequently, through interpretation of measurements, in a calculate context (§7-§12).

The design of this material differs from the design of the current student course material on the topic of electrochemical cells (section 2.4). In this new student course material, the concept of current passage is described from a phenomenological context to a corpuscular context. In current student course material, the concept of current passage is described in a corpuscular context right after the concept of potential difference is described in a measure context concerning half reactions. The new student course material finishes with the concept of potential difference as a possibility of a reaction. In the next part of the section, I will describe the sections of the first student course material.

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[3] The teachers taught in 5 VWO at the Stedelijk Gymnasium (Utrecht), the Christelijk Lyceum (Zeist), the Thuredrechtcollege (Dordrecht), College Leeuwenhorst (Noordwijkerhout), the Dorenweerd College (Doorwerth), the Lindenholtcollege (Nijmegen), the Christelijke Scholengemeenschap W. van Oranje (Oud-Beijerland), Gymnasium Juvenat (Bergen op Zoom), the Goois Lyceum (Bussum) and the Revius Lyceum (Doorn). In one school, the Spectrum College (Utrecht), a 5 HAVO class worked with a part of the student material. HAVO means higher general education. HAVO students get three years of chemical education, VWO students four.

[4] From eight out of eleven teachers, I got the completed evaluation forms back. This form contained three open questions designed according to suggestions of Baird et al. (1991), see Appendix B.

Current passage: from a phenomenological to a corpuscular context
In *§1* and 2, the concept of *electrochemical cell* is introduced by means of a series of experiments[5] with which is tried to create a cognitive conflict, because what can be observed may clash with the existing students' conceptions of *redox reactions*. By means of observing and interpreting these observations, students themselves should construct the phenomenological and corpuscular context. In these experiments, students were asked to pay attention to both characteristics of electrodes: the *object characteristic* (electrode as a bar or a particular substance) and the *function characteristic* (electrode as a place where phenomena, viz. reaction and current passage as an event, take place which can be interpreted as a combination of electron transfer and electron transport).
These sections concern the orientation phase for the location, the identity and the direction of electrode reactions.
An important reason for including this experiment, is that students in current teaching experience difficulties in understanding the location and number of locations of the electrode reactions (3.2).

In *§3*, students are asked to build two different galvanic cells[5]. They can observe and they can interpret their observations. Subsequently, they can read their own interpretations and with the help of these formulate generalizations of characteristics of galvanic cells. Building, observing and interpreting cells themselves gives students the opportunity for context elaboration.
This section concerns the development phase for the location, the identity and the direction of electrode reactions.
Students in current teaching appeared to have difficulties when seeing the teacher build only one galvanic cell (section 3.2). Seeing only one cell and not interpreting observations themselves does not contribute to the students' ability to generalize.

In *§4*, by means of two student experiments[5], it is attempted to make the students see that the process of corroding iron can be considered as the same type of process, but taking place in a short-circuited cell. Corrosion can be observed as two events taking place at the same time on different locations leading to the corpuscular interpretation of electron transfer and electron transport. In these experiments, students' attention was asked for both characteristics of electrode reactions: the *process characteristic* (phenomena take place which can be interpreted as a combination of electron transfer and transport) and the *location characteristic* (the place where the combination of electron transfer and transport takes place).
This section concerns the application phase for the location, the identity and the direction of the electrode reactions.

[5] The description of these experiments can be found in Appendix D1.

I included these experiments because students in current teaching had no idea why the concept of corrosion emerged in the topic of electrochemical cells (section 3.2).

In *§5*, the concept of electrolysis is mentioned. In this section, in which the emphasis is on the concept of spontaneous reaction versus the concept of forced reaction (concerning reaction direction and electrode reaction identity). An inversion of the direction of current passage has consequences for the electrode reactions which will take place, because many electrode reactions are not reversible as to their identity. Again, I opted for the description of this concept from a phenomenological to a corpuscular context.
This section concerns the development phase for the direction and identity of electrode reactions and the orientation phase for the reversibility of the electrode reaction.
The concept of electrolysis did not seem to be a big problem for students in current teaching (section 3.2). They could make assignments in the way they were asked. However, whether they understood the concept remains to be seen until it can be indicated that they are able to apply the concept.

In *§6*, an experiment is described which involves a partly coloured salt bridge[6]. This experiment was added in order to pay more attention to the concept of ion transport, because it has remained implicit so far, in relation to the concepts of electron transport and electron transfer. While executing this experiment, it is possible to make observations concerning colours and colour shifts, and subsequently interpretations concerning identity of ions, ion transport and the direction of ion transport. In this way, students can construct the phenomenological and the corpuscular context.
This section concerns the development and application phase for electron transport, electrode reaction and identity and direction of ion transport.
I included this experiment because students in current teaching had difficulties connecting the key concepts of electron transport, electron transfer and ion transport concerning the current circuit (section 3.2). I suppose this was because within the current teaching, only few experiments were executed in which these concepts concerning current passage can be observed and interpreted in coherence.

Potential difference: from a measure to a calculate context
In *§7* and *8*, the concept of potential difference of an electrochemical cell is introduced and subsequently students are asked to interpret a current-voltage graph of a cell of which the electrode reactions are reversible as to their identity[7]. Although none of the

[6] The description of this experiment can be found in Appendix E1. This experiment needs to be done in an electrolysis cell and can therefore only be executed after the topic of electrolysis has been introduced. When this salt bridge is used in a galvanic cell, it takes more than one lesson before something can be observed in the salt bridge. Experiments are not supposed to take more than one lesson because it is believed that students' attention will wane.
[7] The cell has the following cell diagram Ag(s) | AgCl (s) | $CuCl_2$-solution | Cu(s).

three key concepts of current passage is visible anymore, knowledge of them is necessary to attribute corpuscular descriptions to measurements: the sign of potential difference and knowledge of the composition of the cell in relation with attributing identity and direction of electrode reactions.
This section concerns the orientation phase for the sign and the value of potential difference and can be considered as a check on understanding the concepts of electrode reaction and ion transport.
The above-mentioned relations concerning the concept of potential difference were a problem for students in current teaching (section 3.2). Probably because in current teaching the introduction of the concept of potential difference takes place in the first section together with the introduction of the concept of electrochemical cell, and application of the concepts of electron transport, electron transfer and ion transport is not yet possible for students. In this section, only an event of a meter deflection is discussed (magnitude and direction) and not an event like reaction or transport which can be made visible.

§9 deals with an exception from the Binas-table of reductant and oxidant strengths in aqueous solutions (Binas, 1992). This exception comprises an electrode reaction in which chlorine ions instead of water react at the positive electrode during electrolysis. With the included experiment an attempt is made to create a cognitive conflict concerning the identity of the electrode reaction and the sequence in the Binas-table.
This section concerns the development phase for the relation between the identity of the electrode reaction and the value of potential difference.

§10 contains two experiments in which students themselves measure potential differences, also of coupled cells, in order to observe and interpret their measurements[8]. By means of observations and interpretations, students themselves can construct the measure and the calculate context. The objective is to focus students' attention on relating sign and value of potential difference (measure context) to direction and identity of reaction with which can be calculated (calculate context).
This section concerns the orientation and development phase for the sign and the value of potential difference in relation with the direction and identity of electrode reaction and ion transport.
This section is included because students in current teaching found the measuring and interpreting of potential differences difficult (section 3.2). That they found this measuring difficult was probably because the measure context was not connected to reasonings of a corpuscular nature.

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[8] The descriptions of these experiments can be found in Appendix F1.

In *§11* and *12*, the Nernst equation is introduced and developed through adding an experiment in which a concentration cell is used[9].
These sections concern the development and application phase for the value of potential difference.
Calculating with the Nernst equation did not seem a big problem for the students in current teaching (section 3.2). Whether they understood the concept of the Nernst equation remains to be seen until it can be indicated that they are able to apply this concept.

First teacher course: introduction stage
The main objective of the introduction stage for the teachers is twofold: to gain insight in their own existing conceptions and those of their students, to become aware of development of concepts in a context sequence from a phenomenological context to a corpuscular context and from a measure context to a calculate context.
The teachers started by writing, individually, a sequence of given concepts with the help of their own textbook. Then, they made their own concept map of certain concepts, also individually. Finally, the teachers discussed the results of the two previous assignments in groups of three. I took care that the teachers in one group all used the same textbook, because otherwise it might be difficult to compare the structures the teachers designed. This may seem a little contradictory with the fact that I argued in section 2.4, that the textbooks were very much alike. In spite of this, I chose to put together the groups the way I did because I think the teachers' language would be influenced by the words and titles used in the sections of their own textbooks, and I was afraid that they might be distracted by, for example, the use of different words.
In the second series of assignments, the teachers were to write a list, individually, in which should be mentioned: the most important difficulties for students, possible causes for these difficulties and their own problems with teaching electrochemical cells, in order to become aware of their kind of difficulties. Subsequently, the same groups of teachers as before received parts of transcripts from the current teaching with accompanying questions which they ought to answer together, in order to get more insight into possible teaching problems.
Before teachers started teaching with the new student course material, they obtained experience with it. In groups of three, the teachers executed those student experiments which were new for them and the accompanying assignments which were also in the student text. Moreover, they executed assignments which asked for their opinion about the way concepts were described in this material compared with their own textbooks.

[9] The description of this experiment can be found in Appendix F1.

First teacher course: realization stage

The main objective of the realization stage for the teachers is to develop conceptions of teaching the topic of electrochemical cells within a guiding frame on the basis of their own classroom experiences.

I wrote a condensed teacher guideline for the first student course material in which its objectives were briefly explained. Moreover, it was explained that the material was designed for group work, and that the teachers could give the students feedback by means of answer sheets, but they themselves should be reserved about giving straightforward answers. It was also stated that I expected the class to have already been taught the topic of direct redox reactions. For the greater part, the guideline consisted of practical suggestions, such as descriptions of set-ups and instructions as to which molarities of solutions to take.

The teachers all worked in more or less the same way with the student course material in their classrooms. They divided their classes in groups of two to four students, or they let students do this themselves. The groups worked through one section per lesson. This means they executed the experiment(s), answered accompanying assignments, handed in their group answers and made the exercise assignments for homework. The teacher looked at the group answers, might correct any mistakes and handed them back to the groups the next lesson (students' conceptions). They checked the teacher's comments and incorporated these (if necessary) before they went on with the next section. In this way, the whole student material was worked through. After each lesson the teachers filled in a standard evaluation form (Appendix B).

First teacher course: evaluation stage

The main objective for the teachers of the evaluation stage is the exchange of experiences and becoming aware of new conceptions.

Teachers executed an evaluation assignment with the help of their completed standard evaluation forms of the realization stage. This evaluation assignment concerned their conceptions on teaching with the new student course material. After this, a plenary discussion took place in order to share classroom experiences and provide support for colleagues.

5.5 The second teacher course

The second teacher course was taught in 1994. In this course, eleven teachers were involved[10]. In eight classrooms, audiotapes were made of lessons with the new student course material and standard evaluation forms were filled in[11].
The stage structure of the second teacher course was the same as of the first. The most important change concerned a shift of emphasis on attention paid to content knowledge to an emphasis on attention paid to pedagogical content knowledge. In the second teacher course, the assignments of the four meetings focused more explicitly on the four learning conditions of Posner's model.

The second version of the student course material

The second student course material, which includes twelve sections, is based on the first student course material, and adjusted according to the findings of the first cycle. These findings partly concern students' conceptual difficulties which became apparent from the interpretations of both the classroom and the teacher course transcripts. Partly, the findings concern teacher complaints about students' learning in the student course.
Some changes were meant to improve students' learning, like the extension of an experiment in section 4: instead of only an iron nail, a piece of zinc and a piece of copper were also used in the first student experiment. This was done because students had problems attributing the colour observations to specific particles. In other words, the development phase for the identity of the electrode reaction was ameliorated.
Other changes were meant to improve teachers' teaching and students' learning, like an addition of an experiment in the former section 6: instead of a salt bridge, a copper wire is used in a similar set-up. This addition was made because students often mentioned that they would like to know what happened when a copper wire is used instead of a salt bridge. In this additional experiment, it is possible to observe phenomena concerning electron transfer at the extremities of the copper wire. In other words, the application phase for the concepts of electron transport, electron transfer and ion transport was ameliorated.

The second teacher course: introduction stage

The main objective of the introduction stage for the teachers is threefold: to gain insight in their own existing conceptions and those of their students, to become aware

[10] Eight of these teachers used the second version of the student course material in their classroom. These teachers taught in 5 VWO at the Alfrinkcollege (Zoetermeer), the Johan van Oldenbarneveltgymnasium (Amersfoort), the Openbare Scholengemeenschap De Meergronden (Almere), the Altenacollege (Sleeuwijk), the Marnixcollege (Ede), the Katholiek Gelders Lyceum (Arnhem) and the Gertrudislyceum (Roosendaal). The other three teachers did not have a 5 VWO class, so they could not execute the student material in a classroom.
[11] From five out of eight teachers, I got the completed evaluation forms back (Appendix B).

of development of concepts in contexts, and to become aware of the creation of learning conditions according to Posner's model.
Teachers got introduced to Posner's model. Subsequently, in order to develop a more complete meaning of the model they were asked to relate the model to a text from their own textbook. The teachers were being asked whether their textbook pays attention to the necessity, the intelligibility, the plausibility and the fruitfulness of some particular concepts and in which way this takes place. After this, the teachers discussed their answers in groups of three. The groups were again composed of teachers who were using the same textbook.
A closer look at the model was achieved by asking the same groups of teachers to give their reactions to classroom transcript fragments recorded during the current teaching. At this point, the teachers were asked whether they thought the teacher in the transcript fragment paid attention to the learning conditions of Posner's model. Moreover, they were asked what statement they wanted to leave out or add in order to create these conditions. After they talked about this in their subgroups, the transcript fragment and their answers were discussed in the group as a whole.
Before teachers started teaching with the second student course material, they executed experiments which were new for them, in order to obtain some experience with the material, and answered assignments. The nature of the assignments differed from those in the first teacher course. This time, the assignments concerned their conceptions of the new student course material related to Posner's learning conditions.

The second teacher course: realization stage
The main objective of the realization stage for the teachers is to develop conceptions of teaching the topic of electrochemical cells within a guiding frame in relation to the four learning conditions on the basis of their own classroom experiences.
The realization stage consisted of the same elements as that in the first cycle.

The second teacher course: evaluation stage
The main objective for the teachers of the evaluation stage is the exchange of experiences and becoming aware of new conceptions.
Teachers individually executed an evaluation assignment with the help of their completed standard evaluation forms. In this assignment, they were asked about their experiences with group work and with the experiments and assignments in the student course material. The final assignment concerned the learning conditions of Posner's model in connection with the experiments in the new student course material. After this, a plenary discussion took place about their answers to this assignment.
The evaluation continued with an assignment to compare the way the concepts are described in their currently used textbook and in the new student course material. In the assignment, no references were made to the learning conditions of Posner's model. The teachers carried out this assignment individually.

In the three coming chapters, the results concerning teachers' conceptions and teaching problems will be described. The three earlier mentioned kinds of conceptions of Shulman (section 4.2) and the teaching problems concern the four key concepts in both teacher courses. The chapters are titled: teaching the concepts of electron transfer and transport (chapter 6), teaching the concept of ion transport (chapter 7), and teaching the concept of potential difference (chapter 8).
The results related to the teaching of the four key concepts are presented in the same sequence as the concepts come up in the student course material.

Chapter 6

Teaching the concepts of electron transfer and transport

In this chapter, the research questions will be worked out for two of the key concepts: electron transfer and electron transport. The first research question concerns three kinds of teachers' conceptions, viz. related to content knowledge, to pedagogical content knowledge and to knowledge of students. The second research question concerns teaching problems which are defined by me as teachers' use of contexts and teachers' use of Posner's learning conditions, which cause conceptual difficulties for students. In the first cycle, regarding the pedagogical content knowledge, attention will be paid to teachers' use of contexts (6.1). In the next cycle, regarding this category of knowledge, attention will furthermore be paid to teachers' use of Posner's learning conditions (6.2).
In order to answer the research questions, the use of contexts concerning both concepts in the first student course material will be described (6.1.1). After this, the results of the analysis of the transcripts of discourses of the teacher and student course will be reported on (6.1.2). Subsequently, the second cycle will be described in the same way as the preceding section (6.2.1 and 6.2.2). Finally, the answers on the research questions will be presented in relation to the teaching of the two key concepts (6.3).

6.1 The first cycle

6.1.1 Use of contexts

In this part of the section, I will describe the first version of the student course material concerning the concepts of electron transfer and transport, §1 - §4, from the point of view of use of contexts (Appendix D1).

In *§1*, the concept of *electrochemical cell* is introduced by means of a series of four student experiments. In the first two experiments, a zinc and a copper bar are placed subsequently in different portions of a stock of diluted sulphuric acid. After this, in the third experiment, they are placed together into another portion of this stock of diluted sulphuric acid and connected conductingly by means of a copper wire. In the fourth experiment, a milliammeter is connected with these bars. In this series of experiments, a number of phenomena, e.g. gas bubbles and deflection of an ammeter, may be observed. The phenomena can be explained by electron transport from one place (bar) to another and by electron transfer taking place on those two different interfaces, electrolyte and electrode, at the same time. In this series of experiments, students were asked to pay attention to both characteristics of electrodes: the *object characteristic* in the first two experiments and the *function characteristic* in the last two. With this series of experiments, I tried to create an opportunity for the attribution of a *combination* of electron transfer and transport to half reactions which are separated spatially from each other and which are being part of current passage. Because *existing students' conceptions of redox reactions* concern electron transfer only in one place (interface) without any observations and interpretations of current passage, a cognitive conflict may arise for the students.

By means of observation and subsequently interpretation, the aim of these experiments is that students *themselves construct* the *phenomenological context* and from this the *corpuscular context* for the *combination* of the concepts of *electron transfer and transport.*

In this *introduction* of the combination of the concepts of electron transfer and electron transport, observations and interpretations can be made. This is important for the development of a concept of *current passage in electrochemical cells*, of which chemical reaction is a part.

I chose to use a context sequence from *a phenomenological to a corpuscular context*, because analysis of the historical meanings of the two concepts and of the indicated teaching problems with them have revealed that it is important to pay attention to this *context sequence* (section 5.4). When this context sequence is used, students can design a corpuscular description on the basis of their own observations.

In my opinion, in the *sequence of the corpuscular concepts* the concept of *electron transfer* should come first and should be followed by the concept of *electron transport*. First of all, the phenomenological context of chemical reaction offers an

opportunity for direct observations, like gas development and phase transitions, in order to facilitate the attribution of electron transfer. Moreover, in the preceding curriculum topic of redox reactions, the concept of electron transfer was already introduced by means of *corpuscular descriptions of half reactions*. Besides, students have prior knowledge about *reductor strengths* from the preceding curriculum topic of redox reactions which comprises identity and direction of reactions. From physics education, students have *phenomenological knowledge of current passage and corpuscular knowledge of electron transport* in metallic conductors.
§1 is meant to function in the orientation phase for the location of electrode reactions (the place where electron transfer takes place) which is called electrode, the identity of electrode reactions (which substances are concerned) and the direction of electrode reactions (direction of electron transport).

In *§2*, the *combination of electron transfer and transport* may be further developed by students. The student experiments in §2 concern the building of an electrochemical cell with the same electrodes as in the series of experiments of §1 but with two different electrolytes, viz. diluted sulphuric acid and sodium chloride solution, which are separated in space and connected conductingly with the help of a so-called connection material, like a copper wire or a salt bridge. With the use of the copper wire as a connection material between the electrolytes, a development of the concept of electrode as a combination of electron transfer and electron transport is aimed for. Also, an orientation on, and a development of, the concept of electrolyte is aimed for on the basis of different identities of electrolytes participating in different electron transfers. Use of the salt bridge, considered as a special kind of electrolyte, aims at an orientation on current passage without electron transfer.
§2 is meant to function in the development phase for the concept of electrode and in the orientation and development phase for the concept of electrolyte. This section is also meant to function in the orientation phase for the concept of ion transport, which is developed in §5.

In *§3*, the concepts of electrode and electrolyte may be further developed by students by means of building two different galvanic cells. For this, materials are used which differ from those in §1 and §2 for the electrodes as well as for the electrolytes. The objective is that students interpret these set-ups as combinations of identified electron transfers and electron transport. Building, observing and interpreting cells themselves will again give students the opportunity to *construct the phenomenological and corpuscular context themselves.*
This section is meant to function in the development phase for the location, the identity and the direction of electrode reactions.

In *§4*, the topic of corrosion will come up by means of two student experiments, numbered 4.1 and 4.2. The first experiment comprises the placing of an iron nail into gelatine with sodium chloride and indicators for OH^- and Fe^{2+}. It is the objective that the students will put into words *observations* on different coloured areas and that their *interpretations* will cover a combination of electron transfer and transport. In doing so, the students themselves construct the phenomenological and corpuscular context for the topic of corrosion. As such, students' attention was asked for both characteristics of electrode reactions: the *process* and the *location characteristic*, for corrosion of an object may be considered as two different events taking place at the same time in different locations. However, for students the problem might arise that *one* electrode (one bar) in one electrolyte is taking part in *two* different electrode reactions, the so-called one object problem, i.e. the different identities of electrode reactions at apparently the same interface could pose as a problem, which I could again ask them to solve.
This experiment is meant to function in the application phase for the location and the direction of electrode reactions.
In the second experiment, two iron nails are placed in the same kind of gelatine, partly wrapped in either a piece of zinc wire or copper wire. It is the objective that the students make observations and interpretations and use their *prior knowledge about reductor strengths* to explain them.
This second experiment is meant to function in the application phase for the location, the identity and the direction of electrode reactions.

6.1.2 The function characteristic and the context sequence

In the previous subsection, I described four sections of the student course material which concern the key concepts of electron transfer and electron transport. These two key concepts are related to the concepts of electrode reaction and electrode. A number of assignments in the student course material are directed specifically towards the concepts of electrode reaction and electrode.
For example, assignment 1p, "May the zinc bar in set-up 1.1 be called an electrode?". This assignment regards the orientation on a set-up to which the combination of electron transport and two separated electron transfers can be attributed. Another example is assignment 4i, "Would you use the term electrochemical cell in experiment 4.1?". This assignment regards the application of the combination of electron transfer and electron transport.

In this subsection, I describe the teachers' conceptions and the teaching problems related to the concepts of electron transfer and electron transport.
Transcribed discourses are analysed in search of teachers' statements which will be seen as indicators of their conceptions. Subsequently, teachers' statements will be categorized. For example, if teachers make statements which concern observations like

gas bubbles and colours, I list them under the subcategory heading of teachers' conceptions related to content knowledge. I relate these statements to the phenomenological context and in combination with teachers' statements which I place in a corpuscular context, these statements yield information about the context sequence the teachers use. Subsequently, I list these combined statements under the subcategory heading of teachers' conceptions related to pedagogical content knowledge.
Transcribed discourses are also analysed in search of students' conceptual difficulties and related teachers' statements, which will be seen as indicators for teaching problems. In this cycle, teachers' statements concern their use of contexts. I expect most conceptual difficulties for students to show during the phases of orientation and application of the key concepts, because in current teaching of electrochemical cells, some of the teaching problems could be connected with the introduction of the concept of electrochemical cell and with the concept of corrosion. Therefore, the analysis results I will report on are only related to the orientation and application phase.

The teacher course comprises three stages, viz. the introduction stage, the realization stage and the evaluation stage. Transcripts of discourses which are recorded during these stages will successively be analysed in the following parts of this section. In the introduction and evaluation stage, only teacher course discourses were recorded and in the realization stage only classroom discourses. Consequently, research question 1, concerning teachers' conceptions, can be worked out for transcripts from all three stages. Research question 2, which concerned teaching problems, can be worked out for transcripts from the realization stage.

Orientation on the combination of electron transfer and transport (§1)
In the introduction stage of the teacher course, I asked the teachers to execute an assignment which entailed observing the four experiments from §1 and answering the student assignment whether the zinc bar in set-up 1.1 may be called an electrode. In response to this assignment, the teachers talked about the concepts of electrode and electrode reaction. It appeared that, regarding the concept of electrode, their statements concerned the object and the function characteristic. Regarding the concept of electrode reaction, their statements concerned the process characteristic.
In their statements regarding the object characteristic, they used terms which stress the form or the substance of the object which they name electrode. An example of this can be found in transcript 6.1, statement 01. In this statement, a teacher uses the words bar and piece.
In their statements regarding the function and process characteristic, the teachers emphasized the processes which take place in and at the object which they call an electrode. Examples of this can be found in statements 03 and 04. In statement 03, a teacher comments upon the use of the term electrode instead of bar when in a set-up current passage takes place. In statement 04, another teacher calls the relation between

the term of electrode and the occurrence of current passage in a current circuit a functional property of an electrode.

Transcript 6.1:

Two teachers talk about student assignment 1p (Appendix D1): "May the zinc bar in set-up 1.1 be called an electrode? Explain."

01 T1: *Yes ... they say here it functions as an electrode, now we go back to the first* [set-up], *can you still call it an electrode in this set-up and then you can say ... well it is a bar, but if you throw in a grain of zinc ... I mean then it is a question of form, if you do it because it is a bar it is an electrode, but if you throw in a piece of zinc, then there is also a reaction, but you can not call it an electrode anymore ...*

02 T2: *Also a half reaction takes place ... that is the same ... in fact the same thing is happening, at least part of it ... (...) in our school they are in the cupboard, those electrodes, they are not placed into something* (...)

03 T1: *I think you use an electrode in a certain set-up which I don't recognize in experiment 1.1 (...) because of the reaction you can say it is an electrode, when you look at the set-up then they say ... it is a set-up without an ammeter, so you can't see current passage ...*

04 T2: *Functional ... a bar behaves only as an electrode in the whole of, well also that ... that conducting solution included*

They go on to the next question. (end of transcript fragment)[1]

I interpret the teachers' remarks in this transcript to be about the object, the function and the process characteristic, the object as participating in a reaction as the arising and disappearing of substances, function and process in an electrochemical cell as a combination of reaction and current passage. I understand the teachers' statements as an orientation on the combination of both key concepts (teachers' conceptions related to content knowledge).

In the realization stage, the students executed the experiments and assignments. In response to the assignments, discourses took place between teachers and students. Regarding the assignment about the concept of electrode, teachers' statements could be distinguished concerning giving students the opportunity to formulate explanations and conclusions themselves. An example of a student who formulates an explanation as a reaction on the question of a teacher can be found in transcript 6.2, statements 01 and 04. In his statement 05, the student brings up that you can only call a set-up an (functioning) electrochemical cell when current passage takes place. In statement 06, the student names the parts of the electrochemical cell where current passage has to take place. An example of a student who draws a conclusion can be found in statement 09, where the student formulates a function characteristic, "there has to be a current".

[1] In the transcripts, I give each teacher a number. This is only meant to distinguish the teachers within one transcript fragment. Teacher 1 in transcript 6.1 does not need to be teacher 1 in transcript 6.2.

Transcript 6.2:

Students have executed all four experiments and try to answer assignment 1p (Appendix D1): "May the zinc bar in set-up 1.1 be called an electrode? Explain."

01 T: *Well you could ask yourself ... electrode is in an electrochemical cell ... can you call this an electrochemical cell*

02 S1: *No*

03 S2: *Why not?*

04 S1: *Because there is no current passage*

05 T: *Because there is no current passage ... because an electrochemical cell is a circuit*

06 S3: *So you mean there is no current conducting solution (...) and no copper electrode*

07 T: *No you have a bar ... and can such a bar in a solution form an electrochemical cell (...) it is one half reaction ... what do you normally have in an electrochemical cell?*

08 S2: *Two (...)*

09 S4: *There has to be a current*

10 T: *Exactly*

(end of discourse)

I understand the discourse of the teacher and the students as orienting on the combination of electron transfer and electron transport. One of the students brings up the need for current passage (a first step towards the corpuscular concept of electron transport), and the teacher agrees. The number of half reactions is brought up by the teacher (which he means as a first step towards the corpuscular concept of electron transfer), but he wants the student to construct the context. The teacher's conception related to the topic of electrochemical cells is reflected by his expression 'two half reactions' and 'current circuit' (teachers' conceptions related to content knowledge).
The teacher attempts to give the student the opportunity for context construction, see for example transcript 6.2, statements 05 and 06 (teachers' conceptions related to pedagogical content knowledge).
In the realization stage concerning the teaching of §1, I could not indicate any teaching problems.

In the evaluation stage, the teachers did not talk much about the orientation on the combination of the two concepts. They preferred to talk about some practical troubles they had, like the amount of ammeters necessary for these student experiments. I think they talked so little about the orientation on the combination of the two concepts, because they encountered few conceptual difficulties of students concerning §1 in their classrooms. This little talking is consistent with my analysis of transcripts of discourses in the realization stage concerning §1, in which I could not indicate teaching problems either.

Application of the combination of electron transfer and transport (§4)

In the introduction stage of the teacher course, I asked the teachers to do an assignment which consisted of the execution of the experiments 4.1 and 4.2, and a student assignment, asking whether they would use the term electrochemical cell in experiment 4.1. In response to this assignment which was related to the topic of corrosion, the teachers talked about the concepts of electrode reaction and electrode.
An example of a teacher statement regarding the process and the location characteristic can be found in transcript 6.3, statement 06. In this statement, a teacher mentions "an electron flow from one spot to the other", which I interpret as a remark on the process characteristic. Also he says "all sorts of areas", which I interpret as electron transfer occurring at different places at the same time, viz. the location characteristic.
The teachers realized that one object (a nail) functions as two electrodes. Examples of this can be found in statements 06/08. In statement 06, the teacher says here (one nail) you have a lot of cells and per cell (the nail acts) as two electrodes. In statements 07 and 08, the teachers realize that this one (one object) is both plus and minus at the same time. I interpret the term "this one" as concerning the object characteristic. The phrases "both plus and minus" and "at the same time", I interpret as regarding the function characteristic.

Transcript 6.3:

Three teachers execute student assignment 4i (Appendix D1): "Would you use the term electrochemical cell in experiment 4.1? Explain."

01 T1: *So that's this experiment ... the definition of electrochemical cell was ... a cell with a solution and an electrode*

02 T2: *Yes ... in principle yes, I think it is an electrochemical cell (...)*

03 T1: *But do students see this as an electrochemical cell*

04 T2: *Yes but the point isn't that students, the point is whether it is one of course*

05 T1: *Should you*

06 T2: *Yes for me indeed, but ... there is an electron flow from one spot to the other ... and here is electrode and conductor all of the same material (...) but here you have actually a lot of cells ... because you have all sorts of areas ... of course you cannot call it one cell ... then you really have only one electrode, one plus and one minus ... you don't have that here*

07 T3: *Yes this one is both plus and minus*

08 T1: *At the same time*

Then they start discussing the second experiment. (end of transcript fragment)

I interpret what is said by the teachers in this transcript to be about the object and function characteristic as well as about the process and the location characteristic. I understand the teachers' statements as applying the combination of electron transfer and electron transport (teachers' conceptions related to content knowledge). Their concern for students appears to be of secondary importance compared to their concern for content knowledge (teachers' conceptions related to knowledge of students).

In the introduction stage, I also asked them to execute the following assignment: "What is your opinion on the introduction of the concept of corrosion compared with its introduction in your textbook?". This assignment aims for the application of the combination of electron transfer and electron transport.
The teachers were of the opinion that the students will be actively involved in learning about the topic of corrosion when they use this new student course material. An example of this can be found in transcript 6.4, statement 03, when the teacher says that the students "have to sort out a little more themselves" and "let VWO find out for themselves, what is actually happening". This teacher argues in favour of an opportunity for context construction by the students.
In answering this assignment, the teachers also paid attention to the two student experiments (4.1 and 4.2) which they had executed before. The way they talked about the experiments clearly shows that they have paid attention to observations, i.e. the phenomenological context, for the "visualizing" of corrosion. Examples of discussion of observations can be found in statement 08. In this statement, the teacher remarks upon the "blue complex" which can be seen clearly. The term "complex" which the teacher uses can be considered as expert language.

Transcript 6.4:
Three teachers execute a teacher assignment which is aimed at finding out their opinion on the introduction of the topic of corrosion compared with its introduction in their textbooks.

01 T1: *Let's first take a look at the textbook (...) here oxygen is equally in contact everywhere ... I also thought this was convincing, but well, I have done this sometimes as a student experiment, of course this is ... the beautiful thing here is that when you do these two experiments at once you introduce the protection at the same time ... of course here they do so on ... sacrifice metals, here you have killed two birds with one stone with a beautiful experiment (...)*

02 T2: *Protection against corrosion ... clear experiments anyway ... yes here they take as a starting-point that two years ago they were told what corrosion is ...*

03 T1: *Here they have to sort out a little more the reactions themselves ... while they are here for taking ... of course concerning this ... this is more suited for HAVO*[2] *you could say, let VWO find out for themselves, what is actually happening ... yes it is of course ... this is not an experiment is it ... I have sometimes done it as an experiment, but it is not mentioned as a demonstration experiment*

04 T3: *Very little*

05 T1: *Student experiment is of course clearer*

06 T2: *Clear experiment for corrosion isn't it*

07 T1: *Well that is ... especially that sacrificing ... that is of course very clear in this way ... I think that's a fine experiment that sacrifice metal (...)*

[2] Higher general education.

08 T3: *And it is also visualized ... because here you see clearly that blue complex, which you don't see there and I think that's nice about it (...) this is with an electrochemical background ...*

(end of discourse)

I interpret their discourse as regarding how to teach the application of the combination of the concepts of electron transfer and electron transport. I understand the teachers' statements as giving students the opportunity to construct the phenomenological and corpuscular context themselves (teachers' conceptions related to pedagogical content knowledge). The teachers talk more about observations than about interpretations. In my view, the corpuscular context is so obvious for the teachers that they do not talk much about it.

In the realization stage, the students executed the experiments 4.1 and 4.2 and the accompanying assignments. In response to the student assignment asking whether a nail in gelatine can be considered as an electrochemical cell, discourses took place between students and teachers. I could indicate two categories of teachers' statements. Namely, teachers' statements about offering to students the opportunity to construct contexts and teachers' statements concerning constructing contexts themselves.

I will go first into the first category of teachers' statements. Examples of discourses in which a teacher and a student construct a context together can be found in transcript 6.5, statements 01, 06 and 10. In statement 01, the student says "one electrode", which I interpret to be about the object characteristic. In statement 06, the teacher says "a number of half reactions", which I interpret as to be about the process characteristic. In statement 10, the teacher says "different zones", which I interpret as to be about the location characteristic. The teacher tries to make clear that half reactions in this case take place at two different locations. I interpret his statements as attempts to describe the location characteristic.

The teacher links up with what the student has said before. An example of the same use of terms can be found in statement 12. In statement 11, the student ends up using the term electrochemical cell. In statement 12, the teacher tries to go back to the definition of electrochemical cell. The student compares properties of redox reactions with properties of reactions in an electrochemical cell. The student's conceptual difficulty is that there are no differences between the written notation of half reactions and the written notation of electrode reactions.

<u>Transcript 6.5:</u>

Teacher and student have a discourse about student assignment 4i (Appendix D1): "Would you use the term electrochemical cell in experiment 4.1? Explain." The student has executed, with his group, the experiments 4.1 and 4.2 and the assignments concerning observations and interpretations. The rest of the group listens.

01 S: *One nail in gelatine with salt solution isn't an electrochemical cell ... isn't it (...) because it is only one electrode, it is just a reaction it er ... the nail and the water and that oxygen ...*

02 T: *Nail water oxygen ... can you ... in fact say that it is a reaction ... like for example ... magnesium that reacts with oxygen*
03 S: *Yes*
04 T: *Could you say it is exactly one such reaction ... to put it like that*
05 S: *Except for the water*
06 T: *Yes well I was hoping you would say no (...) you have, in my opinion ... a number of half reactions*
07 S: *Yes those two ...*
08 T: *Yes exactly and is it now*
09 S: *Those react just with each other ... because the current isn't going like this and like that*
10 T: *Well that remains to be seen ... because I thought I had seen clearly that there were different zones at that nail*
11 S: *Red and blue (...) but that is the same with the magnesium, there you have also half reactions when magnesium reacts with oxygen ... that's no electrochemical cell either*
12 T: *When is something an electrochemical cell when you can find two electrodes (...) with a conducting connection around and one inside round to say it like that, yes so liquid conducting and metal conducting ... (...) I want to get back to the phenomena*
13 S: *This one just reacts also with oxygen and that are also two half reactions and this just reacts also with oxygen ... coincidentally it needs water ... and it is also just two half reactions and why is this one actually an electrochemical cell and why isn't the reaction of magnesium with oxygen (...)*
14 T: *We should try to interpret the observed phenomena (...) let's just take a look at the nail which is in a salt solution and which is coloured with certain colouring agents and at some point you see a red and blue zone arising*

Then they start describing the electrode reactions in a corpuscular way. (end of transcript fragment)

I understand the discussion of the teacher and the student in transcript 6.5 as applying the location of the combination of electron transfer and electron transport. The teacher offers the opportunity to the student to formulate his conceptual difficulty a number of times (teachers' conceptions related to pedagogical content knowledge). The student's description of this problem becomes more and more clear.
In this transcript a teaching problem could be indicated. This problem concerns the dominance of the corpuscular context in the teacher's statements because he pays much attention to the number of half reactions but less attention to their location (teachers' conceptions related to content knowledge). The student's conceptual difficulty concerns understanding that two related half reactions can take place in one location or two different locations, and that this has consequences for calling it a direct or an indirect redox reaction.

Discourses in which teachers' statements of the second category can be distinguished, comprised teachers' statements which do not link up with the terms the students use. Examples of those teachers' statements can be found in transcript 6.6, statements 02 and 08. In statement 02, the teacher talks about the (number of) half reactions whereas

the student has not used the term half reaction. In statement 08, the teacher delivers a monologue and constructs the phenomenological and corpuscular context himself. This teacher does not take students' conceptions into account, because in his statement following the student's statement 05, he refers to the definition of electrochemical cell, when he should have gone into the problem of the student. In statement 05, the student talks about one nail which I interpret as the one object problem (section 6.1.1).
The teacher's statements concerned also the location characteristic. An example of a teacher's statement regarding this characteristic can be found in statement 08. In this statement, the teacher talks about the locations where the reactions take place, "hop the other takes place next to it".

Transcript 6.6:
Students are trying to execute student assignment 4i (Appendix D1): "Would you use the term electrochemical cell in experiment 4.1? Explain." The teacher arrives at the group as one of the students asks a question.

01 S1: *Question i ... electrochemical cell*
02 T: *How many half reactions do you have*
03 S2: *Two*
04 T: *Two*
05 S1: *Yes but you have only one nail in the solution*
06 T: *Well you could look at the definition of what an electrochemical cell is ...*
07 S1: *Yes two electrodes*
08 T: *You have two electrodes and you have two half reactions ... and what we are getting now, the phenomenon that you have now in fact one electrode ... that's the iron, that acts as two ... because both half reactions are set at the iron ... then you'll say I can't see current ... no because the electrons are passed on at the same place ... it's on the spot ... those electrons circle through that nail and from the one reaction ... hop the other takes place next to it ...*

(end of discourse)

I understand the discourse of this teacher and his students as applying the combination of electron transfer and electron transport. The teacher gives few opportunities to the students for context construction (teachers' conceptions related to pedagogical content knowledge).
In this transcript, a teaching problem could be indicated. The teaching problem concerns the emphasizing of one particular context. In this case, the emphasized context is the corpuscular context of half reactions. The student's conceptual difficulty concerns understanding whether to choose for one object or more places where the reaction(s) take place.

In the evaluation stage, I listened to the teachers talking about teaching the topic of corrosion. The teachers talked mainly about the assignment in which was asked whether a nail in gelatine could be considered an electrochemical cell. The teachers talked about interpretations of corrosion (the application of the combination of the two

concepts) which appeared to them to be difficult to make for students. Examples of teachers discussing students' conceptual difficulties can be found in transcript 6.7, statements 01 and 03, when the teacher says "for those students that had nothing to do with the previous" and "but for those students really something else is suddenly happening".
Also the teachers talked about the position where the syllabus topic of corrosion should be discussed in a sequence of other syllabus topics concerning electrochemical cells for VWO. Examples can be found in statements 06 and 08. In statement 06, the teacher says that he wants the topic of corrosion placed nearer to the end of the student course material. In statement 08, the teacher argues in favour of the generally used sequence of topics in VWO.

<u>Transcript 6.7:</u>
This transcript is part of the plenary discussion on the evaluation of teaching with §4, including the experiments, on corrosion.

01 T1: *Well of course it is nice to see that nail in that electrolyte as a cell ... but maybe it is nice for us to see that, but for those students that had nothing to do with the previous ... in first instance ... why that section there*
02 TE[3]: *Could you explain why it was possible for you*
03 T1: *Because I can see a cell in it ... what I observe in that dish, but for those students ... really something else is suddenly happening there at once, you don't have two ... electrodes anymore ... no salt bridge ...*
04 TE: *What did you do when you encountered this*
05 T1: *Well I had them do those assignments first ... and asked whether they could see in one way or another a cell in it ... well in the end that succeeded ... (...)*
06 T2: *I would have placed that corrosion further on*
07 TE: *And for what reason?*
08 T2: *Well let's first finish those electrochemical cells as in the start ... maybe old fashioned ... up to and including Nernst and then later on come to corrosion ... as a practical example (...) just to finish the electrochemical cell ... with all that comes with it and then the practical examples ... for myself (...) I thought it was a very nice one, that corrosion experiment*

Then they start discussing on §5. (end of transcript fragment)

I understand the discussion of the teachers in this transcript as evaluating the application of the combination of both concepts in teaching.
In my view, when a teacher argues in favour of a *topic* sequence which is just like the one in current teaching, he does not recognize the importance of the *context* sequence in the student course material (teachers' conceptions related to pedagogical content knowledge).
The teachers also discuss students' understanding of the sequence in the student course material and their difficulties with this sequence (teachers' conceptions related to knowledge of students).

[3] TE means teacher educator. An explication of the notation of the transcripts is given in Appendix A.

6.2 The second cycle

6.2.1 Use of learning conditions and contexts

In this part of the section, §1 - §4 of the second version of the student course material will be described from the point of view of the use of Posner's four learning conditions and the use of contexts (Appendix D2; Acampo & De Jong, 1995). The sections in the student course material have not been changed much compared to the first version (see section 5.5).

§1 and *§2,* in which the *combination* of the concepts of electron transfer and transport emerges for the first time, can be considered as aiming for the creation of the *learning condition of necessity* for two reactions related by electron transport and are taking place at the same time in different places. The existing students' conceptions of redox reactions only comprise electron transfer. For the first two experiments, these existing conceptions are sufficient, thus students can use their prior knowledge concerning reductor strengths. For the third and the fourth experiment, it is necessary for students to combine identified electron transfer and the direction of electron transport, because otherwise they cannot make interpretations based on their observations.
§1 and §2 aim also at creating the *learning conditions of plausibility and intelligibility* for the location, the identity and the direction of electrode reactions. The third and fourth experiment which are described in section 6.1 aim at observations of phenomena related to the key concepts, and contribute to the creation of the learning condition of plausibility. The accompanying assignments aim at the interpretations of the above-mentioned observations and contribute to the creation of the learning condition of intelligibility.
In §2, the variation of electrolytes and electrodes aims at creating the learning condition of intelligibility for the identity of electrode reactions.

In *§3* and *§4,* experiments are described in which the students have to use the combination of concepts they may have developed in the previous two sections in order to understand these experiments. §3 and §4 aim at using the new concepts in other situations, thus at creating the *learning condition of fruitfulness* for the combination of the concepts of electron transfer and transport.
Both sections also aim at creating the *learning conditions of plausibility and intelligibility* because of the possible observations and interpretations of the previously described experiments.

6.2.2 The necessity and the corpuscular context

The same two analysis categories are used as in the first cycle, viz. teachers' conceptions and teaching problems.
Again, transcribed discourses are analysed in search of teachers' statements which will be seen as indicators of their conceptions. The subcategory of teachers' conceptions related to pedagogical content knowledge is now extended by teachers' use of learning conditions. For example, when teachers talk about giving students the opportunity to interpret observations themselves, I relate the teachers' statements to the creation of the learning condition of intelligibility and place this in the category of teachers' conceptions related to pedagogical content knowledge.
Transcribed discourses are also analysed for teachers' statements related to students' conceptual difficulties which will be seen as indicators of teaching problems. In this cycle, teachers' statements, in addition to teachers' use of contexts, concern their use of the four learning conditions. Teaching problems can be indicated in the stage which takes place in the classroom, viz. the realization stage, because their indicators are students' conceptual difficulties related to teachers' statements.

Orientation on the combination of electron transfer and transport (§1)

In the introduction stage of the teacher course, I asked the teachers to execute a teacher assignment which entailed observing the four experiments, answering some student assignments and discussing whether the learning condition of necessity is created for the concept of electrode. Regarding this learning condition, an example can be found in transcript 6.8, statement 01. In this statement, the teacher connects the learning condition of necessity with the need to "introduce" new words.
Regarding the concept of electrode, an example of a teacher talking about the reason why he thinks that the learning condition of necessity has been created for the concept of electrode can be found in statement 03. In this statement, the teacher puts into words why he thinks it is necessary to call a bar an electrode when the combination of the concepts of electron transfer and transport can be attributed. I interpret his statement "difference in function" to be a statement regarding the function characteristic of electrode, i.e. regarding the fact that reaction and metallic conduction together play a role in current passage. This teacher also makes a statement which I interpret as regarding the object characteristic, "it is about a bar at which current passage takes place". Also in statement 05, the teacher makes a statement regarding the function characteristic, where he says that "there is a difference in function".

<u>Transcript 6.8:</u>
Three teachers are discussing whether the learning condition of necessity has been created for the concept of electrode in the second version of the new student course material (see also section 5.5 of this thesis).

01 T1: *Electrode ... necessary according to us ... do we absolutely have to introduce the word electrode while doing this (...) do we absolutely have to*

mention electrode ... no, but because it's a generally used term, it will be clever to do so

02 T2: *Difficult question*

03 T3: *Yes it is difficult, it is about a bar at which current passage takes place ... if this concept (...) actually I think yes, because in experiment one, two and three and four one always uses bars ... you always use zinc bar, copper bar ... apparently there is a difference in function of this this bar in experiment one compared with the other three experiments*

04 T2: *Yes*

05 T3: *And then it is ... well maybe necessary is a bit strong, but really clever to define the function it has in the other three experiments ... of current passage separately (...) yes I think it is necessary and I also think that it becomes by these four experiments ... at least for the difference between experiment one and the other three experiments ... it also becomes clear that there is a difference in function (...) honestly I have to say that I myself had to think very hard about it when I had to answer this question on what exactly is an electrode (...) and that I then thought, yes that function is rather different there and there ... so for me it did have the effect that I suddenly understood why you have to name it exclusively*

Then they go on to discussing the intelligibility of the concept of electrode. (end of transcript fragment)

I interpret the teachers' statements in this transcript as referring to the function and object characteristic. In doing so, the teachers talk about the learning condition of necessity (teachers' conceptions related to pedagogical content knowledge).
I understand the teachers' statements as an orientation on the combination of electron transfer and electron transport by explicating current passage together and in connection with the concept of reaction which they did not put into words (teachers' conceptions related to content knowledge).

In the realization stage, I also listened to how the teachers talked, together with their students, about the concept of electrode. This concept was discussed as a result of the experiment in which the zinc and copper bar were connected with a copper wire and placed together into a portion of diluted sulphuric acid. Teachers paid most attention to the creation of the learning conditions of plausibility and intelligibility. Examples of creating the learning condition of plausibility can be found in transcript 6.9, statements 01, 03 and 15. In these statements, the teacher asks for the students' observations. An example of creating the condition of intelligibility can be found in statement 07. In this statement, the teacher asks the student to give a corpuscular interpretation.
The teachers did not always use the possibilities to create the learning conditions of intelligibility and plausibility for the combination of the concepts of electron transfer and electron transport on moments that they could have done so. Examples of this failure to use those possibilities can be found in statements 17 and 19. In statement 17, the teacher starts with creating the learning condition of plausibility because he offers the students the opportunity to do an experiment themselves. However, he formulates

the observations himself and in this way he does not complete the creation of the learning condition of plausibility for the concept of electron transport. Moreover, he does not create the learning condition of intelligibility with the experiment which he gives the students the opportunity to execute, because if electrons moved through the solution they would meet H^+-ions way before they reached the copper bar. Also, another part of the learning condition of plausibility is not created because there is no current circuit anymore in the proposed experiment. Finally, in statement 19, he does not create the learning condition of intelligibility for the concept of electron transport when this was possible, because he formulates the conclusion himself.

<u>Transcript 6.9:</u>
Two students executed the experiment in which both bars are placed into a portion of diluted sulphuric acid and try to give an explanation for their observations.

01 T: *What do you see*
02 Ss: *Bubbles*
03 T: *What is the difference with experiment 1*
04 S1: *Now also at the copper*
05 T: *Yes there is also gas at the copper now ... how can that be according to you*
06 S2: *Those electrons they go now*
07 T: *Yes, what are the electrons from the zinc doing ...*
08 S1: *Hmm they go to the copper ... let's see ... zinc gives them away ... electrons from zinc they go to the copper*
09 T: *How*
10 S1: *I think through the sulphuric acid*
11 T: *You think through the acid ... and what do you think*
12 S2: *The electrons will go this way*
13 T: *Through the solution ... yes ... that's not right no*
14 S1: *Well then they'll go through the wire*
15 T: *Yes then they'll go through the wire (...) how can you check if this is right ...*
16 S2: *Well remove that wire again*
17 T: *Yes ... well try it ... (...) ... so you see it ... at the copper it stops*
18 Ss: *Hmm ... yes*
19 T: *So it has to go through the wire*
(end of discourse)

I understand the discussion of this teacher and his students as an orientation on the combination of electron transfer and electron transport (teachers' conceptions related to pedagogical content knowledge).
In this transcript, a teaching problem could be indicated. This teaching problem concerns teachers who do not create the learning conditions of plausibility and intelligibility for the combination of the concepts of electron transfer and transport. The students' conceptual difficulty is that they do not understand that there needs to be a combination of electron transfer at the electrode and electron transport through the electrode, and no electron transport through the electrolyte.

In the evaluation stage, I listened to how the teachers discussed the teaching of §1 of which the four experiments were part. The teachers discussed their use of learning conditions and their use of contexts.
An example of a teacher statement which I interpret as concerning the learning conditions can be found in transcript 6.10, statement 01. In this statement, the teacher talks about creating the learning condition of plausibility for the concept of current passage because of the experiments.
An example of teachers talking about their use of contexts can be found in statement 02. In statement 02, the teacher proposes to extend one of the experiments. He wants to place both bars together in the diluted sulphuric acid, first without a connection wire in order to show students that, in this case, no gas bubbles will arise at the copper. I interpret this statement as an extension of the phenomenological context in order to facilitate the construction of the corpuscular context.
Teachers talked also about conditions which contribute to the active learning of students. An example of this can be found in statement 03, where the teacher says that the experiments give the students something to think about.
The teachers also talked about the difficulties they themselves have regarding the object and the function characteristic of electrodes. In statement 07, the teacher realizes that both characteristics are necessary to call an object an electrode.

Transcript 6.10:
This transcript is recorded during the plenary evaluation of §1.
01 T1: *Well I would like to say ... that students in general have very little knowledge of electrical current, that is very magical ... (...) it becomes very plausible ... these experiments contribute a lot to a certain model (...)*
02 T2: *In experiment 1.2 I thought it would also be sensible ... first without a connection wire then they'll see, hey, at the copper nothing is happening ... that I think yes, there are students who think that zinc two plus ions move to the copper bar and do something there (...) you prevent that then (...)*
03 T3: *Well it gives them something to think about ... really an eye-opener for those students, what happens at that copper bar ... very good about that experiment*
04 TE: *Electrode (...) has it become clear for your students that that new word has a function (...) but do you have electrodes or bars in the cupboard*
05 T4: *Bars*
06 T5: *That distinction is for me ... yes very good ... yes you see I have written it wrongly ... use two platinum electrodes* (teacher 5 is also a textbook author)
07 T4: *Every time again I keep on having been inclined, also when there is no current passage, to talk about electrodes (...)*
Then they go on about §4. (end of transcript fragment)

I understand the discussion of the teachers in this transcript as evaluating the orientation on the combination of both concepts in teaching. Some statements concern the object and function characteristic (teachers' conceptions related to content knowledge). Other statements deal with learning conditions and active learning (teachers' conceptions related to pedagogical content knowledge).

Application of the combination of electron transfer and transport (§4)
In discourses in the introduction stage on the application of the concepts of electron transfer and electron transport, the teachers talked about the concepts of electrode and electrode reaction in relation to the topic of corrosion. They talked about how to enhance students' understanding in response to the assignment in which was asked whether a nail in gelatine with salt solution can be called an electrochemical cell.
Examples of teachers talking about students' understanding of the concept of electrode can be found in transcript 6.11, statements 04 and 11. In statement 04, the teacher talks about the 'one-object' problem which the students experience according to him, "for them it's just one electrode". In statement 11, another teacher argues the same thing, "because only one electrode".
The teachers also talk about the location characteristic of the concept of electrode reaction. An example of this can be found in statement 08, where the teacher talks about half reactions taking place at different places.
Moreover, they talk about how to enhance students' understanding, see statement 06. However, in statement 06, the teacher ignores in his proposition the possibility of creating the learning condition of necessity for the combination of the concepts of electron transfer and transport. Because in his proposition, the location characteristic would be put into words by either the teacher or this would be done in the student course material, because he says "to be seen in different places". The only thing left for the students to answer would then be the identity of the electrode reactions.

Transcript 6.11:
Three teachers are executing student assignment 4e (Appendix D2): "Would you call the nail in gelatine with a solution of table salt and two indicators an electrochemical cell? Explain."

01 T1: *Would you call the nail in gelatine an electrochemical cell*
02 T2: *What's the definition of an electrochemical cell ... a set-up with electrodes and current conducting substances in between*
03 T1: *Students will say no two poles (...)*
04 T2: *Here there is nothing in between ... yes I am looking at it with students' eyes ... is of course the old problem with this corrosion ... that ... in order to see it like this you really have to want to see it like this ... for them it's just one electrode isn't it*
05 T3: *Yes that's true ... they only see one electrode and then you get the same idea as a zinc bar in hydrochloric acid ... you don't call that an electrochemical cell either*
06 T2: *Shouldn't one in fact just ask directly ... colours, to be seen in different places ... could the same half reaction take place there*
07 T3: *That the half reactions take place that'll be clear*
08 T2: *The attention should be directed towards the fact that that happens in different places*

09 T3: *Yes*
10 T2: *I think different places is putting it rather ... well ... elastic* (...)
11 T1: *Well not for students ... because only one electrode ... so*
Then they talk about what students know about batteries before they encounter this topic in chemistry lessons. (end of transcript fragment)

I understand the discussion of the teachers in this transcript to be an orientation on teaching the combination of electron transfer and electron transport. Teachers' statements concern students' understanding of these concepts (teachers' conceptions related to knowledge of students).

In the realization stage, the students executed the experiments and assignments of §4 on the topic of corrosion. In response to the assignments, discourses regarding the concept of electron transfer and electron transport took place between the teachers and the students. During these discussions, teachers' statements could be indicated concerning the opportunities that they gave students to observe and interpret. I interpret this as their creating the learning conditions of plausibility and intelligibility for the combination of the two concepts.
An example of a teacher trying to create the learning condition of plausibility can be found in transcript 6.12, statement 04, in which the teacher asks for an explanation of the different colours, which question concerns the plausibility of different electron transfers (process characteristic) on different places (location characteristic).

<u>Transcript 6.12:</u>
A group of students executed experiment 4.1 and tried to answer assignment 4d (Appendix D2): "Why is the table salt added to the gelatine with two indicators?" Then they ask the teacher for help.
01 S1: *Our theory was that OH^- arises from oxygen from the air and the water ... purple colour ... and Fe^{2+} that blue and at zinc that white stuff*
02 T: *Yes*
03 S1: *Well the question with that table salt ... well of course in a salt bridge that is also like this ... but why does that have to be connected ... that's not really necessary in itself*
04 T: *Well except for those discoloration's, you of course observe something else when you make a drawing ... er ... is it the same everywhere*
05 S2: *No some pieces green ... some purple ... is it for conducting then*
06 T: *You have to look for it in that direction yes*
(end of discourse)

I understand the talking of the teacher and students in transcript 6.12 to be an application of the process and location characteristic of the combination of electron transfer and electron transport. The teacher created the learning condition of plausibility (teachers' conceptions related to pedagogical content knowledge).

In the evaluation stage, I established how the teachers talked about applying the combination of electron transfer and electron transport. Teachers' statements concerned the use of the learning conditions for several concepts like corrosion and electron transport.
Examples of teachers discussing the learning conditions can be found in transcript 6.13, statements 01/03. In statement 01, the teacher talks about the learning condition of fruitfulness for the concept of corrosion because of the connection with society, "their bikes which rust". In statement 02, the teacher talks about the learning condition of necessity for the concept of corrosion which he thinks is not created because it is not clear to the students why this topic is in the material, at least not when they start with the section on corrosion. In statement 03, the teacher implicitly considers the learning condition of intelligibility for the concept of electron transport when he says "you see very clearly that there has to be electron transport".

Transcript 6.13:
This transcript is recorded during the plenary evaluation of the teaching of §4.

01 T1: *This section I like best ... I think it's really beautiful ... and it is also fruitful at the same time ... it has really something to do with a very concrete problem that they all know from their bikes which rust ... and ... yes ... what they see happening then makes it clearer ... about rusting and so ... very nice ... I think the fruitfulness is the strongest part of this section*

02 T2: *Not so much this necessity, they will only see afterwards that, oh, it is also an electrochemical cell ... beforehand they really thought what's this section doing here*

03 T3: *I have difficulties expressing this in those four terms ... I think these are immensely nice experiments ... they are very enlightening ... you see very clearly that there has to be electron transport ... different zones very clearly visible ... and the surprise was also very big for students ... and also the concept of sacrifice metal is very well explained for student purpose*

Then they start talking about some practical aspects. (end of transcript fragment)

I understand the talking of the teachers in this transcript to be the evaluation of the application of the combination of both concepts. Their statements concern three of the four learning conditions (teachers' conceptions related to pedagogical content knowledge).

6.3 Teachers' conceptions and teaching problems

In this section, the answers will be presented on the research questions about teaching the concepts of electron transfer and transport. The results of the analysis of both cycles will be combined. The motive for combining the results of both cycles is that they partly overlap, i.e. some conceptions could be indicated in the first and in the second cycle.
The teachers' conceptions concern three categories of their knowledge mentioned by Shulman (1987), namely:
- content knowledge, i.e. knowledge of the key concepts of electron transfer and electron transport including the four characteristics, viz. object, function, location and process characteristic, and knowledge of the use of contexts in texts concerning electron transfer and electron transport,
- pedagogical content knowledge, i.e. knowledge concerning creating Posner's learning conditions and knowledge concerning use of contexts concerning electron transfer and electron transport,
- knowledge of learners and their characteristics, i.e. knowledge concerning both existing students' conceptions of electron transfer and electron transport, and knowledge concerning the development of their conceptions.

First, concerning the four characteristics conceptions of teachers could be indicated.
Teachers' conceptions concerning the object characteristic could be shown. Concerning these conceptions, an electrode is described as a bar or a particular substance. In transcripts 6.1, 6.6 and 6.11, examples can be found of teachers' statements which reflected these conceptions. But in the last two transcripts as cognitive conflict with accompanying teaching problems for corrosion.
Also, *teachers' conceptions concerning the function characteristic* could be pointed out. Concerning these conceptions, an electrode is considered as a part of a current passage circuit (phenomenological context) or as the combination of electron transfer and electron transport. In transcripts 6.2, 6.3, 6.8 and 6.10, examples can be found of teachers' statements communicating these conceptions.
Next, *teachers' conceptions concerning the location characteristic* could be stated. Concerning these conceptions, an electrode reaction is considered as taking place at a bar, at an interface (phenomenological context) or at a spot (corpuscular context). The topic of corrosion seemed easy to teachers beforehand but as appears from the transcripts of the realization stage this is not the case. When they taught this topic, the location characteristic of the concept of electrode reaction showed their problems with the teaching of the topic of corrosion very clearly. In transcripts 6.3, 6.5, 6.6, 6.11 and 6.12, examples of teachers' statements revealing these conceptions can be found.
Finally, *teachers' conceptions concerning the process characteristic* could be given. Concerning these conceptions, an electrode reaction is considered as an event

(phenomenological context) and can be described in a corpuscular way. In transcript 6.1, 6.3, 6.5 and 6.12, examples of teachers' statements can be found which reflect these conceptions.

Second, teachers' conceptions concerning contexts could be indicated.
Teachers' conceptions concerning paying attention to the phenomenological context could be pointed out. Concerning these conceptions, the importance of paying attention to the phenomenological context of the two key concepts was mentioned, especially for the concepts of corrosion and sacrifice metal in an electrochemical background. In transcripts 6.4, 6.5, 6.9, 6.10 and 6.13, examples of teachers' statements can be found communicating these conceptions.
Also, *teachers' conceptions concerning paying attention to the combination of the phenomenological and corpuscular context* could be indicated. Concerning these conceptions, attention was paid to observations and interpretations. In transcripts 6.4, 6.5, 6.9 and 6.12, examples of teachers' statements reflecting these conceptions can be found.

Third, teachers' conceptions related to learning conditions can be indicated.
Conceptions of teachers concerning the creation of the learning condition of necessity for the function characteristic could be given. Concerning these conceptions, the necessity of the concepts of electrode and electrode reaction was discussed. In other words, for calling a bar an electrode, the combination of the concepts of electron transfer and transport is necessary. In transcripts 6.1, 6.2 and 6.8, examples of teachers' statements communicating these conceptions can be found.
Teachers' conceptions concerning the creation of the learning conditions of plausibility and intelligibility could be stated. Concerning these conceptions, attention was paid to students making observations and interpretations. Also it appeared that the experiments were considered to clarify the concepts of electron transport and transfer for students because of these observations. In transcripts 6.10, 6.12 and 6.13, examples can be found of teachers' statements revealing these conceptions.

Fourth, two other teachers' conceptions could be indicated, which are not directly related to either characteristics, contexts or learning conditions.
Teachers' conceptions concerning giving students the opportunity to formulate their own conceptual difficulties could be pointed out. Also the educational situations in which conceptual difficulties for students might possibly occur were discussed. In transcript 6.5, examples of teachers' statements can be found which reflect these conceptions.
Teachers' conceptions concerning taking account of students' existing conceptions could be indicated. Concerning these conceptions, conceptual difficulties of students were discussed. For example, the so-called 'one-object-problem' in the experiments

about corrosion was held to be one of the most important difficulties for students. In transcripts 6.3, 6.6 and 6.11, examples can be found of teachers' statements which communicate these conceptions.

Besides teachers' conceptions also teaching problems could be indicated.
Teaching problems which concerned the dominance of the corpuscular context in relation to the phenomenological context could be indicated. Concerning these teaching problems, counting of half reactions took place. One conceptual difficulty of students concerns understanding that two related half reactions can take place in one location or in two different locations, and that this has consequences for calling it a direct or an indirect redox reaction. The other conceptual difficulty of students concerns understanding whether to choose for one object or more places where the reaction(s) take place. In transcripts 6.5 and 6.6, examples concerning these teaching problems can be found.
Also *teaching problems concerning teachers constructing contexts themselves* could be pointed out. Concerning these teaching problems, the students' conceptual difficulties concern the characteristics of the concepts of electrode and electrode reaction, like the location characteristic of the concept of electrode. In transcript 6.6, an example of these teaching problems can be found.
Other *teaching problems which concerned not creating the learning conditions of plausibility and intelligibility* could be indicated. Concerning these teaching problems, the teachers offered no possibilities for students to observe and subsequently interpret for the combination of the concepts of electron transfer and transport, in educational situations where they should have done this. Again this caused conceptual difficulties for students in understanding the characteristics of both concepts. An example of these teaching problems can be found in transcript 6.9.
Finally, *teaching problems related to not taking account of students' prior knowledge* could be indicated. The students' conceptual difficulties concern understanding there needs to be a combination of electron transfer at the electrode and electron transport through the electrode, and no electron transport through the electrolyte. Examples of these teaching problems can be found in transcripts 6.6 and 6.9.

Chapter 7

Teaching the concept of ion transport

In this chapter, the research questions will be worked out for the key concept of ion transport. The way in which this is done will be the same as in the previous chapter.

7.1 The first cycle

7.1.1 Use of contexts

In this part of the section, I describe the first version of the student course material on the concept of ion transport, §6, from the point of view of use of contexts (Appendix E1).

In *§6,* more attention is paid to the *concept of ion transport,* because so far *its relation with the concepts of electron transfer and electron transport* has remained implicit. There should be a *link between the concepts of electron transfer, electron transport and ion transport* in order to design a coherent corpuscular description of current passage in an electrochemical cell. I tried to achieve this by means of a demonstration experiment involving a partly coloured salt bridge.
This demonstration experiment, number 6.1, comprises the building of an *electrolysis cell* including two separated but identical electrolytes, viz. potassium bromide solution, and an indicator for OH^-. In each electrolyte a graphite bar is placed. The electrolytes are conductingly connected by means of a partly coloured salt bridge. This salt bridge consists of a middle part which has been coloured green and which contains a copper tetra amine chromate solution in agar gel, and two outer parts which are colourless and contain a potassium chloride solution in agar gel. During electrolysis, at one extremity of the green part a yellow colour arises and at the other extremity a blue colour. While carrying out the experiment, students may make *observations* of colours and colour shifts, and subsequently offer *interpretations* which consider the identity of ions, ion

transport and the direction of ion transport. In this way, *students can construct the phenomenological and the corpuscular context* within the period of one lesson hour.
I chose for a context sequence from a *phenomenological to a corpuscular context*, because analysis of the historical meanings of the concept of ion transport and of the indicated teaching problems with this concept, have revealed that it is important to pay attention to this *context sequence* (section 5.4).
When students only pay attention to the colours in the salt bridge and make corpuscular interpretations on the basis of these observations, I call the resulting corpuscular context an *incomplete corpuscular context.*
When they generalize about all ions present in the salt bridge, on the basis of their interpretations of observations of colours, I call the result a *corpuscular context elaboration.* These generalizations concern the identity of ions, ion transport and direction of ion transport in the *colourless* parts of the salt bridge.
When students attribute identity, transport and direction of transport of ions and electrons to the other parts of the cell, viz. electrolytes, electrodes and wires, I call this a *corpuscular context application.* For this, the students have to use their prior knowledge of both electron transfer and electron transport.
When students describe ion transport, electron transfer and electron transport in an electrochemical cell in coherence, I call this a *complete corpuscular context.*
This section is meant to function in the development and application phase for the concept of ion transport (identity and direction). A former section, §2, is meant to function in the orientation phase for the concept of ion transport (see 6.1.1). §6 aims at establishing a coherence between the concept of ion transport and the previously developed and applicated concepts of electron transfer and electron transport.

7.1.2 A complete corpuscular context for current passage

In the previous subsection, I described the section of the student course material which concerns the key concept of ion transport.
Some assignments from the student course material are especially aimed at the construction of the phenomenological context. For example assignment 6c, "Describe your observations.". These observations concern the demonstration experiment 6.1 during electrolysis.
Other assignments are aimed at the construction of the corpuscular context. For example, assignment 6e, "Which ions are moving in the salt bridge?". This assignment requires a corpuscular context elaboration. Another example is assignment 6f, "Indicate the movements of electrons and ions with the help of arrows in the drawing (in the whole set-up).". This assignment requires a corpuscular context application. Together, these assignments aim at a complete corpuscular context.

Transcribed discourses will be analysed in search of teachers' statements which will be seen as indicators of their conceptions. Subsequently, teachers' statements will be

categorized. For example, when teachers make statements which concern interpretations of observations, like the direction of colour shifts interpreted as negatively and positively charged particles moving in particular directions, I relate these statements to the corpuscular context and place them in the subcategory of teachers' conceptions related to content knowledge.
Transcripts of discourses are also analysed in search of teachers' statements related to students' conceptual difficulties, which will be seen as indicators for teaching problems. In this cycle, teachers' statements are related to teachers' use of contexts.

The teacher course comprises three stages, viz. the introduction, the realization and the evaluation stage. Transcripts of discourses which are recorded during these stages will successively be analysed in the following parts of this section. In the introduction and evaluation stage, only teacher course discourses were recorded and in the realization stage, only classroom discourses. Consequently, research question 1, which concerns teachers' conceptions, can be worked out for transcripts from all three stages. Research question 2, which concerns teaching problems, can be worked out for transcripts from the realization stage.

Development and application of the concept of ion transport (§6)
In the introduction stage of the teacher course, I asked the teachers to execute some student assignments. These assignments comprised describing observations and corpuscular interpretations concerning demonstration experiment 6.1. Two categories of teachers' statements could be indicated by me. These were teachers' statements which are indicators for an incomplete corpuscular context and teachers' statements which are indicators for a corpuscular context elaboration.
I shall first go into the first category of teachers' statements. In response to the student assignment, the teachers made observations, which I interpret as belonging to the phenomenological context. They also offered interpretations which I interpret as belonging to the corpuscular context.
Examples of teachers' observations can be found in transcript 7.1, statements 01, 02, 04 and 06. In statements 01 and 02, the teachers' observations are on colours and gas bubbles, respectively. In statements 04 and 06, the observations consider colour shifts and colours, respectively.
Examples of teachers' interpretations can be found in transcript 7.1, statements 09/12. In statement 09, the teacher interprets a colour as a specific kind of ions. In statements 10 and 12, the teacher interprets a colour shift as movement of a specific kind of ions. In statement 11, again a colour is interpreted as a specific kind of ions. In statement 12, the direction of the movements of copper ions is indicated.

Transcript 7.1:
A group of three teachers observed the demonstration of experiment 6.1 and executed student assignments concerning the description of observations and corpuscular interpretations (Appendix E1).
01 T1: *Yellow plus blue ...* (writes)
02 T2: *At both sides gas bubbles I would say (...)*
03 T3: *Interface is different now*
04 T2: *There is something sliding*
05 T3: *The idea is rather nice*
06 T1: *The execution is also nice (...) solution yellow*
07 T2: *Regarding question e which ions move in the salt bridge, table 65 Binas*[1]
08 T1: *The copper ions* Cu^{2+} *table 65 ... are the colours ... we know them by heart*
09 T2: *So copper ions are ... blue*
10 T1: *Copper ions like this* (draws)
11 T2: *And the others must be the chromate ions ... and those are actually yellow*
12 T1: *Copper ions, just a sec, with some* NH_3 *around it ... so ... thus these Cu ions to the minus (...) yes that is crystal clear*
(end of discourse)

From the teachers' statements in this transcript, I can figure out that the teachers start to pay attention to the development of the concept of ion transport as far as identity, transport and direction of transport are concerned. An *incomplete corpuscular context* can be indicated (teachers' conceptions related to content knowledge).

Also, there were discourses in which attention was paid to the coloured as well as the colourless parts of the salt bridge. Teachers' statements concerned observations and interpretations. Their interpretations concerned a *corpuscular context elaboration.*
Teacher statements in which observations are made can be found in transcript 7.2, the statements 01/05. These statements comprise teachers' observations of gas development, colours and colour shifts.
The teachers also offered interpretations. An example of these statements which belong to a corpuscular context can be found in transcript 7.2, statement 07. In this statement, a colour shift is interpreted by the teacher as particles moving in a certain direction.
From the teachers' statements also a corpuscular context elaboration can be indicated. An example of this can be found in statement 07, where the movements of the particles from the colourless parts of the salt bridge are taken into account, because the teacher says "yes the Cl^- also again and there the K^+, but those are colourless". With the words "also again" and "there", he refers to the direction of the movements of the particles.

[1] Binas is the title of the students' book of data used in Dutch schools for VWO (Binas, 1992).

Transcript 7.2:
Two teachers observed experiment 6.1 and executed student assignments concerning the description of observations and corpuscular interpretations (Appendix E1).

01 T1: *Bromine vapour ... left ... gas development*
02 T2: *Solution becomes purple ... at the other side the solution becomes yellow, a little bit of gas development (...)*
03 T1: *Look here it becomes more yellow ... it looks as if this one slides to the right*
04 T2: *And here more blue*
05 T1: *It becomes more yellow and there more blue (...)*
06 T2: *Now you see it indeed very clearly ... blank next to it (...)*
07 T1: *Question e: which ions move in the salt bridge ... o yes so right it becomes ... those go to that side chromate and to the left go* Cu^{2+} *(...) yes the* Cl^- *also again and there the* K^+*, but those are colourless (...)*

(end of discourse)

I understand the teachers' statements in transcript 7.2 as the development and application of the concept of ion transport as far as identity, transport and its direction are concerned. Also, it is possible to indicate a *corpuscular context elaboration* (teachers' conceptions related to content knowledge).

In the introduction stage, I also asked the teachers to execute the following assignment: "What is your opinion of the corpuscular description of current passage in this student course material compared with that in your textbook?". This assignment aims for the complete corpuscular context. In response to this assignment, the teachers talked about how to teach the concept of ion transport and in their discussion they took students' learning into account. Examples of statements which comment on opportunities for students for context construction can be found in transcript 7.3, statements 01 and 03, where among other things is said "they have to do it themselves" and "they have to find out themselves". This demonstration experiment offers a possibility for students to observe and interpret things themselves.
An example of a statement concerning giving an opportunity for constructing the phenomenological context by making observations can be found in transcript 7.3, statement 03. In this statement is said "on the basis of what happens in the salt bridge". An example of a statement on giving an opportunity for construction of the (incomplete) corpuscular context by making interpretations can be found in statement 05, where a teacher remarks "you have to reason it all out if you want to explain those colours".

Transcript 7.3:
Two teachers are executing a teacher assignment in which they were asked to compare the corpuscular description of current passage in their own textbook with that in the first student course material.

01 T1: *Yes and of course here* [in the new student course material] *they have to do it themselves*
02 T2: *On the basis of the observations don't they (...)*

03 T1: *In 5 V there is a figure in which all the arrows are drawn, introduced at a very early stage I would say ... here also too but they have to find out themselves ... on the basis of what happens in the salt bridge ... very good*
04 T2: *Yes very good, very good (...) yes now indeed it becomes clearer*
05 T1: *Salt bridge is now complete (...) you have to reason it all out if you want to explain those colours*
06 T2: *Yes that is good*
Then they go on with the next assignment. (end of transcript fragment)

I interpret their discourse as regarding how to teach the development of the concept of ion transport. However, the teachers reduce the assignment by talking only about ion transport instead of about current passage. Thus although the complete corpuscular context was the aim, this is not achieved. A corpuscular context elaboration can be indicated, and I was also able to distinguish attention for the phenomenological context (teachers' conceptions related to content knowledge).
I understand the discussion of the teachers in transcript 7.3 as intended to give students the opportunity to construct the phenomenological and the corpuscular context themselves (teachers' conceptions related to pedagogical content knowledge).

In the realization stage, the teachers demonstrated experiment 6.1 for their students and the students started doing the assignments. These assignments has as their objective to have the students make observations and offer interpretations. In response to the assignments, discourses took place between teachers and students. I was able to indicate two categories of teachers' statements. Namely, teachers' statements concerning giving students the opportunity to construct contexts and teachers' statements concerning construction of these contexts by teachers themselves.
I shall first go into the first category of teachers' statements. An example of a discourse in which the teacher offers the students the opportunities mentioned can be found in transcript 7.4. In response to the assignment, the students discuss how to indicate the movements of ions and electrons with the help of arrows in their own drawing. This assignment is aimed at a corpuscular context application. The teacher arrives at the group of students and joins the discussion when a conceptual difficulty arises. This difficulty comprises the possibility of electrons moving through an electrolyte (stat. 01), which can also be considered an existing student conception. In reference to the arisen conceptual difficulty, the teacher asks the students to clarify which particles move in the different parts of the cell (stat. 04). After the students give the answer "ions" (stat. 05), the teacher continues to ask for more clarification, probably because he remembered statement 01 made by the student, where the student says "those have to go through that salt bridge". In statement 06, the teacher asks whether electron transport is the only form of current passage. Student 2 in statement 02 has already indicated a relation between electron transport and electron transfer. In further statements, the teacher keeps asking for clarification. Examples of this can be found in statements 09, 11 and 13. In statement 09, he asks the students to clarify the

term current circuit. In statement 11, he asks for clarification of the term current. In statement 13, he asks whether the moving particles have to be only electrons. Finally, in statement 15, the teacher asks a leading question. The teacher of this transcript continues to talk in a corpuscular context during this discourse. He makes no reference to the phenomenological context. The teacher does not use the possibilities to refer to the students' observations of experiment 6.1.

Transcript 7.4:
The students observed experiment 6.1 and are executing assignment 6f: "Indicate the movements of electrons and ions with the help of arrows in the drawing (in the whole set-up)." (Appendix E1).

01 S1:	*Sir, those electrons (...) those have to go through that salt bridge*
02 S2:	*No that's not necessary, those are accepted here by that oxidant (...) so here they are given away by the reductant and then they go like this (...)*
03 S1:	*O ... but what if they* [the electrons] *are not all accepted ...*
04 T:	*But what moves in this* [salt bridge] *(...)*
05 Ss:	*Those ions*
06 T:	*So what you said just now, do those electrons go the whole way round ... do they absolutely need to be ... you talked about a closed current circuit*
07 S2:	*No not in this case because they are accepted*
08 S1:	*They are accepted*
09 T:	*What do you mean by current circuit*
10 S1:	*That the current goes through it*
11 T:	*Then you have to say what you mean by current*
12 S1:	*Electrons which move*
13 T:	*Yes ... do they absolutely have to be electrons*
14 S1:	*I don't know ... I think so*
15 T:	*Could you also say charged particles which move*
16 S1:	*O yes they can also be just ions*
17 T:	*Exactly*

(end of discourse)

I understand the teacher's statements in transcript 7.4 as trying to apply the concept of ion transport in relation to the concept of electron transfer and electron transport. The *corpuscular context application* has not been achieved. Also the phenomenological context is lacking (teachers' conceptions related to content knowledge). The teacher asks a number of times for clarification and offers the student possibilities for corpuscular context construction (teachers' conceptions related to pedagogical content knowledge).

The absence of references to the phenomenological context combined with a number of leading questions of the teacher causes a teaching problem. The conceptual difficulty of student 1 stays the same until the leading question of the teacher (stat. 15): he believes in electron transport.

A second teaching problem can be indicated. On the basis of what student 1 says, I interpret that he thinks ions and electrons move at the same time through the electrolyte (stat. 03). The teacher neglects the problem which the student poses. The conceptual difficulty of the student concerns the contribution of electron transport to current passage through the electrolyte. I presume that the conceptual difficulty of this student stays the same. I call this a teaching problem concerning the rule which prohibits electron transport in the electrolyte.

In discourses in which teachers' statements of the second category can be distinguished, teachers formulated, in the form of monologues, their own observations and interpretations. An example of a statement in which a teacher constructs contexts himself can be found in transcript 7.5. The teacher talks about "yellow" and "blue" colours (phenomenological context) and next he talks about negative and positive ions (corpuscular context). He makes few references to the phenomenological context, the corpuscular context dominates. He does not make a connection between a particular colour and a particular kind of ions. The particles in the colourless parts of the salt bridge are not mentioned. The corpuscular context elaboration stays implicit. In this monologue, some steps are taken implicitly, i.e. from colours to identity of ions and from colour shifts to direction of ion transport.
A corpuscular context application does take place because the teacher says "you get a movement of ions which move in a certain direction namely the negative ions which are present in the salt bridge move to this half cell".

Transcript 7.5:
After the students observed experiment 6.1 (Appendix E1), the teacher delivers the following monologue.

01 T: *If you had a good look at that set-up you would have seen that that yellow colour was here and the blue colour at the other side ... there is of course also an explanation for why those ions move like this in your current source ... in the salt bridge sorry ... if you look here then you move from the solution via the electrode reaction negative ions ... one property of a solution is that it always is electrically neutral ... because negative ions are removed here in the solution there would be a surplus of positive ions ... so this solution would become positive ... that is not possible therefore you get a movement of ions which move in a certain direction namely the negative ions which are present in the salt bridge move to this half cell (...) because there are negative ions removed from the solution and the solution has to stay neutral*

After this monologue, the teacher repeats it for the other half cell. (end of transcript fragment)

I understand this teacher's statements in transcript 7.5 as focused on the development and application of the concept of ion transport in relation to the concepts of electron transfer and electron transport. In this transcript a *complete corpuscular context* can be indicated: the teacher himself mentions the "movements" of all particles (teachers' conceptions related to content knowledge). The teacher constructs this context himself and offers his students no possibility for context construction (teachers' conceptions related to pedagogical content knowledge).

In the evaluation stage, I asked the teachers to execute an assignment which concerned the difficulties they encountered during the teaching of the concept of ion transport. The objective was to establish difficulties in teaching the construction of the phenomenological and corpuscular context.
In response to this assignment, the teachers emphasize that there were still difficulties. Examples of this can be found in transcript 7.6, statements 01/03. In statement 01, the teacher says that one difficulty he encountered was that "it was still an obvious matter to students that electrons could move through a liquid". In statement 02, another teacher says that his students had this conceptual difficulty too. In statement 03, another teacher mentions that he expected that "the problem would be solved by that coloured salt bridge", but subsequently says "it only got worse".

Transcript 7.6:
This transcript is a part of the plenary discussion on the evaluation of experiment 6.1.

01 T1: *Positive ... students liked it and they worked hard ... they made beautiful drawings ... they were very enthusiastic about experiment 4 and 6* [§4 and §6] *... I think students deserve to see more experiments like these ... I really thought yes I am very enthusiastic about it and so were the students (...) one of the problems I encountered is that it was still an obvious matter to students that electrons could move through a liquid and I didn't feel like telling that is not possible ... and when I didn't do that it was an obvious thing to them (...)*

02 T2: *To make clear to those students that no electrons go through that liquid ... we had that problem also*

03 T3: *I thought the problem would be solved by that coloured salt bridge ... it only got worse ... because when they saw that colour difference and they had to write down a few times the observations ... so they thought ... hey that colour there, something must have happened to those ions ... so there have been electrons moving through that salt bridge (...) and then they made up redox reactions with things from the salt bridge ... and then I said where do those electrons come from ... well from those electrodes and they go through there ... yes it is very easy for them ...*

(end of discourse)

I understand the discussion of the teachers in this transcript as evaluating the teaching of the development and application of the concept of ion transport in relation with the concepts of electron transfer and electron transport. In this discussion, in my view, they indicate that the qualitative part of the phenomenological context did not help in order to construct the corpuscular context (teachers' conceptions related to content knowledge).
At this point, the teachers put into words the students' conception concerning electrons moving through an electrolyte and argued that this conception caused difficulties with respect to teaching (teachers' conceptions related to knowledge of students). This difficulty hampers the construction of a complete corpuscular context. The quantitative part with measuring of equivalent weights and the concept of carrier electrolyte is necessary.

Second, the teachers expressed a difficulty with respect to associations of students. Students appeared to associate a change of colour with electron transfer and not with the intended ion transport. A distinction between reaction as disappearing *and* appearing of substances, and concentration changes as disappearing *and* appearing of amounts, for the carrier electrolyte while retaining the total amount, has not been made explicit.

7.2 The second cycle

7.2.1 Use of learning conditions and contexts

In this subsection, §7 of the second version of the student course material will be described from the point of view of the use of Posner's four learning conditions and the use of contexts[2] (Appendix E2; Acampo & De Jong, 1994a).

As a result of conceptual difficulties with the mentioned difference between concentration changes and reaction, changes were made in experiment 6.1. The step from a corpuscular context application to a complete corpuscular context should be better-founded phenomenologically and it should be more structured.
Because of this a demonstration experiment is added to the former demonstration experiment 6.1, now numbered 7.1A. The new experiment, experiment 7.1B, concerns building the same set-up but instead of connecting the electrolytes by means of the salt bridge, they are connected by means of a piece of copper. Both experiments should be demonstrated simultaneously. During electrolysis, students can make observations concerning electrode reactions at the extremities of the piece of copper. The new experiment gives students the opportunity to *compare* the observations and subsequent interpretations concerning electron transfer and electron transport *at and in the piece of copper* in the 'copper bridge' experiment, with their observations concerning ion transport *at and in the (partly coloured) salt bridge* in the 'salt bridge' experiment. The 'copper bridge' experiment aims at a corpuscular context application for electron transfer and electron transport, and the 'salt bridge' experiment aims at a corpuscular context elaboration for ion transport. Together the experiments aim at a route to a complete corpuscular context which is filled in with more details.

§7 can be considered as aiming at the creation of three of Posner's learning conditions as a preparation for the *necessary combination of electron transfer, electron transport and ion transport.*

[2] In the second version of the student course material, the former §6 on current passage has been renumbered into §7 (Appendix E2).

First, the combination of the demonstration experiments has as its objective observations of phenomena concerning the three concepts, and thus for the creation of *the learning condition of plausibility.*
Second, the assignments have as their objective the interpretations of the previously mentioned observations, and thus for creating *the learning condition of intelligibility.*
Third, some interpretations have as their objective the creation of *the learning condition of fruitfulness.* These interpretations are:
- interpretations of the colourless parts of the salt bridge by using the preceding interpretations of colours;
- interpretations by using the identity of electron transfer and its direction at both extremities of the copper wire for the other parts of the copper wire, namely electron transport and its direction.

Concerning the sequence of the *phenomenological* and *the corpuscular context*, I took care that in the new experiment observations are possible at the extremities of the piece of copper (a colour at one side and gas development at the other side). Subsequently, corpuscular interpretations of these observations can be made (electron transfers and electron transport).

7.2.2 The necessity of the measure context

The same two analysis categories are used as in the first cycle, viz. teachers' conceptions and teaching problems.
Again, transcribed discourses are analysed in search of teachers' statements which will be seen as indicators of their conceptions. The subcategory of teachers' conceptions related to pedagogical content knowledge is now extended with teachers' use of learning conditions. For example, when teachers talk about corpuscular interpretations of the colourless parts of the salt bridge, I relate these teachers' statements to the learning condition of fruitfulness, and place them in the subcategory of teachers' conceptions related to pedagogical content knowledge.
Transcribed discourses will also be analysed for teachers' statements related to students' conceptual difficulties which will be seen as indicators for teaching problems. In this cycle, teachers' statements concern, in addition to teachers' use of contexts, their use of the four learning conditions. Teaching problems can be indicated in the stage which takes place in the classroom, viz. the realization stage, because their indicators are students' conceptual difficulties related to teachers' statements.

Development and application of the concept of ion transport (§7)

In the introduction stage of the teacher course, I asked the teachers to execute an assignment in which they were asked to describe their observations and corpuscular interpretations related to demonstration experiments 7.1A and 7.1B. I could indicate two categories of teachers' statements. These were, one category of statements with regard to the plausibility required for ion transport as well as for electron transfer and electron transport and a second category of statements only considered the plausibility required for ion transport.

I shall first go into the first category. In response to the assignments, the teachers made observations and offered interpretations concerning both demonstration experiments. An example can be found in transcript 7.7. Teachers' observations concern the phenomenological context of both experiments, see statements 03/05 and 07/10. In the statements 04, 05 and 08/10, observations which concern colours are made. In statements 03, 05 and 07, an observation concerning gas bubbles is made and in statement 07, also an observation concerning colour shifts.

The teachers only incidentally offered interpretations of their observations. For example, in statement 04, a colour is interpreted as a specific kind of particles. Interpretations concerning the concept of electron transfer can be found in statements 11 and 12. Here, a corpuscular description of the electrode reactions at the extremities of the piece of copper is given.

In statement 10, one of the teachers realizes the sequence in the student course material is different from that in the textbook. He says that the experiment, which focuses on current passage phenomena is "a terribly nice experiment" and that his textbook "starts right away with voltage".

Transcript 7.7:

The teachers observe the experiments 7.1A and B, and execute student assignments concerning the description of observations and corpuscular interpretations (Appendix E2).

01 T1: *And now you go to demonstrate the difference between the salt bridge and the copper wire (...)*

02 T2: *I was watching to see if something was happening to those copper bars (...)*

03 T1: *Bubbles*

04 T2: *Yes but here you get iodine (...) I am trying to see if maybe something is happening to that copper bar, because if some student sees something happening to it (...) if you have a student who says I see copper ions ... I see the blue colour of copper ions (...) but it is a splendid experiment (...)*

05 T3: *At that side gas development, at that side brown, gas development at the graphite bar, brown colour at the copper bar ... pink in the beaker (...)*

06 T2: *Do you have gas development here as well (...)*

07 T1: *Negative ... gas, that salt bridge will slide of course ... those colours (...)*

08 T3: *Both (...) become pink (...)*

09 T1: *At both of them pink ... both pink and brown isn't it (...)*

10 T2: *That's much better ... it is beautifully blue (...) I think this is a terribly nice experiment (...) because the textbook starts right away with voltage my stopgap always was look otherwise you have a diffusion potential (...) they all considered that very plausible and that you have to have a closed current circuit was also very plausible (...)*

11 T1: *Wait a second ... the copper wire ... here it is the negative and there the positive (...) so here $2I^-$ give I_2 plus electrons*

12 T3: *And at the other the water again (...)*

(end of discourse)

I interpret the teachers' statements in transcript 7.7 as regarding the development of the concept of ion transport as far as identity and transport are concerned in relation with identity of electron transfer and direction of electron transport. In my view, the learning condition of plausibility is paid attention to, because the teachers compare the observations of both experiments with each other (teachers' conceptions related to pedagogical content knowledge).

In discourses in which teachers' statements of the second category can be distinguished, the teachers made also observations and offered interpretations. First I will discuss statements concerning the 'copper bridge' experiment, and subsequently the other experiment. The teachers do not express the observation of gas development at the copper wire, but they say that the piece of copper can function as a connection material. An example of this can be found in transcript 7.8, statement 01, where a teacher says "piece of copper also does the trick". So, because their statements do not concern observations at the copper wire, only a part of the phenomenological context is described.
Concerning the experiment with the partly coloured salt bridge, teachers did describe their observations. Examples of this can be found in statements 02/05, 07 and 08. In statements 02/05 colours are described. In statements 07 and 08, in my view, colour shifts are described, "becomes continually lighter ... that blue" and "that is pulled into it". One could also interpret these statements merely as descriptions of reactions. Subsequently, the colours are interpreted as a specific kind of particles. An example of this can be found in statement 03. However, the colour shifts are not explicitly interpreted as movements of a particular kind of particles in a certain direction. So, the corpuscular context is not described entirely, because colour shifts are not interpreted and no direction of ion transport is given. No generalization about all kinds of ions, including those in the colourless parts of the salt bridge, takes place. So, no corpuscular context elaboration is made either.

<u>Transcript 7.8:</u>
Two teachers observe the experiments 7.1A and B, and answer student assignments concerning observations and interpretations (Appendix E2).

01 T1: *Nice experiment and this thing with this copper strip is absolutely splendid (...) because I always thought one starts building* [cells] *so quickly ... fine ... piece of copper does the trick also ... and this is very illustrative (...)*

02 T2: *What an idea to build it like this ... describe your observations ... well the salt bridge has all kind of colours ... copper complex ... CuNH*$_3$

03 T1: *Chromate CrO*$_4^{2-}$ *it is the CuNH*$_3$ *four times CrO*$_4$ *... substance you use and then you have a blue coloured copper ammonia complex ... and a yellow chromate so just CrO*$_4^{2-}$

04 T2: *And green that is copper chrome is that*

05 T1: *No the combination of those two that blue and that yellow together give a green colour*

06 T2: *O wait a mixture colour yes yes yes*

07 T1: *And you can also see very clearly at one side of that bridge you see the yellow colour coming and you see also here ... the green colour continually gets thinner at that right side ... continually gets lighter ... that blue*
08 T2: *That is pulled into it*
(end of discourse)

I interpret the teachers' statements in transcript 7.8 as talking regarding the development of the concept of ion transport as far as identity and transport are concerned. The teachers only develop the learning condition of plausibility required for ion transport because no comparison is made between the observations of both experiments (teachers' conceptions related to pedagogical content knowledge).

In the introduction stage, I asked the teachers also to execute a teacher assignment which asked whether they think the concept of corpuscular description of conduction is made necessary, intelligible, plausible and fruitful for students. In response to this assignment, the teachers talked about students' conceptions and about learning conditions. Examples of statements concerning the learning condition of necessity can be found in transcript 7.9, statements 01 and 02. In these statements, this learning condition for the concept of ion transport is connected with a coherent corpuscular description and with the impossibility of electron transport through liquids.
An example of a discussion concerning the learning condition of intelligibility can be found in statement 02. In this statement, this learning condition is connected to a closed current circuit and when no electron transport is possible the transport has to be ion transport.
Examples of a discussion concerning the learning condition of plausibility can be found in statements 03 and 04. In these statements, this learning condition is connected with the observations which might possibly be made.
Finally, examples of statements concerning the learning condition of fruitfulness can be found in statements 05 and 06, where this learning condition is connected with applications.

<u>Transcript 7.9:</u>
The teachers execute an assignment about their opinion on the corpuscular description of conduction in the new student course material.
01 T1: *Description of the conduction ... yes that's necessary*
02 T2: *That's necessary because electrons cannot swim (...) intelligible because indeed something else happens (...) if those electrons could swim no reactions would take place ... then you have a closed current circuit and they just go through it ... just like an ordinary conductor*
03 T1: *Plausible*
04 T2: *See observations with the experiments (...)*
05 T1: *Fruitful*
06 T3: *Applications*
(end of discourse)

I understand the remarks made by the teachers in this transcript in the context of this assignment as the development and application of the concept of current passage in electrochemical cells. In the teachers' discussion, particular meanings as described above are assigned to all four learning conditions of Posner by the teachers (teachers' conceptions related to pedagogical content knowledge).

In the realization stage, the teachers demonstrated both experiments for their students and students started doing the assignments. These assignments were designed in order to have students make observations and corpuscular interpretations. In response to the assignments, discourses between teachers and students took place. In these discourses, the teachers used the three learning conditions mentioned before. The following examples concern the learning condition of intelligibility and hereby I could indicate two categories of teachers' statements. Namely, teachers' statements concerning creating the learning condition of intelligibility and teachers statements concerning the not-creating of this learning condition.
First, I will go into the category of teachers' statements in which the teacher gives his students the opportunity to offer corpuscular interpretations. See, for example, transcript 7.10, statements 04 and 17, where the teacher asks the students to explain or refine their statements. In statement 17, the teacher asks also for the comparison between the two experiments, "and with this one with the copper wire". In statement 16, just before the teacher asks for the comparison, the student makes a corpuscular context elaboration. In the end of the discourse, statement 21, the teacher draws a conclusion which he should have left to the student. Here he says that in the set-up in which the copper wire is included, the current circuit is closed by electron transport. Moreover, his conclusion is not complete, because the concept of electron transfer is absent, notwithstanding the fact that the student has mentioned this concept in statement 20.

Transcript 7.10:
Two students have observed the experiments 7.1A and B, and are executing the assignment concerning the indication of the movements of the particles with arrows in their drawings (Appendix E2).

01 S1:	*One starts with electrons ... bzzz coming out here ... then here a reaction takes place*
02 T:	*Has to be conduction*
03 S1:	*But you have also ions in the water which can move ...*
04 T:	*Yes which ions go to where*
05 S1:	*OH^- ions go to there*
06 T:	*Yes and if there are positive ions, potassium ions, what happens to them*
07 S1:	*Just keep sitting*
08 T:	*No ... there has to be a current*
09 S1:	*O yes*
10 T:	*Well then you have the salt bridge ... is the next part*
11 S1:	*Hmm yes that iodide and OH^- ions go to sit here*

12 T: *Yes*
13 S1: *And they attract Cu^{2+} and repel CrO_4^{2-}*
14 S2: *Attract is a putting it rather strongly ...*
15 T: *Yes and so yellow and blue in the end ...*
16 S1: *CrO_4^{2-} ions to that side ... in the solution K^+ to that side and minus to that side and here reaction two I^- become I_2 plus two e^-*
17 T: *So the circuit is closed ... and with this one with the copper wire*
18 S1: *First the same story*
19 T: *But in between*
20 S1: *But then ... is here a reaction I^- to I_2 plus e^- ... here electrons are moving bzzz*
21 T: *So in this case the current circuit is closed by electron transport, whereas here it is closed by ion transport*
(end of discourse)

I understand the teacher's statements in transcript 7.10 as a *complete corpuscular context* (teachers' conceptions related to content knowledge). Because the teacher offers the opportunity for students to make the comparison between the corpuscular interpretations concerning both demonstration experiments, he creates the learning condition of intelligibility (teachers' conceptions related to pedagogical content knowledge).

In discourses in which teachers' statements of the second category can be distinguished, teachers themselves make the corpuscular interpretations. Examples of such statements can be found in transcript 7.11. The student assignment is about how many half cells can be indicated in each of the demonstration experiments. In other words, how many electrode reactions can be indicated, which is a part of the comparison between ion transport on the one hand and electron transfer and electron transport on the other hand. The teacher in this transcript does not pay attention to the phenomena concerning electron transfer (electrode reaction) at the extremities of the copper wire, but he does count objects, i.e. bars. The aspect of electron transfer is missing in his definition of electrode, see statement 04. The teacher mainly gives corpuscular descriptions of transport, viz. ion transport and electron transport. Also in statement 04, the teacher gives a definition of electrode which could also be applied to the extremities of the coloured part of the salt bridge. Not once does the teacher ask the student for his observations and interpretations.

Transcript 7.11:
Students have observed the experiments 7.1A and B (Appendix E2), and are discussing the assignment in which is being asked how many half cells each set-up comprises. Then the teacher arrives at the group.
01 S: *Sir, how many half cells are there (...)*
02 T: *Well ... they differ don't they ... here you have ... a half cell is a combination of an electrode with a solution (...) so here you have one half cell and another half cell ... two ... but here you have this electrode with solution, that*

electrode within a solution but also those copper bars with those solutions ...

03 S: *So (...) in principle in the right one four electrodes and in the left one two (...) but when is something now an electrode*

04 T: *It's always a solid material ... and when it ... hangs in a solution and provides current passage, whether or not it reacts itself ...*

05 S: *Yes ... but the salt bridge is also current conducting (...)*

06 T: *In a salt bridge move ions ... in that copper wire electrons can move ... so in both cases charge moves through those connecting materials ... that's necessary because when they aren't conductively connected nothing happens*

07 S: *But why is the salt bridge not an electrode ... because there is current passage*

08 T: *Look at the definition of the concept of electrode ... they have to be bars ... conducting ... electron conducting bars*

09 S: *Electron conducting (...) so electron current passage*

(end of discourse)

I understand the teacher's statements in transcript 7.11 as *a corpuscular context application* (teachers' conceptions related to content knowledge). The teacher does not ask for interpretations, therefore he does not create the learning condition of intelligibility (teachers' conceptions related to pedagogical content knowledge).
In this transcript, a teaching problem could be indicated. This problem concerns the fact that teachers do not create the learning condition of intelligibility for the concept of ion transport in distinction with the concepts of electron transfer and electron transport. The conceptual difficulty of the student is that the coherent reasoning of the trio of concepts remains unclear for him. He keeps using the term current passage, see statement 09, which masks the explication in the corpuscular context.

In the evaluation stage, I listened to the teachers talking about teaching the three concepts. In doing so, the teachers talked about the learning conditions of plausibility and intelligibility.
Examples of teachers' statements concerning the learning condition of plausibility can be found in transcript 7.12, statements 01/03, where the teachers talk about "see those different colours", "so nice, it's a relief" and "all kinds of drawings were made".
Examples of teachers' statements concerning the learning condition of intelligibility can be found in statements 02 and 04. In these statements, the teachers say "very clarifying they were, those experiments" and "the comparison with other conductors".

<u>Transcript 7.12:</u>
This discourse is part of the plenary discussion about the experiments 7.1 A and B.

01 T1: *Well what comes to mind first are the experiments ... I really liked a number of experiments, especially with that corrosion, lived up to their promise too ... and another experiment with that salt bridge ... when you see those different colours (...) further it struck me that the sequence is different ... you start with current and only after that voltage ... that ... I noticed that students*

yes of course they have no reference material ... that I noticed they think it is a logical sequence (...)

02 T2: *I can endorse these things ... what previously was a boring, dry subject ... students experienced as nice and indeed ... those experiments they were both for them and for me sometimes so nice, it's a relief (...) but very clarifying they were, those experiments ... I cannot say anything else than that they liked working on them (...) well those corrosion experiments and the like, the ion transport in that salt bridge and the like yes we haven't had such experiments going for us which could ... explain this so clearly, most of the time it never got beyond a theoretical talk (...)*

03 T1: *Yes especially that corrosion ... in the textbook it is postulated as an electrochemical process, all kinds of drawing are made ... but to be honest I myself could not imagine it clearly ... and now it is much easier ... and with that salt bridge particularly the possibility of having a copper wire too*

04 T2: *Yes I just wanted to say that ... the comparison with other conductors ... never came up in our textbook*

Then they go on talking about group work. (end of transcript fragment)

I understand the talking of the teachers in this transcript as evaluating the teaching of the development of the concept of ion transport as far as identity and transport are concerned.
The teachers mention the topic sequence and the sequence from the phenomenological to the corpuscular context (teachers' conceptions related to content knowledge).
The teachers evaluate the student course material with the help of the terms of the learning conditions of plausibility and intelligibility (teachers' conceptions related to pedagogical content knowledge).

7.3 Teachers' conceptions and teaching problems

In this section, the answers to the research questions will be presented about teaching the concept of ion transport in relation with electron transfer and electron transport. The results of the analysis of both cycles will again be combined. But in the second cycle aiming to ameliorate the relation between the concepts of electron transfer, electron transport and ion transport by the copper bridge experiment.
The teachers' conceptions concern three categories of their knowledge mentioned by Shulman (1987), namely:
- content knowledge, i.e. knowledge of the key concept of ion transport and knowledge of the use of contexts in texts concerning ion transport,
- pedagogical content knowledge, i.e. knowledge concerning creating Posner's learning conditions and knowledge concerning use of contexts concerning ion transport,
- knowledge of learners and their characteristics, i.e. knowledge concerning both existing students' conceptions of ion transport, and knowledge concerning the development of their conceptions.

First, teachers' conceptions concerning contexts could be indicated.
Teachers' conceptions concerning an incomplete corpuscular context could be pointed out. Concerning these conceptions, only a part of the corpuscular context was being described: particular colours or gas bubbles were interpreted as a specific kind of particles, colour shifts as movements of those particles and direction of colour shifts as direction in which positively and negatively charged ions move. No generalizations about all ions in the salt bridge were made. Examples of teachers' statements reflecting these conceptions can be found in transcripts 7.1 and 7.8.
Teachers' conceptions concerning a corpuscular context elaboration could be stated. A corpuscular context elaboration is made by means of generalizing on the basis of the interpretations of the colours which arise in the salt bridge. The generalizations concern the identity of ions, ion transport and the direction of ion transport in the colourless parts of the salt bridge. Examples of teachers' statements which reveal these conceptions can be found in transcripts 7.2 and 7.3.
Also *teachers' conceptions concerning a corpuscular context application* could be shown. Concerning these conceptions, interpretations as to the identity of ions, ion transport and its direction are made. Electron transfer and its direction and electron transport and its direction are attributed to other parts of the cell, viz. the electrolytes, electrodes and connecting wires. Examples of teachers' statements reflecting these conceptions can be found in transcripts 7.10 and 7.11.
Finally, *teachers' conceptions concerning a complete corpuscular context* could be stated. Concerning these conceptions, ion transport, electron transfer and electron transport in an electrochemical cell as a whole are described in coherence. Examples of teachers' statements communicating these conceptions can be found in transcript 7.5.

Second, teachers' conceptions concerning learning conditions of Posner could be indicated. These concerned mainly the learning conditions of plausibility and intelligibility.
Teachers' conceptions concerning the learning condition of plausibility could be pointed out. Concerning these conceptions, the plausibility required for ion transport concerns the observations of colours and colour shifts. The plausibility required for electron transfer concerns observations of gas development and arising of colours. Examples of teachers' statements revealing these conceptions can be found in transcripts 7.7 and 7.8.
Teachers' conceptions concerning the learning condition of intelligibility could be shown. Concerning these conceptions, the concepts of ion transport, electron transfer and electron transport were being described corpuscularly in coherence. Examples of teachers' statements reflecting these conceptions can be found in transcript 7.10.
Also, *teachers' conceptions concerning the four learning conditions* could be stated. Concerning these conceptions, a particular meaning was assigned to each of the four learning conditions of Posner, e.g. to the necessity, a meaning of coherent reasonings,

and to the plausibility, a meaning of observations. Examples of teachers' statements communicating these conceptions can be found in transcript 7.9.

Third, two other teachers' conceptions could be indicated, which I do not express in terms of either contexts or learning conditions.
Teachers' conceptions of students' active learning could be stated. Concerning these conceptions is being described that students themselves ought to observe and interpret, and in this way be actively involved in learning about the concept of ion transport. Examples of teachers' statements communicating these conceptions can be found in transcripts 7.3, 7.4 and 7.12.
Finally, *teachers' conceptions concerning students' conceptions* could be pointed out. Concerning these conceptions, existing conceptions of students were paid attention to, for example, the student conception of electrons moving through an electrolyte (a salt bridge). Examples of statements of teachers reflecting these conceptions can be found in transcript 7.6.

Besides teachers' conceptions, also some teaching problems could be indicated.
Teaching problems of emphasizing the corpuscular context could be shown.
Concerning these teaching problems, students' conceptual difficulties concern current passage in the electrolyte in the form of electron transport. Examples of these teaching problems can be found in transcripts 7.4 and 7.6.
Also *teaching problems concerning not creating the learning condition of plausibility* could be indicated. Concerning these teaching problems, no attention was paid to the observations which can lead to the interpretations of electron transfer and electron transport. Students' conceptual difficulties concern the lack of information in order to describe ion transport, electron transfer and electron transport in an electrochemical cell coherently. An example of these teaching problems can be found in transcript 7.8.
Finally, *teaching problems concerning not creating the learning condition of intelligibility* could be stated. Concerning these teaching problems, the opportunity to compare the observations and subsequent interpretations concerning electron transfer and electron transport at and in the piece of copper in the 'copper bridge' experiment, with those concerning ion transport at and in the (partly coloured) salt bridge in the 'salt bridge' experiment was not given. The students' conceptual difficulties concern the inability to describe ion transport, electron transfer and electron transport coherently. An example of these teaching problems can be found in transcript 7.11.

Chapter 8

Teaching the concept of potential difference

In this chapter, the research questions will be worked out for the key concept of potential difference. The way in which this is done will be the same as in chapter 6.

8.1 The first cycle

8.1.1 Use of contexts

In this part of the section, I describe the first version of the student course material concerning the concept of potential difference, §7, §10 and §11, from the point of view of use of contexts (Appendix F1).

In §7, the concept of *potential difference of an electrochemical cell* is introduced. With this, some new terms like standard potential are mentioned. Students were asked to execute some assignments in which the objective is to connect their prior knowledge to characteristics of the new concept of potential difference, particularly to connect identified electron transfer and its direction to the sign of potential difference. In the student course material, the battery characteristic of voltage is also called potential difference. In the case of measuring with the help of a voltmeter, when there is no current passage in the cell, the potential difference is called electromotive force.
§7 is meant to function in the orientation phase for potential difference and is considered as an application of the concepts of electron transfer, electron transport and ion transport by means of using the identity and direction of electron transfer and the direction of electron transport and ion transport.

§10 contains two experiments in which students themselves have to:
- observe the set-up of the cell and realize which chemical substances are present,
- measure the value and the sign of the potential difference, i.e. deflection of the voltmeter, its value and its direction,
- interpret the observations and measurements, and
- calculate with the obtained 'measure values' of potential difference and 'table values' of standard potentials[1].

In the first experiment, number 10.1, students were asked to build electrochemical cells with the help of two of the following half cells: a copper half cell ($Cu(s)$ | $Cu(NO_3)_2$ solution, 1M), a zinc half cell ($Zn(s)$ | $Zn(NO_3)_2$ solution, 1M) and two lead half cells ($Pb(s)$ | $Pb(NO_3)_2$ solution, 1 M). Each half cell has a bottom of semipermeable membrane. Before they start measuring, students were asked which connection wire goes into the 'plus-entrance' of the voltmeter. Of each of the (four) different combinations, the potential difference is measured. In this experiment, the students were asked to place a combination of two half cells on a salt bridge bottom in a petridish and connect them both to the voltmeter. This procedure should be repeated for all four combinations. Subsequently, the students were asked to calculate the potential difference of each combination with the help of table values of standard potentials concerning the relevant half reaction from their book of data (Binas, 1992).

In the second experiment, number 10.2, students were asked to build two coupled electrochemical cells with the help of the following single cells which were placed on the salt bridge bottom: Cu-Pb and Pb-Zn[2]. A gutter was made in this salt bridge bottom and one of the single cells should be placed on one side and the other on the other side of the gutter. Students were asked to make the two possible connections (viz. Cu-Pb=Pb-Zn and Cu-Pb=Zn-Pb)[3]. Of each of the coupled cells, the sign and the value of the potential difference should be measured. The objective is to focus

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[1] The table values for the standard potentials are thermodynamic values (Binas, 1992, table 48). For students, no references to these thermodynamic backgrounds are made. The tabulated values are represented as potentials, but of course these are potential differences because the standard hydrogen electrode functions as a reference.

[2] Cu-Pb means $Cu(s)$ | $Cu(NO_3)_2$ solution 1M || $Pb(NO_3)_2$ solution 1M | $Pb(s)$.
Pb-Zn means $Pb(s)$ | $Pb(NO_3)_2$ solution 1M || $Zn(NO_3)_2$ solution 1M | $Zn(s)$.

[3] Another representations of the two possible connections:

```
                Cu - Pb                     Cu - Pb
                 I    I                      I    I
      Voltmeter ==I===           Voltmeter ==I===
                 I    I                      I    I
                Zn - Pb                     Pb - Zn
```

The sign "=" in de text means that the two half cells at each side of this sign are connected to each other with the help of a wire.
The sign "=" in the drawing above means the gutter in the salt bridge bottom; two half cells on the same side are connected by means of the salt bridge bottom.
The sign "I" in the drawing means a connection with the help of connecting wires.

students' attention on relating the identity and direction of electrode reactions (corpuscular context) to the sign and the value of potential difference (measure context). Subsequently, it is possible to calculate with measured values of potential differences (calculate context).

For *the sign of potential difference,* I opted for a *context sequence* from a *corpuscular* context to a *measure* context. Although no phenomena concerning one of the three key concepts of current passage are visible anymore when potential differences are being measured, because currentless measuring means no chemical conversion, knowledge of those concepts is necessary to attribute corpuscular descriptions to measurements (*context application*). Thus, the identity and direction of electrode reactions lead up to the sign of potential difference.

For *the value of potential difference*, I chose a *context sequence* from a *measure* context via a *corpuscular* context to a *calculate* context. I did so because analysis of the historical meanings of the concept of potential difference in an electrochemical cell and of the indicated teaching problems which arise with this concept, have pointed out that it is important to pay attention to these *context sequences* (section 5.4).

§10 is meant to function in the development phase for the sign and the value of potential difference in relation with the identity and direction of electron transfer and the direction of electron transport and ion transport.

In *§11*, the Nernst equation is introduced and developed by means of a demonstration experiment in which a concentration cell is used. In this experiment 11.1, an electrochemical cell is built with two separated, identical electrolytes, viz. potassium permanganate solution. In each electrolyte, a graphite electrode is placed and the electrolytes are connected by means of a salt bridge. Subsequently, the electromotive force is measured. Next, water is added to one of the electrolytes and again the electromotive force is measured. This procedure is repeated several times in order to show that the value of the potential difference is dependent upon the difference in electrolyte concentration between the two half cells.

§11 is meant to function in the development phase for the value of potential difference in an electrochemical cell and in the application phase for the sign of potential difference in an electrochemical cell because the Nernst equation comes up.

8.1.2 The coupling of the corpuscular and the measure context

In the previous subsection, I described three sections of the student course material which concern the key concept of potential difference in an electrochemical cell.

Some assignments are especially aimed at the application of the direction of current passage in the corpuscular context which leads to the development of the sign of potential difference. For example, assignment 10a, "Which connection wire should go into the 'plus-entrance' of the voltmeter? Explain.".

Other assignments from the student course material are especially aimed at the development of the sign and the value of potential difference in an electrochemical cell in a measure context. For example assignment 10b, "Measure the electromotive force for each combination.".
Some assignments are aimed at the development of the sign and the value of potential difference in the corpuscular and calculate context. For example assignment 10d, "Calculate the electromotive force for each combination (with the help of table 48).".

In this part of the section, I describe the teachers' conceptions and teaching problems related to the teaching of the concept of potential difference.
Transcribed discourses are analysed in search of teachers' statements which will be seen as indicators of their conceptions. Subsequently, teachers' statements will be categorized. For example, when teachers use corpuscular descriptions of electrode reactions in calculating with potential difference, I relate the teachers' statements to the calculate context and place them in the subcategory of teachers' conceptions related to content knowledge.
Transcripts of discourses are also analysed in search of students' conceptual difficulties and related teachers' statements which will be seen as indicators for teaching problems. In this cycle, teachers' statements concern teachers' use of contexts I expect most conceptual difficulties for students in the development of the concept of potential difference, because in current teaching of electrochemical cells some of the indicated teaching problems could be connected with the concept of potential difference and these concerned the development of this concept (chapter 3). Therefore, the analysis results I report on are only related to the development phase.

The teacher course comprises three stages, viz. the introduction, the realization and the evaluation stage. Transcripts of discourses which are recorded during these stages will successively be analysed in following parts of this section. In the introduction and evaluation stage, only teacher course discourses were recorded and in the realization stage, only classroom discourses. Consequently, research question 1, which concerns teachers' conceptions, can be worked out for transcripts from all three stages. Research question 2, which concerns teaching problems, can be worked out for transcripts from the realization stage.

Development of the concept of potential difference (§10)
In the introduction stage of the teacher course, I asked the teachers to execute an assignment which concerns the execution of the experiments 10.1 and 10.2, and the answering of a student assignment. This assignment is about predicting which connection wire should go into the 'plus-entrance' of the voltmeter in order to get a positive deflection. In response to the assignment, the teachers communicate their observations and interpretations.

In these discourses, the teachers' statements concern the direction of the current passage in relation to the sign of the potential difference of an electrochemical cell. See for example transcript 8.1, statements 02, 03 and 09. In statement 02, the teacher formulates an expectation when he says "this has to change". In his statement, the term "this" refers to the direction of the deflection of the voltmeter. In statement 03, another teacher specifies this expectation "this has become the plus and this becomes the minus". In statement 09, when the first teacher says "it will go to the other side", he comments on the direction of the deflection of the voltmeter.
An example of a statement in which the corpuscular context is connected to the measure context can be found in statement 12. In this statement, the teacher says that "the weakest reductant ... becomes the positive electrode", because the "strongest reductant gives away electrons" and "is the minus".
It becomes clear that the teachers use the Binas-table in which corpuscular descriptions of electrode reactions are given (corpuscular context). These corpuscular descriptions lead to identified electron transfer and its direction, the latter on the basis of the place in the table. Subsequently, they take decisions about measuring, like which electrode should be connected to the 'plus-entrance' of the voltmeter in order to get a positive sign for the potential difference (measure context).

Transcript 8.1:
Two teachers are executing experiment 10.1 (Appendix F1). During their discourse, the teachers are measuring the potential difference between a copper half cell and a lead half cell. Subsequently, they talk about the first student question: "Which connection wire should go into the 'plus-entrance' of the voltmeter? Explain."

01 T1:	*Here is the lead ... here the copper ... shall we (...) 0,35*
02 T2:	*Yes ... 0,35 ... and now this has to change*
03 T1:	*Now this has become the plus and this becomes the minus ... hasn't it*
04 T2:	*Now why are you doing that*
05 T1:	*You have to reverse the polarity ... if it is correct*
06 T2:	*Doesn't say anywhere what should be at the plus or the minus*
07 T1:	*No but we know before*
08 T2:	*Yes okay but that*
09 T1:	*Otherwise it will go to the other side ... (...)*
10 T2:	*O well but I just want the proof, let's reverse the polarity (...) it has to, nice*
11 T1:	*You see now it goes*
12 T2:	*That's very nice ... good ... (...) so that of the weakest reductant ... that becomes the positive electrode (...) because the electrons go from minus to plus strongest reductant gives away electrons so is the minus ...*

(end of discourse)

I interpret the teachers' statements in transcript 8.1 as regarding the development of the sign of potential difference. From their statements, a coupling between the corpuscular context of electrode reactions and the measure context of connecting wires to the voltmeter can be indicated (teachers' conceptions related to content knowledge).

In the introduction stage, I also asked the teachers to execute an assignment which concerned their opinion on the understandability of experiment 10.2 for students. In response to this assignment, the teachers' statements concerned comments on the student course material and the expected conceptual difficulties experienced by students.
Examples of teachers discussing the student course material can be found in transcript 8.2, statements 01 and 02. In these statements, they say that they cannot make the connection between students' understanding and the experiments and assignments of the text, before they have used them in teaching.
Besides, teachers talked about the conceptual difficulties which they expect students to have. See, for example, statements 03 and 05. In statement 03, my interpretation of "as those values corresponded better" is that the teacher talks about the problem that the measured values of potential differences of coupled cells do not correspond with the sum and the difference of the measured values of potential differences of single cells. Subsequently, my interpretation of "they would see it more quickly" is that the value of the potential difference of a coupled cell is difficult to understand for students. In statement 05, another conceptual difficulty for students is mentioned, when the teacher says "to students that's not immediately clear". I interpret his words as meaning that it is not immediately clear to students that there are only two different coupled cells.

Transcript 8.2:
Three teachers have executed the experiments 10.1 and 10.2 (Appendix F1) and are discussing whether experiment 10.2 is understandable for students.

01 T1: *I cannot see from the text whether students can apply this knowledge*
02 T2: *I have not got enough experience with it ... yes for myself I say yes*
03 T3: *Yeah it's nice ... but it would be nicer if those values corresponded better ... then they would see it more quickly*
04 T2: *Then when it doesn't correspond*
05 T1: *I had also another coupling of two cells which one can think of ... I can think of four (...) they are two by two the same, but to students that's not immediately clear, thus when there stands the other one*
06 T2: *In fact there should stand four combinations (...) in Chemie they ask for all combinations*
07 T1: *And then you'll find out*
08 T2: *Yes and then it appears they are two by two the same ... yes ... can of course measure them easily*

They go on discussing which problems are covered. (end of transcript fragment)

I interpret the teachers' statements in transcript 8.2 as regarding the development of the concept of the value of the potential difference, which is called electromotive force. In their discussion, the teachers realize the difference between the potential difference of a coupled cell in a measure context and these calculated from the measured values of potential differences of the single cells (teachers' conceptions related to pedagogical content knowledge).

In the realization stage, the students executed the experiments and assignments. In response to the assignments, discourses took place between the students and the teachers. I could indicate two categories of teachers' statements, i.e. teachers' statements concerning the emphasizing of the corpuscular and the calculate context by teachers themselves and teachers' statements concerning the opportunities to be given to students to construct these contexts.

First, I will go into the first category of statements. Examples of such statements can be found in transcript 8.3, statements 02 and 04. In statement 02, the teacher emphasizes the calculate context when he says, among other things, "so minus minus 0,13". In statement 04, the teacher emphasizes the combination of the corpuscular context and the calculate context when he says "first the strongest oxidant and then you subtract the other one from it". The teacher does not refer to the measurements which the student has done before. So, the teacher does not connect the corpuscular context via the measure context to the calculate context, and does not make clear why there should be a positive value for the potential difference (stat. 04). The student keeps searching for a calculation rule by means of the terms "weakest" and "strongest" which he does not understand (stats. 01 and 03).

Also, this teacher uses incorrect language. For example, in statements 02 and 04, the teacher uses two terms, voltage and voltage difference, incorrectly, at least within secondary school chemistry[4]. The teacher uses the term voltage instead of potential and also he uses the term voltage difference instead of potential difference. This kind of language can be considered as expert language.

<u>Transcript 8.3:</u>

A student has measured the potential difference of a combination of half cells, viz. Cu-Pb, with his group. Subsequently, he has to calculate the potential difference of that combination of half cells with the help of table 48 (Binas, 1992) (§10, Appendix F1).

01 S: *What do you have to subtract from each other, how do you know that*

02 T: *When you do it right ... you always come to the right figure ... only in this case it is minus and in the other case possibly plus ... well here ... if you want a positive figure from these ... then you get plus 0,34* [Cu] *and it is about a difference and a difference you always calculate by ... subtracting one from the other, so minus ... and then the voltage of the other, well if that is positive then it just becomes a smaller positive figure but in this case it is always negative ... so minus minus 0,13* [Pb] *and then you come exactly to ... let's see if I did it right 0,47* [Cu-Pb] ...

03 S: *So first write down the strongest and then subtract from that the weaker one*

04 T: *First the strongest oxidant and then you subtract the other one from it ... (...) and if your voltage difference is minus 1,10* [Zn-Cu] *or minus 0,63* [Zn-Pb] *then the meter would have deflected to the other side and to avert that ... you put the copper in the plus pole and you should also first write down the copper*

(end of discourse)

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[4] The values in the Binas table are represented as potentials, but these are potential differences with the standard hydrogen electrode as a reference.

I understand the teacher's statements in transcript 8.3 as paying attention to the development of the concept of the sign and the value of potential difference. The teacher gives few opportunities for context construction by the students. The teacher emphasizes the coupling of the corpuscular and the calculate context of table values (teachers' conceptions related to pedagogical content knowledge).
In this transcript, a teaching problem could be indicated. A teaching problem caused by the teacher who uses expert language and who does not link up with what the student already knows. The student experiences conceptual difficulties in understanding the tools he wants to use in order to formulate a rule for the calculation of potential differences.

In discourses in which the second category of teachers' statements can be distinguished, the teachers gave students the opportunity to construct contexts. Examples of such teachers' statements can be found in transcript 8.4, statements 01, 13 and 15 which concern experiment 10.1. In statement 01, the teacher asks the students to write down the corpuscular description of the electrode reactions in order to find out which connection wire should go into the 'plus-entrance' of the voltmeter. Then he states as a problem the contradictory expectations which the students have put into words (stat. 13) and gives the students the opportunity to test, in a measure context, the hypothesis concerning which connection wire should go into the 'plus-entrance' (stat. 15).

Transcript 8.4:
Students are measuring the potential difference of a combination of half cells, and do not understand when an electrode is called plus or minus (§10, Appendix F1). The question in the student material which they are discussing runs as follows: "Which connection wire should go into the 'plus-entrance' of the voltmeter? Explain."

01 T: *Which belongs where it says plus ... write down the half reactions (...)*
02 S1: *Zinc with copper*
03 T: *Yes ... well zinc in zinc sulphate copper in copper sulphate (...)*
04 S2: *Zn^{2+} SO_4^{2-} and H_2O we have in one beaker*
05 S1: *But also just Zn (...) strongest reductant is the zinc become Zn^{2+} and $2e^-$ Zn^{2+} is oxidant (...)*
06 T: *You have to look at them both*
07 S2: *In the other beaker has to react the oxidant (...)*
08 T: *Yes back again to the question (...)*
09 S1: *On the plus*
10 S3: *The reductant*
11 S1: *No on the contrary because Zn gives the electrons away and at the plus they are accepted so you have to from Zn they are given away they go to the plus*
12 S4: *He said that Zn should be in minus ... no*
13 T: *He said Zn the minus .. you say copper the minus ... what would happen if you do it wrong*
14 S1: *Nothing*
15 T: *Well try it (...) red is the plus*
16 S2: *So that has to be the zinc (...)*

17 T: *So now we know what the plus pole is don't we*
18 S1: *This was plus so this is the plus*
19 T: *Yes copper is the plus*
20 S2: *The explanation ... here come electrons free at the zinc*
(end of discourse)

I interpret the teacher's statements in transcript 8.4 as developing the concept of the sign of potential difference. Hereby, a coupling can be indicated between the corpuscular context with the table and the measure context (teachers' conceptions related to pedagogical content knowledge).

In the evaluation stage, I listened to the teachers evaluating their teaching of the experiments 10.1 and 10.2. In this evaluation, the teachers mainly commented on practical issues, like which cuvets to use in experiments. Examples of this can be found in transcript 8.5, statements 01 and 02. Besides practical issues, the teachers talked about students' conceptual difficulties, see statements 04 and 05. In statement 04, the teacher says that he does not think that the students know "what it is exactly that they are doing I don't think they know". The conceptual difficulty the teacher refers to concerns calculating the potential difference with the help of the Nernst equation, whether or not with the table values. In statement 05, the teacher remarks on students' conceptual difficulties in understanding the concepts of the oxidant and the reductant. In my view, this discourse stresses that according to the teachers students' conceptual difficulties exist concerning the concept of potential difference of an electrochemical cell.
Coupling the measure and the calculate context appears to be a problem for teachers. This can be seen in statement 05, where the teacher says "I had to say a few times it was for one half cell". The teacher uses the term "say" and with this, in my opinion, he does not refer to the experiment in the measure context which was meant to introduce the Nernst equation.

Transcript 8.5:
This transcript is a part of the plenary discussion on evaluating teaching the experiments 10.1 and 10.2.
01 T1: *Yes I liked it that we were going to measure (...) but I think the practical realization should be handier (...)*
02 T2: *We used little plastic cuvets (...) worked perfectly*
03 T3: *My lab assistant arranged it perfectly (...) with tubes of an aquarium (...)*
04 T4: *It* [the Nernst equation] *is in the syllabus so it has to be done, but it is not as if one is eager to do it ... concentration cell prepares for it indeed ... students can easily fill that out, that's what happens ... but what it is exactly that they are doing I don't think they know (...)*
05 T5: *In my case some students had difficulties with the oxidant and the reductant ... because then some of them thought it was ΔV ... I had to say a few times it was for one half cell (...) but they did those assignments in a quarter of an hour without problems*
Then they talk about some calculation problems. (end of transcript fragment)

I understand the teachers' statements in transcript 8.5 as evaluating their teaching of the concept of the value of potential difference. During this evaluation, it appeared that the coupling of the measure and the calculate context was a problem for teachers (teachers' conceptions related to pedagogical content knowledge).
The teachers expressed a conceptual difficulty that students experienced which concerned the manner of calculating the potential difference by means of the Nernst equation and the table values. The conceptual difficulty was the fact that the Nernst equation has to be used twice, viz. for each of the two half cells to calculate the potential difference of an electrochemical cell.
Second, the teachers expressed a conceptual difficulty experienced by students. In my view, this conceptual difficulty concerns the understanding of the oxidant and the reductant in an electrochemical cell. The conceptual difficulty concerned the fact that both half cells have to be taken into account before choosing the oxidant and the reductant. This depends upon their place in the table.

8.2 The second cycle

8.2.1 Use of learning conditions and contexts

In this part of the section, §8, §9 and §11 of the second version of the student course material will be described from the point of view of the use of Posner's four learning conditions and the use of contexts (Appendix F2; Acampo & De Jong, 1996a)[5].

The experiments 10.1 and 10.2 have been changed because students had conceptual difficulties. These difficulties concerned the value of potential difference (see transcript 8.3).
Therefore, between the experiments on measuring the potential difference of single cells (combination of two half cells) and of coupled cells (combination of two single cells), now information is presented on standard potentials and on reference half cells. The intention is that the knowledge about the sign and the value of potential difference in single cells can be used in the next section concerning the coupled cells.

In *§8*, after an introduction of the new concept of potential difference, the students were asked to execute experiment 8.1. There is no difference between the new experiment 8.1 and the former experiment 10.1. The aim of this section is for students to get acquainted with new terms and to activate their prior knowledge of the three key concepts of electron transfer, electron transport and ion transport, and thus to create the

[5] In the second version of the student course material:
- the new §8 is a combination of experiment 10.1 and the former §7,
- the new §9 concerns the former experiment 10.2,
- the new §11 is the same as the former §11 (Appendix F2).

learning condition of fruitfulness of the complete corpuscular description of current passage and functions in *the learning condition of necessity* for the characteristic of an electrochemical cell which is called potential difference. Another aim of the section is for students themselves to observe and measure, and thus for creating the *learning condition of plausibility*. The assignments in this section aim at interpretations and calculations, and thus at creating the *learning condition of intelligibility*.

In *§9*, the described experiment 9.1 comprises measuring the potential difference of coupled cells which has as its objective the creation of the *learning condition of fruitfulness for the sign and the measured value of potential difference of the single cell*. There is no difference between the new experiment 9.1 and the former experiment 10.2. The coupling of cells belongs to this condition because the concept of the sign and measured value of potential difference has to be applied in reasoning about coupled cells.

In *§11*, the introduction of the Nernst equation takes place by means of a demonstration experiment of a concentration cell. Apart from some practical changes, this demonstration experiment is the same as in the previous version. The assignments which accompany this experiment aim for creating *the learning conditions of plausibility and intelligibility for the concentration dependent value of potential difference of the single cell.*

8.2.2 The fruitfulness and the necessity of the single cells

The same two analysis categories as in the first cycle are used, viz. teachers' conceptions and teaching problems.

Again, transcribed discourses are analysed in search of teachers' statements which will be seen as indicators of their conceptions. The subcategory of teachers' conceptions related to pedagogical content knowledge is now extended with teachers' use of learning conditions. For example, when teachers do not only talk about interpretations or calculations of single cells but also about interpretations or calculations of other cells or of coupled cells, I relate these statements to the learning condition of fruitfulness for the sign and value of potential difference of the single cell and place them in the category of conceptions related to pedagogical content knowledge.

Transcribed discourses will also be analysed for teachers' statements related to students' conceptual difficulties which will be seen as indicators for teaching problems. In this cycle, teachers' statements concern, in addition to teachers' use of contexts, teachers' use of the four learning conditions. Teaching problems can be indicated in the stage which takes place in the classroom, viz. the realization stage, because their indicators are students' conceptual difficulties related to teachers' statements.

Development of the concept of potential difference (§8 and §9)

In the introduction stage, I asked the teachers to execute some student assignments which concerned measuring the sign and the value of potential difference of single and of coupled cells. In response to this assignment, the teachers reported the sign and values of potential differences. An example of this can be found in transcript 8.6, statement 01. In this statement, the teacher's measurements consider values and the sign of potential differences. In doing so, the teacher adds and subtracts the values of potential differences of single cells previously measured. Subsequently, the teachers used these values of measurements (deflection of the voltmeter) for determining the polarity of the electrodes (plus or minus). Examples of this can be found in statements 02, 04 and 05. In statement 02, the observations concern connections of the half cells to the voltmeter and to each other. In statement 04, the connection to the voltmeter is linked to the direction of the deflection of the voltmeter. In statement 05, the connection to the voltmeter is linked to reductant strengths.

Transcript 8.6:

Three teachers executed experiment 9.1 and answered a number of student assignments (Appendix F2). Beforehand, they have executed experiment 8.1, in which they measured the value for the potential difference of single cells.

01 T1: *Should be somewhat less, should be 0,33 minus 0,27 ... or do I see it wrong copper lead zinc lead (...) copper lead is 0,33 ... and zinc lead is 0,27 and then against each other ... should be 0,06 and added ... 0,60 and that is somewhat more (...)*

02 T2: *This was copper Cu^{2+} then again Pb^{2+} Pb (...) and then you connected this (...)*

03 T1: *I like this ... are simple experiments but well thought out (...) voltage or potential difference ... let's read (...)*

04 T3: *If you don't connect it the right way the meter deflects to the wrong side ... deflect good is the connection plus in plus*

05 T1: *Well seems a correct answer to me ... they could also say something about metals being noble ... reductant strength (...)*

(end of discourse)

I interpret the teachers' statements in transcript 8.6 in relation to this assignment as talking regarding the development of the concept of the sign and the value of potential difference. Hereby, the fruitfulness of the concept of potential difference for the single cell can be indicated (teachers' conceptions related to pedagogical content knowledge).

In the introduction stage, I also asked the teachers to execute a teacher assignment in which was asked whether the concept of potential difference is made necessary, plausible, intelligible and fruitful for students. In response to this assignment, the teachers talked about the four learning conditions. Examples of such statements can be found in transcript 8.7. The learning condition of necessity is discussed in statements 01, 02, 04 and 08, and it is connected with the question "why there is a current". Examples of talking about the learning condition of intelligibility can be found in statements 04, 05 and 10. This learning condition is not provided with characteristics by the teachers, but they do decide whether they think it has been created or not. The learning condition of plausibility is discussed in the statements 05, 08, 10 and 11, and it is connected with the measurements. Finally, the learning condition of fruitfulness is discussed in statement 06, and it is connected with the deflection of the meter.

Transcript 8.7:
Three teachers talk about whether the new concepts of potential difference and of standard potential are made necessary, plausible, intelligible and fruitful for students.

01 T1: *Voltage potential difference ... necessary ... intelligible and plausible ... fruitful (...) in itself I can imagine that one ... in this way ... you have to make clear why there is a current ... you have to do something with a cause of the presence of current ... so the necessity of such a concept is (...)*
02 T2: *Well I don't think it is necessary*
03 T1: *Don't you ... well they noticed in those seven previous sections that there runs a current ... that that current in some cases is bigger than in others ... there has to be something with which you can explain that ... that a current is present and in one case more current than in another*
04 T2: *Okay ... it doesn't become intelligible ... yes you are right ... necessary yes ... is it becoming intelligible here ... that that current is present*
05 T1: *No at the very most it becomes plausible (...) that there is a current and that for example with copper lead ... is voltage plausible yes intelligible no*
06 T2: *Fruitful .... yes ...*
07 T3: *Fruitful ... meter deflects (...) electromotive force*
08 T1: *Intelligible no ... plausible yes ... has just been measured ... fruitful also yes ... standard potential ... necessary ... yes ... because you measure differences*
09 T3: *So it is there*
10 T1: *Yes ... intelligible yes ... I think by that experiment (...) in experiment 8.1 (...) where the lead is the reference, plausible ... yes I think so ... fruitful also ... good ... (...) in experiment 9.1 a problem for students comes up in another sequence of the four half cells, do you think the elaboration intelligible and plausible for students ... if yes explain ... from the measurements yes ... indeed ... if they are counteracted those voltages then you have to subtract them ... not add them ... (...) well, not intelligible in fact, plausible yes ... plausible because of the measurements*
11 T2: *Yes because of the measurements*
(end of discourse)

I interpret the teachers' statements in transcript 8.7 as attention for the development of the concept of potential difference. In the teachers' discussion, particular meanings as described above are assigned to three of the four learning conditions of Posner by the teachers (teachers' conceptions related to pedagogical content knowledge).

In the realization stage, the students executed the experiments and assignments. In response to the assignments, discourses took place between teachers and students. I could indicate two categories of teachers' statements in response to these assignments. Namely, teachers' statements concerning teachers themselves making the observations, the interpretations and the calculations and teachers' statements concerning giving students the opportunity to do this.

I will first go into the first category of teachers' statements. An example of such a statement can be found in transcript 8.8, statement 04. In this statement, the teacher gives an interpretation himself when he says "say you take for example lead lead two plus as standard half cell ... well then you can subsequently if you measured all those things you can also say with regard to each other ... if I take copper and zinc that then the difference is so much".

In statement 06, the student asks for the concentration dependence of the value of potential difference. In statement 07, the teacher refers to a next section where this will be elaborated upon. The question of the students concerns the learning condition of necessity for the Nernst equation.

Transcript 8.8:
Students are executing the following assignment: "A cell is built with the following cell diagram: C(s)|$KMnO_4$ solution (1M), $Mn(NO_3)_2$ solution (1M), H_2SO_4 solution (0,5M)||HNO_3 solution (1M)|H_2 (g;p^0)|Pt(s).".
First, students were asked to draw the cell, then to give the equations for the electrode reactions when the cell delivers current (Appendix F2).

01 S1: *With 2b you have more oxidants together, does in that case only the strongest react or do they all react*

02 T: *No ... only the strongest (...)*

03 S1: *You just said that in first instance only the strongest will react ... so is the rest only in it to confuse you or something*

04 T: *No that's in there (...) look the others are in there because you, you want fixed circumstances in which you measure, because in this way you always can compare those cells with each other again ... so they first have measured a lot of those cells with regard to H^+/H_2 half cell ... if we do that we can subsequently in this way ... say you take for example lead lead two plus as standard half cell ... well then you can subsequently if you measured all those things you can also say with regard to each other ... if I take copper and zinc that then the difference is so much ... but therefore you have to take certain fixed circumstances otherwise it is of course not fair when you take it one time in this way and another time in another way ... so what they did, they said well we will take for all concentrations one molar of all concerned particles ... so when you have a half reaction sorry a ... redox couple MnO_4 plus 8 H^+ at the one side and Mn^{2+} at the other side then we take of all those particles a concentration of one molar ... and of MnO_4 and of H^+ and of Mn^{2+} ... all concerned particles 1 molar*

05 S1: *Ooo*

06 S2: *What happens now when you don't take one molar but half a molar*

07 T: *Good question ... section 11*

(end of discourse)

I interpret the statements of the teacher and the students in transcript 8.8 as development of the concept of the concentration dependent value of potential difference. Hereby, the learning condition of intelligibility of the concept of the concentration dependent value of potential difference of the single cell can be indicated (teachers' conceptions related to pedagogical content knowledge).

In discourses in which teachers' statements of the second category can be distinguished, the teachers gave students the opportunity for making observations, interpretations and calculations. An example of this can be found in transcript 8.9. In this transcript, the teacher is trying to create the learning condition of intelligibility, see statements 01/05, 07 and 15. In statements 01/05, the teacher is trying to get a clarification for the student's connections of half cells to the voltmeter. The student refers in statements 04 and 10 to the measure context. The teacher refuses to take this into account: "think for yourself for a second" and "no don't look at that". In statement 07, the teacher asks for a corpuscular description of the direction of electron transport. In statement 15, the teacher gives a corpuscular description of the choice for reductant and oxidant. In my view, the teacher does not connect the corpuscular context via the measure context to the calculate context.

Transcript 8.9:
Students are executing experiment 8.1, and measuring the potential difference for the combination Cu-Zn (Appendix F2), when the teacher comes along.

01 T: *Which one belongs in the plus*
02 S1: *That's er ... copper*
03 T: *Because*
04 S2: *He deflects negatively*
05 T: *Yes think for yourself for a second ... what's this, forced current passage or a current delivering cell*
06 S1: *A current delivering cell*
07 T: *Good well then the question where do the electrons come from*
08 S2: *From the copper*
09 T: *Or from the zinc*
10 S2: *O no from the zinc because it deflects*
11 T: *No don't look at that ... think if it's from the zinc, zinc will become* Zn^{2+} *plus two electrons or copper becomes* Cu^{2+} *plus two electrons*
12 S2: *Zinc is only a reductant copper can be both oxidant and reductant*
13 T: *Why ... here you also have a zinc two plus solution*
14 S2: *O*
15 T: *So you have to determine which of the two is the strongest reductant and which of the two is the strongest oxidant ...*

(end of discourse)

I interpret the teacher's statements in transcript 8.9 as a development of the concept of the sign of potential difference. Hereby, the learning condition of intelligibility of the sign of potential difference of the single cell can be indicated (teachers' conceptions related to pedagogical content knowledge).
In this transcript, a teaching problem can be indicated. The teacher talks in a corpuscular context connected with the table, while the student talks in a measure

context. The student's conceptual difficulty concerns the choice of the oxidant and reductant (stat. 12).

In the evaluation stage, I listened to the teachers' discussion of the way to teach the topic of potential difference. In this evaluation, the teachers argue about a sequence of topics. An example of this can be found in transcript 8.10, statement 01. In this statement, the teacher says that starting with current and then going on to voltage seems logical to students. This teacher also mentions working for the exams when he says "when they have to do exam questions it appears they did not understand it".
Furthermore, besides talking about some practical troubles, i.e. "the additionality of the ΔV values did not concur" (stat. 02), the teachers talked about suggestions for improvement. An example of this can be found in statement 02. In this statement, the teacher talks about strengthening the measure context when he says "isn't it better to turn this around ... to take concentration differences and measure and maybe temperature differences ... and then to talk about standard potentials".

Transcript 8.10:
This transcript is a part of the plenary discussion on evaluating the § 8-11.

01 T1: *What I liked were of course the experiments and what furthermore comes to mind is that the sequence is different ... er ... you start with current and then voltage ... that ... I notice that students, yes of course they have no comparison material ... but I notice they find it a logical sequence (...) also what I notice .... in the chapter from the textbook, I used it for years, that in general they do not find it difficult to follow the book, they learn the tricks, but when they have to do exam questions it appears they did not understand it ... and now it is better...*

02 T2: *Yes I had very high grades for the test ... which I did not expect ... but I want to remark that the additionality of the ΔV values did not concur ... at least not with us ... (...) I think 11.1 is a nice experiment ... but ... only now the concentration dependence arises ... and before one uses the term standard potentials ... isn't it better to turn this around ... to take concentration differences and measure and maybe temperature differences ... and then to talk about standard potentials ...*

Then they talk about some practical aspects of the experiments. (end of transcript fragment)

I understand the teachers' statements in transcript 8.10 as evaluating their teaching of the development of the concept of potential difference. In doing so, the teachers' statements concerned the topic sequence and strengthening the measure context (teachers' conceptions related to content knowledge). From their statements, attention for the learning condition of plausibility can be indicated (teachers' conceptions related to pedagogical content knowledge).

8.3 Teachers' conceptions and teaching problems

In this section, the answers to the research questions will be presented about teaching the concept of the sign and the value of potential difference. The results of the analysis of both cycles will again be combined.
The teachers' conceptions concern three categories of their knowledge mentioned by Shulman (1987), namely:
- content knowledge, i.e. knowledge of the key concept of potential difference and knowledge of the use of contexts in texts concerning potential difference of an electrochemical cell,
- pedagogical content knowledge, i.e. knowledge concerning creating Posner's learning conditions and knowledge concerning use of contexts concerning potential difference of an electrochemical cell,
- knowledge of learners and their characteristics, i.e. knowledge concerning both existing students' conceptions of potential difference of an electrochemical cell and knowledge concerning the development of their conceptions.

First, teachers' conceptions related to contexts could be indicated.
Teachers' conceptions concerning the coupling of the corpuscular context and the measure context for the sign of the potential difference could be pointed out. Concerning these conceptions, identified electron transfer and its direction on the basis of the place in the table, lead to reasonings about the plus or minus sign of the electrodes and the way to connect the wires to the voltmeter in order to get a positive deflection. Examples of teachers' statements in which these conceptions are reflected can be found in transcripts 8.1, 8.4 and 8.9.
Teachers' conceptions concerning differences between the measured values of potential differences and the calculated values of potential difference of coupled cells could be shown. Concerning these conceptions, differences in values for the potential difference of coupled cells which were measured and which were calculated were mentioned. Examples of teachers' statements in which these conceptions are communicated can be found in transcript 8.2.
Teachers conceptions concerning the coupling of the corpuscular context and the tabulated values of potential difference in the calculate context could be stated. Concerning these conceptions, potential differences were calculated with the help of corpuscular descriptions of the electrode reactions and the table of potentials in the book of data (Binas, 1992). Examples of teachers' statements in which these conceptions are reflected can be found in transcripts 8.3 and 8.8. In the latter as a problem with the place in the table and in the first as a mathematical problem.

Second, teachers' conceptions related to learning conditions could be indicated.
Teachers' conceptions concerning the learning condition of plausibility could be shown. Concerning these conceptions, the importance of students' observations and measurements was mentioned. Examples of teachers' statements in which these conceptions are reflected can be found in transcripts 8.5 and 8.10.
Teachers' conceptions concerning the learning condition of intelligibility could be pointed out. Concerning these conceptions, corpuscular descriptions of identified electron transfer which lead to the sign of the potential difference were formulated. Examples of teachers' statements revealing these conceptions can be found in transcripts 8.8 and 8.9.
Teachers' conceptions concerning the learning condition of fruitfulness of the 'single cell' could be stated. Concerning these conceptions, the measured value and the sign of potential difference in the singe cell was applied in the experiment of the coupled cell. Examples of teachers' statements reflecting these conceptions can be found in transcript 8.6.
Also, *teachers' conceptions concerning the four learning conditions* could be given. Concerning these conceptions, a particular meaning was assigned to each learning condition, e.g. the plausibility was connected with measurements and the fruitfulness with deflections of the voltmeter. Examples of teachers' statements communicating these conceptions can be found in transcript 8.7.

Third, besides teachers' conceptions, also some teaching problems could be indicated.
Teaching problems concerning students not constructing the calculate context themselves could be pointed out. Concerning these teaching problems, rules concerning the calculation of the potential difference with the help of tabulated values of standard potentials were established without references to the measure context. The students' conceptual difficulties concern understanding these calculation rules. Examples of these teaching problems can be found in transcripts 8.3 and 8.5.
Teaching problems concerning not creating the learning condition of plausibility could be shown. Concerning these teaching problems, no attention was paid to the observations of the set-up of an electrochemical cell in relation with the measurements of the sign and the value of potential difference which can lead to interpretations. The conceptual difficulties concern students' observations and measurements which they were hampered to use. An example of these teaching problems can be found in transcript 8.9.

Chapter 9

Summary, proposals and recommendations

In this chapter, first a summary of this dissertation will be given (9.1). Subsequently, the contributions to the two educational structures, viz. the educational structure of electrochemical cells and the educational structure of creating conditions for learning electrochemical cells, will be outlined (9.2 and 9.3). The chapter will be concluded by a section on the evaluation of this study and recommendations for further research (9.4).

9.1 Summary

Looking back, the thesis can be considered as consisting of two parts:
- Chapter 1 up to and including chapter 5, which part deals with the development of the field of study, the research questions and the research method. This explorative part of my research was effected by describing important concepts, analysing teaching materials as well as current teaching at secondary school level, and developing a framework for description and design of electrochemical cell education.
- Chapter 6 up to and including chapter 8, which part presents the results of my developmental research concerning the questions about teachers' conceptions and teaching problems. These three chapters are concerned with the construction of corpuscular reasonings about current passage in an electrochemical cell and with the construction of corpuscular, measure and calculate reasonings about the characteristic of potential difference of an electrochemical cell.

In ***chapter 1***, I outlined the focus and the relevance of the study. In this chapter, I indicated that the topic of electrochemistry in secondary education is considered as

difficult by both students and teachers. After a description of the topic of electrochemistry in syllabi, the choice to investigate *conceptions* concerning the topic of *electrochemical cells* is made on the basis of content reasons. The main research objective for this thesis is to *contribute to two educational structures*:
- an educational structure of electrochemical cells and
- an educational structure of creating conditions for learning electrochemical cells.

In this section, the choice for an *in-service* teacher course is made, as a chronological combination of student and teacher course.

In ***chapter 2***, I started by selecting a number of important electrochemical concepts, viz. *electrolyte*, *electrode*, *electrode reaction* and *potential difference* as characteristics of electrochemical cells.

For the scientific historical environment, I have analysed the contexts in which the concepts were developed, and subsequently described and named these contexts. Five contexts were described and named:
- *the phenomenological context*, including *the measure context*,
- *the corpuscular context*, including *the electrostatic corpuscular context,*
- *the chemical thermodynamic context.*

In doing so, I could also indicate *context sequences*. The context sequence for the development of the concepts of electrolyte, electrode and electrode reaction appeared to proceed from a mainly phenomenological context to a mainly corpuscular context. For the concept of potential difference, the context sequence appeared to be from an initially principally measure context to a finally principally chemical thermodynamic context.

For the tertiary educational environment, I tried to apply the named contexts in an analysis of the four concepts in a physical chemistry textbook and in an electrochemistry textbook. I could not indicate the electrostatic corpuscular context in these textbooks. In addition to context sequences, it was also possible to show *mixing of contexts*.
For the concepts of electrolyte and electrode, it was possible to indicate a mix of the phenomenological context and the corpuscular context. For the concept of electrode reaction, the context sequence appeared to have changed when compared with the sequence in the previous environment: in the textbooks, it was possible to point out a sequence from a corpuscular context to a measure context instead of the other way around. For the concept of potential difference, a mix of the measure context and the chemical thermodynamic context could be indicated.

For the secondary educational environment, I also tried to apply the named contexts in an analysis of the four concepts in two generally used textbooks. I could point out

context sequences and mixing of contexts. I could not indicate the electrostatic corpuscular context and the chemical thermodynamic context. Moreover, it was possible to indicate one new context, *the electrochemical calculate context*, i.e. with respect to potential-concentration relations.
For the concepts of electrolyte and electrode, it was possible to indicate a mix of a corpuscular context and a phenomenological context, as was also the case in the tertiary educational environment. For the concept of electrode reaction, in contrast with the other concepts, a mix appeared to be lacking. This concept appeared to be mainly described in a corpuscular context without a phenomenological one. For the concept of potential difference, it was possible to point out a mix of a measure context and an electrochemical calculate context.
Finally, context sequences could not be indicated in the secondary educational environment, because there was either a mix of contexts or only one context could be indicated in which a concept is being described.

In ***chapter 3***, I go into *current teaching* concerning the topic of *electrochemical cells* in order to indicate possible teaching problems which particular use of contexts may bring about. Teaching problems are defined by me as teachers' use of contexts which causes conceptual difficulties for students in understanding concepts. There were some topics which could be connected to these teaching problems, viz. electron transfer on distance, ion transport, salt bridge, corrosion, the Nernst equation and the calculation of the electromotive force.
Teachers' use of contexts and conceptual difficulties of students in relation to these topics were investigated in an empirical way. By means of audiorecording, the whole lesson series on electrochemical cells of two teachers was registered. The audiorecordings were written out into transcripts. Subsequently, the transcripts were analysed in order to describe teaching problems. During and after the lesson series, interviews were held with each teacher in order to clear up some vaguenesses for me in their teaching and to get teachers' conceptions of the indicated teaching problems. These interviews were also audiorecorded, and the recordings written out into transcripts which were subsequently analysed.
Three kinds of teaching problems could be indicated: *emphasizing a particular context*, *mixing of contexts* and *constructing contexts by the teachers themselves*. The teaching problems were discussed from two perspectives: the expert-novice perspective and the top-down teaching perspective.
Teaching problems occurred with a number of electrochemical concepts, which are called *key concepts*. These concepts yielded difficulties both for teachers and students. The key concepts are the *concepts of electron transfer*, *electron transport*, *ion transport* (these three are being situated in a corpuscular context) and *potential difference* (this can be situated in either a measure context, a chemical thermodynamic context and an electrochemical calculate context).

The use of contexts will be a criterium for the design of both teacher and student courses.

In ***chapter 4***, I described a framework for description and design of a teacher course regarding teaching electrochemical cells. For the main structure of the teacher course, of which the student course is a part, I chose social constructivism, which is made concrete by giving the teachers opportunities to get social and physical experiences in all the stages of the teacher course: the introduction to, the realization and the evaluation of the student course. During these stages, the teacher can become aware of his teaching frame. In the course, I asked the teachers to take account of concepts, of the use of contexts and of activities of the students. I take account of the same aspects but then for students and teachers at the same time (speaking/listening, writing/reading, observing/interpreting). For the contents of the teacher course, I chose three categories of knowledge as described by Shulman:
- *content knowledge* (the four key concepts and the use of contexts in textbooks),
- *pedagogical content knowledge* (teachers' use of contexts and their use of learning conditions) and,
- *knowledge of learners* (existing students' conceptions and development of students' conceptions).
For the first three key concepts, the choice concerning starting from the phenomenological context is of importance, for the fourth key concept, the choice for starting from the measure context.
The learning conditions are being formulated according to Posner's model for learning, i.e. necessity, plausibility, intelligibility and fruitfulness. For the student course, I chose as a tool for its structuring the phase model of Van Dormolen, i.e. orientation, development and application. The relation of these phases with use of contexts and Posner's model can be described as follows:
- the necessity is connected with context introduction in the orientation phase,
- the plausibility and the intelligibility are connected to context coupling and context elaboration in the development phase,
- the fruitfulness is connected to context application in the application phase.

In ***chapter 5***, I have described the structure of the teacher course, of which the student course is a part. The main structure of the teacher course is an introduction to the new student course material, followed by a realization of teaching with this new course material and an evaluation of this teaching. The main structure of the student course is from a phenomenological to a corpuscular context and from a measure to a calculate context.
I start this chapter with outlining the design of the *cycles of my developmental research*. First, the central research questions are described, which concern teachers' conceptions when teachers take part in an in-service course including the use of new

student course material on electrochemical cells, and teaching problems which can be indicated during teaching with this material. Next, the research methods are discussed:
- *the cyclical method*, in which cycles of teacher course are described, and
- *transcript analysis*, of which kind of analysis the advantages and disadvantages are described.

After this, the design of the two subsequent teacher courses is described.

In ***chapter 6***, I state the teachers' conceptions and the teaching problems concerning the *teaching* of the key concepts of *electron transfer* and *electron transport* in an electrochemical cell. These key concepts are related to the concepts of electrode reaction and electrode.

First, *teachers' conceptions* could be indicated concerning the *object characteristic* of an electrode and the *location characteristic* of an electrode reaction. *Teaching problems* could be indicated concerning the latter characteristic in teaching and learning the topic of corrosion (pit corrosion). Teachers' activities concerned counting of half reactions in a corpuscular context. Students appeared to experience difficulties in understanding that two related half reactions can take place in one location or in two different locations. This introduction of corrosion is indicated by me as a matter of *introduction of the corpuscular context of electrode.*

Also *teachers' conceptions* concerning the *process characteristic* of an electrode reaction could be pointed out. These were mainly corpuscular conceptions.

Teachers' conceptions of the *function of the electrode* in an electrochemical cell appeared to be phenomenological as well as corpuscular, i.e. phenomenologically seen as being part of a current circuit, and corpuscularly seen as a combination of electron transfer and electron transport.

Teachers' conceptions concerning *Posner's learning condition of necessity* could be pointed out as far as the concept of electrode is concerned. In previous education, the students learned about direct redox reaction as a corpuscular description given by the teacher and the textbook. In the new topic of electrochemical cells, arises for teachers the necessity to call a bar an electrode on the basis of their observations of two spatially separated and distinguishable identities.

In ***chapter 7***, I state the teachers' conceptions and the teaching problems concerning the *teaching* of the key concept of *ion transport* in an electrochemical cell.

Four kinds of teachers' conceptions concerning a corpuscular description of current passage in an electrochemical cell could be pointed out.

First, *teachers' conceptions* concerning an *incomplete corpuscular context* could be shown. These conceptions are called incomplete because identified ion transport is not attributed to all ions in the salt bridge.

Second, *teachers' conceptions* concerning a *corpuscular context elaboration* were restricted to interpretations for the salt bridge, and no interpretations of the electrolytes were given.
Third, *teachers' conceptions* concerning a *corpuscular context application* could be indicated. Hereby, identity, transport and direction of transport of ions and electrons were attributed to the other parts of the cell, viz. electrolytes, electrodes and wires.
Fourth, *teachers' conceptions* can be indicated which can be considered as a *complete corpuscular context* for an electrochemical cell, viz. describing electron transfer, electron transport and ion transport in coherence as a description of current passage. I could indicate *teaching problems* concerning achieving *a complete corpuscular context* for current passage. The teachers made no references to the phenomenological context of the experiment or the combination of experiments (e.g. 'copper bridge' and 'partly coloured salt bridge' experiment). The students' conceptual difficulties concern the inability to describe ion transport, electron transfer and electron transport coherently.

Teachers' conceptions concerning the *context sequence* from *phenomenological to corpuscular* could be indicated.
Also, *teachers' conceptions* concerning the *dominance* or *their emphasizing* of the *corpuscular context* in relation to the phenomenological context, and the *construction of contexts by teachers themselves* could be indicated. In connection with these conceptions *teaching problems* could be indicated. Teachers' activities concerned not taking into account prior knowledge or existing conceptions of students. Also it appeared that teachers do not offer students the opportunity for context construction. Students' conceptual difficulties concern, among other things, current passage in the electrolyte in the form of electron transport.

Finally, also *teachers' conceptions* concerning *the four learning conditions of Posner* could be indicated. For instance, to the learning condition of necessity, a meaning of coherent corpuscular reasonings of current passage was assigned, and to the learning condition of plausibility, a meaning of observations and measurements.

In ***chapter 8***, I state the teachers' conceptions and the teaching problems concerning the *teaching* of the key concept of *potential difference* of an electrochemical cell.
Teachers' conceptions concerning the *corpuscular context* could be pointed out. Concerning these conceptions, there is either a link with the measured values of potential differences (measure context) or a link with the tabulated values of potential differences (chemical thermodynamic context).
Teachers' conceptions can also be indicated concerning *differences in values of potential differences*, anyway for coupled cells but probably also for single cells. Differences were noticed by the teachers between measured values of potential differences and values of tabulated potential differences of single cells, as well as

differences between measured values of potential difference of coupled cells and calculated values by means of measured values of potential differences of single cells. *Teachers' conceptions* concerning *calculating potential differences* were of *corpuscular or calculate* nature. Rules for potential difference calculations are being announced without going back to the value and the sign of the measured potential difference. *Teaching problems* concerning *students not constructing the calculate context themselves* could be indicated. Concerning these teaching problems, the teachers made no references to the phenomenological context, as was the case with the learning condition of intelligibility concerning the corpuscular context of current passage. The students' conceptual difficulties concern understanding these calculation rules.

Teachers' conceptions concerning *Posner's learning condition of fruitfulness* could be indicated. Concerning these conceptions, the measured value and sign of potential differences of single cells as parts of the coupled cells are applied in predicting the value and sign of the potential difference of a coupled cell to be measured. This fruitfulness is seen by me as *context application.*

The *lack of teachers' conceptions* concerning the *electrochemical calculate*, the *chemical thermodynamic* and the *measure context*, whether or not in connection can be an object of further research.

9.2 An educational structure of electrochemical cells

An educational structure

In this section, I will connect the research results concerning teachers' conceptions and teaching problems with each other in the form of an educational structure of electrochemical cells. In this structure, chemical concepts and their sequence are being described.

I think that the educational structure should be started with the concept of *electrode reaction* because it can be connected with prior knowledge of students about direct redox reactions. Another reason is that in chemistry education, the emphasis is on reactions. After this concept, in my view, the concept of *electrode* should follow, because this adds the location characteristic for electrode reaction. This concept is of importance because of the object characteristic and its connection with the location characteristic of the previous concept. After this concept, the concept of *electrolyte* should follow, in my opinion, in order to get a coherent phenomenological reasoning for an electrochemical cell as a whole. After these three phenomenological concepts, the combination of the three corpuscular key concepts should follow: *electron*

transfer, *electron transport* and *ion transport*. For this trio of concepts, the context sequence from a phenomenological to a corpuscular context is of importance.
After this trio of concepts, the concept of *corrosion* could be placed, because this concept is the application of the complete corpuscular context. The contexts which are used in secondary school chemistry are limiting for this concept, cf. in secondary school chemistry no explanation can be found for the fact that the iron does not react in the same way in each location of the object. For developing this concept to its full extent, an introduction to a solid substance context has to be made.

I believe that after the corpuscular description of current passage, the concept of *sign and measure value of potential difference* can be introduced. The concept of sign of potential difference can be connected with prior knowledge of identified electron transfers. The concept of measure value of potential difference is of importance because it is again a characteristic of electrochemical cells. This concept should be followed, in my view, by the concept of *concentration dependent value of potential difference*, because this concept can also be considered in a measure context.

I believe that after the previous two characteristics of the concept of potential difference, the concept of *potential difference as tabulated value* could follow. However, I also think that this concept cannot be achieved within school chemistry, because no thermodynamic aspects are offered in secondary school chemistry. Concerning the concept of potential difference, the concept of activity is not elaborated upon and the thermodynamic aspects in the tabulated values of potentials stay implicit.

Proposals for the syllabus
In connection with the above-described educational structure, I can make the following proposals for the syllabus.

A first proposal is that *the topic of electrochemical cells should be placed before the topic of direct redox reactions* which can be considered as descriptions by means of half reactions. This offers the possibility to make a phenomenological introduction of the corpuscular *half* reactions which subsequently can serve as means for description of *direct* redox reaction.
In earlier stages of education, textbook and teacher should not mention the term oxidation for reactions as for example $Cu + O_2 \rightarrow 2CuO$, where in fact both oxidation and reduction are meant. In such cases it is better to use terms like reactions with oxygen, in order to prevent students' conceptual difficulties in the future.

Another proposal is *to remove the Nernst equation from the syllabus* in favour of measuring of potential differences as the values obtained for a chosen concentration range (calibration curve). Because now, parts of the chemical thermodynamic context

in the tertiary educational environment emerge in the electrochemical calculate context of the secondary educational environment. In that calculate context, the book of data which contains thermodynamic data is used (Binas, 1992). However, these thermodynamic data are used by the teachers as analytical chemical measuring data, in other words, this comes down to describing the Nernst equation in a measure context with concentrations instead of activities while amputating the chemical thermodynamic context. In doing so, it is implicitly established that instead of activities, concentrations are used and all electron transfer is represented by nF for the specified half reactions, and as a consequence, implicitly is assumed that there are no mixed potentials. In the electrochemical calculate context, the relation between potential difference and energy becomes a relation between potential difference and concentration, and the activities have disappeared.
For the concept of potential difference, the choice for the measure context has consequences. For instance, measuring potential differences and subsequently determining the concentrations with the help of a calibration curve. In my opinion, it is enough to focus on such a calibration measure context. The concepts of potential difference as measure value and concentration dependent value could be oriented on, developed and applied. Therefore, I am pleased that in the proposals for a new exam programme for chemistry on VWO level, the Nernst equation is not mentioned anymore (Stuurgroep Tweede Fase, 1995, p.308).

Proposals for teaching
In connection with the above described educational structure, I can give the following proposals for the teaching of electrochemical cells.

A proposal for teaching the topic of electrochemical cells is to *start with the concept of current passage instead of with the concept of potential difference*. Opting for the development of the concept of current passage is a choice related to an (electro)chemical point of view, because in this way the (amount of) converted substance can be correlated to the (amount of) charge transport and charge transfer. This choice has the advantage that it can be developed from a phenomenological context of visible (half) reactions when in a cell current passage takes place, to a corpuscular context.
Hereby, ionic conducting and electrical neutrality should get a lot of attention, because of the difficulties with a complete corpuscular context (see section 7.3). Other authors also mention students' conceptual difficulties concerning describing ionic conducting and electrical neutrality (e.g. Ogude & Bradley, 1994). The students appeared to have three alternative conceptions of current passage in the electrolyte:
- only electron transport (also through the salt bridge),
- electron transport in the wires and bars and electron 'hopping' in the electrolyte and,
- electron transport in the wires and bars and electrons on carriers in the electrolyte.

A final proposal for teaching electrochemical cells is a choice for *teaching within a guiding frame*. It has become clear that teaching within a transmitting frame is not very effective and therefore teachers should more often teach within a guiding frame. I agree with Baird (1988) when he states that developing observational and intellectual skills, reasoning abilities, cognitive strategies and meta-cognitive proficiencies is central to the task of the science teacher. Teachers must foster both cognitive and affective development by nurturing a sense of wonder, a need to know and, concurrently, by teaching skills for generating understanding. Therefore I feel that it is necessary to start education with phenomena. In order to create a physical experience which is as large as possible, there ought to be no explanation following the descriptions of experiments in student course material. Neither ought teachers to give these explanations.

Thus, the mainly transmitting method of teaching should be replaced by a mainly guiding method of teaching in which students themselves get much more opportunity to develop concepts in contexts. Let students work in small groups which work independent of the teacher to give them the opportunity to develop their physical and social experiences in connection. Therefore, student experiments, demonstration experiments and assignments should be designed to fit this kind of teaching.

9.3 An educational structure of creating learning conditions

An educational structure

In this section, I want to connect the research results concerning teachers' conceptions and teaching problems with each other in the form of an educational structure of creating conditions for learning electrochemical cells. In this structure, concepts and their sequence are being described.

I think the structure should start with *the concept of concept* because it can be connected to prior knowledge of the teachers about chemical concepts. This could be effected by asking teachers to make concept maps, in this case of the topic of electrochemical cells. After this concept, *the concept of context* should follow, because concepts have meaning in contexts. This concept is of importance because of its (implicit) use by textbooks and teachers. The concept of context can be developed through paying attention to the use of language with regard to chemical and educational events in textbooks and in transcripts of classrooms. In doing so, properties of the concept of context can be developed.

After this concept, in my opinion, *the concept of key concept* should follow because in the concept of key concept the previous two, viz. concept and context, are applied. For example electron transfer, electron transport and ion transport in a complete corpuscular context are key concepts. This concept is of importance because of its connection to content knowledge. Developing key concepts can again take place through the analysis of textbooks and classroom transcripts. After this, in my view, *the concept of use of contexts* should follow, because then the concern for students' learning can come up, and applying of the learned concepts in own teaching. This concept is of importance because in this concept, content knowledge and pedagogical knowledge are combined. The properties of use of contexts, e.g. sequence and mixing, can be learned by means of analysing texts and classroom transcripts. After this concept, *the concept of Posner's learning conditions* should follow, because knowledge of these learning conditions can be used, among other things, to describe the results of the teachers' use of contexts. This concept is of importance because I think it can also be used to describe own teaching. Then *the concept of creating learning conditions* should follow in order to apply their knowledge. This concept is of importance because again hereby content knowledge and pedagogical content knowledge are being combined. This concept can be developed by paying attention in their own teaching to these conditions and to the existing conceptions of their students. Also evaluation of this paying of attention after teaching could be of help.

Proposals for teacher courses

In connection with the above described educational structure, I can give the following proposal for teacher courses.

A proposal for the teacher course is that attention should be paid to the teachers' knowledge of *concepts, contexts and learning conditions*, because it is of immense importance. I believe that when a teacher himself knows not enough about these three, he is not able to use concepts, contexts and learning conditions in a way that contributes to students' learning. Fuller and Bown (1975) argued that beginning teachers' first concern is for themselves, viz. "do I understand the content knowledge myself", and only later on they concern themselves with students' understanding. More experienced teachers come again in the same situation when they have to teach with new materials. An example of the importance of content knowledge concerns the experiment with the partly coloured salt bridge (section 7.1). Teachers who cannot themselves make the context elaboration concerning the colourless parts can probably not help their students when they have conceptual difficulties establishing a complete corpuscular context.

In this thesis, the teachability of contexts and of learning conditions has been elaborated upon and the possibility of making use of contexts and learning conditions offers the teachers tools for making changes in their teaching. Learning about contexts and learning conditions had best be done by offering the teachers opportunities for physical and social experiences in an in-service course.

Teachers ought to be aware of their conceptions concerning school chemical concepts. In that case, they can act within a guiding frame as well as within a transmitting frame. But a teacher who is not aware of them, can only act in a transmitting frame, and in that case, it is difficult for the teacher to help his students with their conceptual difficulties. Carlsen (1993) also argues that when teaching unfamiliar topics, teachers tend to talk more often and for longer periods of time, ask questions frequently, and rely heavily on low cognitive level questions.

9.4 Research evaluation and recommendations

Evaluation of this study

First, empirical studies done in current teaching concerning, in this case, the topic of electrochemical cells, are necessary to recognize and to describe problems with regard to teaching school chemistry. When the backgrounds of teachers' conceptions and teaching problems are clearer, solutions can be searched for and found.

A weak point of this kind of qualitative research is, among other things, the generalization of findings, because I only observed a limited number of teachers. However, I chose to observe and work with a limited number of teachers in each teacher course, because in that way the teachers could *interact* with each other.

I did not choose to follow one teacher in a longitudinal study because I wanted to get as many *kinds of* teachers' statements and reasonings as possible.

Also, in this study, there is a close relation between designer and evaluator of both student and teacher course material. It is difficult to change aspects in the teacher and student course if one is closely involved in the development of both. On the other hand, it is a strong point at the same time because one is closely involved in aspects where something goes wrong. However, analysis of the conceptions and the teaching problems of the teacher educator should to be done in order to create a better and more detailed structure for the teacher course.

Furthermore, for registration, I chose to use audio and not video, because I focused mainly on the use of language. However, for the connecting of single cells in the form of coupled cells, video would have been a great help because both the teachers and the students talk in a very shortened way when they indicate parts of the set-up.

For the development of new student courses for all kinds of topics, it is important that developers of syllabi, textbook authors and teachers, listen to students. However, this is not always easy, certainly not for the first two categories of people. In order to listen to students, audiotapes could be made of real educational situations. But audiotaping classroom discourses requires the prior permission of students, teachers and school management. This is not always an easy task. Besides in some countries, e.g. Germany and the United States, district and parental permission are also required. This also means that local educational authorities can determine the extent to which research can be done in this field. This rule does not appear to stimulate schools to participate in research involving 'listening in on classrooms'. In all cases, it is important to convince the participants of the value of the classroom transcript analysis method for classroom practices.

Recommendations for further research

In connection with the results described before, I can give the following recommendations for further research.

Three suggestions for further research are in the field of electrochemical cell teaching. Research should be done into the students' conceptual difficulties concerning the prohibitive rule of electrons through liquids. Experiments should be developed in order to prevent these students' conceptions in school chemistry.
Also research should be done into what extent thermodynamics could and should be used in secondary school chemistry concerning the topic of electrochemical cells.
Third, research should be done into the place of the electrostatic corpuscular context. I do not believe that this context should be introduced in secondary school chemistry. The only place where this context could come up is the reaction of chloride instead of water in the electrolysis. In secondary school chemistry, this is called an exception to the rule which comprises that the strongest reductant according to the table on standard potentials reacts. This exception contributes to an electrostatic corpuscular context, but can at the same time be considered as an introduction to the concept of overvoltage. Overvoltage can be considered as the difference between the measured value and the thermodynamic value. Further research should be done into whether this topic should be used in education.

In this research, experimentally tested and testable educational structures are being developed, because both the student course as well as the teacher course are executed in real educational situations (experimentally tested educational structures) and can be executed again (testable educational structures). The established educational structure is a qualitative descriptive theory with restricted explaining and predicting possibilities.
One type of further research could be focused on a comparison between teachers' and students' conceptions after education designed according to my educational structure for electrochemical cells and their conceptions after prevailing education. A possible result could be that the percentage of students with conceptions concerning a complete corpuscular context of an electrochemical cell is higher after teaching designed according to my educational structure.

In this research, it appeared that the learning conditions of plausibility and intelligibility got more attention than the learning conditions of necessity and fruitfulness. Further research could be done into why this is the case. However, more interesting research should concern, in my view, the ways to pay more attention to the learning conditions of necessity and fruitfulness in designs of educational material.

Yet another type of further research could be focused on a try-out of a teacher course designed according to my proposal for an educational structure of creating conditions for learning. In this educational structure, I used three categories of knowledge of teachers according to a description of Shulman (1987). These categories are used a lot in research, but they are of a very general nature. I tried to give the categories further meaning by connecting them with key concepts, contexts and learning conditions in the framework of teaching a specific topic. Because of the indicated connections between key concepts, contexts, Posner's learning conditions and Shulman's categories of knowledge, the results of this research can be useful for research into other educational topics, even outside the field of chemistry education and for teaching other topics.

References

Acampo, J. & De Jong, O. (1991). Een muzikale fruitmand - een elektrochemisch proefje. *NVON Maandblad, 16(10)*, 438-439.

Acampo, J. & De Jong, O. (1992). Elektrochemie: een stroom van problemen. *NVON Maandblad, 17(9)*, 430-431.

Acampo, J. & De Jong, O. (1993a). Onduidelijkheden binnen elektrochemieonderwijs - wordt het niet tijd om heldere afspraken te maken? *NVON Maandblad, 18(6)*, 230-231.

Acampo, J. & De Jong, O. (1993b). Corrosie in 5 VWO - een andere behandeling binnen het onderwerp elektrochemische cellen. *NVON Maandblad, 18(8)*, 343-345.

Acampo, J. & De Jong, O. (1993c). Education in electrochemistry - a study of teacher problems. In: H. Kramers-Pals & G. Niehaus (Eds.), *Chemiedidaktische Forschung, Lopend onderzoek in de chemiedidaktiek*. Essen: Westarp-Wissenschaften, 136-138.

Acampo, J. & De Jong, O. (1994a). Stroomdoorgang in elektrochemische cellen - twee verhelderende demonstratieproeven. *NVOX, 19(6)*, 229-331.

Acampo, J. & De Jong, O. (1994b). 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*. Hong Kong: ICASE, 229-237.

Acampo, J. (1995). Chemistry teachers' learning processes concerning education in electrochemistry for 5 VWO. In: D. Psillos (Ed.), *European research in science education II*. Thessaloniki: Art *of*Text S.A., 441-448.

Acampo, J. & De Jong, O. (1995). Een nieuwe start met elektrochemische cellen - ervaringen met een 'sleutelproef'. *NVOX, 20(7)*, 308-309.

Acampo, J. & De Jong, O. (1996a). Ervaringen met een voltammogram in het VWO. *NVOX, 21(5)*, 199-200.

Acampo, J. & De Jong, O. (1996b). Korrosion für die Sekundarstufe II - Eine andere Unterrichtsvariante für die Thematik elektrochemische Zellen. *Praxis der Naturwissenschaften, 45(5)*, 26-28.

Aguirre, J.M., Haggerty, S.M. & Linder, C.J. (1990). Student-teachers' conceptions of science, teaching and learning: a case study in preservice science education. *International Journal of Science Education, 12(4)*, 381-390.

Allsop, R.T. & George, N.H. (1982). Redox in Nuffield advanced chemistry. *Education in Chemistry, 19*, 57-59.

Atkins, P.W. (1994). *Physical Chemistry*. Oxford: Oxford University Press, fifth edition.

Ausubel, D.P. & Robinson, F.G. (1969). *School learning - An introduction to educational psychology*. London: Holt, Rinehart and Winston, Inc.

Baird, J.R. (1988). Teachers in science education. In: P. Fensham (Ed.), *Development and dilemmas in science education*. London: The Falmer Press, 55-75.

Baird, J.R., Fensham, P.J., Gunstone, R.F. & White, R.T. (1991). The importance of reflection in improving science teaching and learning. *Journal of Research in Science Teaching, 28(2)*, 163-182.

Bard, A.J. & Faulkner, L.R. (1980). *Electrochemical Methods. Fundamentals and Applications*. New York: John Wiley & Sons, Inc.

Barnes, D. (1975). *From communication to curriculum*. Leeds: Penguin Books.

Barral, F.L., Garcia-Rodeja Fernandez, E. & Otero, J.R.G. (1992). Secondary students' interpretations of the process occurring in an electrochemical cell. *Journal of Chemical Education, 69*, 655-657.

Beasley, W.F. (1992). Curriculum innovation and teacher development. *Journal of Chemical Education, 69(1)*, 57-58.

Bell, B. & Gilbert, J. (1996). *Teacher development. A model for science education.* London: The Falmer Press.

Berg, T. & Brouwer, W. (1991). Teacher awareness of student alternate conceptions about rotational motion and gravity. *Journal of Research in Science Teaching, 28(1),* 3-18.

Binas (1992). *Informatieboek vwo-havo voor het onderwijs in de natuurwetenschappen.* Groningen: Wolters-Noordhoff.

Bodner, G.M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education, 63(10),* 873-878.

Boeck, H. (1994a). Behandlung der Elektrochemie in der Sekundarstufe I (Teil 1). *Chemie in der Schule, 41(6),* 226-231.

Boeck, H. (1994b). Behandlung der Elektrochemie in der Sekundarstufe I (Teil 2). *Chemie in der Schule, 41(7/8),* 278-281.

Bojczuk, M. (1982). Topic difficulties in O- and A-level chemistry. *School Science Review, 69,* 545-551.

Botsch, W. (1993). Geschichte der Elektrochemie. *Praxis der Naturwissenschaften - Chemie, 42(7),* 15-21.

Brickhouse, N.W. (1990). Teachers' beliefs about the nature of science and their relationship to classroom practice. *Journal of Teacher Education, 41(3),* 53-62.

Briscoe, C. (1991). The dynamic interactions among beliefs, role metaphors, and teaching practices: a case study of teacher change. *Science Education, 75(2),* 185-199.

Brock, W.H. (1992). *The fontana history of chemistry.* London: Fontana Press.

Bromme, R. (1992). *Der Lehrer als Experte. Zur Psychologie des professionellen Wissens.* Bern: Verlag Hans Huber.

Bruner, J.S. (1966). *Toward a theory of instruction.* Cambridge, MA: The Belknap Press of Harvard University Press.

Bucat, R.B. & Fensham, P.J. (1995). Exploring more effective teaching in chemistry classrooms. In: O. De Jong, P.H. Van Roon & W. De Vos (Eds.), *Perspectives on Research in Chemical Education.* Utrecht: CD-β Press, 87-95.

Butts, B. & Smith, R. (1987a). HSC chemistry students' understanding of the structure and properties of molecular and ionic compounds. *Research in Science Education, 17,* 192-201.

Butts, B & Smith, R. (1987b). What do students perceive as difficult in HSC chemistry? *Australian Science Teachers' Journal, 32(4),* 45-51.

Carey, S., Evans, R., Honda, M., Jay, E. & Unger, Ch. (1989). 'An experiment is when you try it and see if it works': A study of grade 7 students' understanding of the construction of scientific knowledge. *International Journal of Science Education, 11,* 514-529.

Carlsen, W.S. (1993). Teacher knowledge and discourse control: quantitative evidence from novice biology teachers' classrooms. *Journal of Research in Science Teaching, 30,* 471-481.

Carter, K. (1990). Teachers' knowledge and learning to teach. In: W. Robert (Ed.), *Handbook of Research on Teaching Education.* Houston: MacMillan, 291-310.

CMLS (1978). *Advies aan de minister van onderwijs en wetenschappen: leerplan scheikunde voor 5- en 6-vwo (deel 1 en deel 2).* 's-Gravenhage: Staatsuitgeverij.

Cornett, J.W., Yeotis, C. & Terwilliger, L. (1990). Teacher personal practical theories and their influence upon teacher curricular and instructional actions: a case study of a secondary science teacher. *Science Education, 74(5),* 517-529.

Davies, A.J. (1991). A model approach to teaching redox. *Education in Chemistry, 28,* 135-137.

De Jong, O. (1982). Moeilijke onderwerpen. *Chemisch Weekblad, 78,* 90.

De Jong, O. (1990). *Rekenen aan Reakties.* Utrecht: Rijksuniversiteit Utrecht, dissertation.

De Jong, O. (1991). Expertise van docenten: bron van moeilijkheden bij leren probleemoplossen? In: F.A.J. Korthagen, O. De Jong & Th. Rensman (Eds.), *Van anders naar beter. Doelgericht inspelen op veranderingen in secundair en tertiair onderwijs.* Utrecht: IVLOS, 45-51.

De Jong, O. & Acampo, J. (1993). Creating conditions of learning: chemistry teachers' actions and reflections. In: J.T. Voorbach (Ed.), *Teacher Education 9 - Research and developments on teacher education in the Netherlands.* De Lier: Academisch Boeken Centrum, 121-128.

De Jong, O. & Acampo, J. (1994). Teaching bridge concepts in changing science contexts: a case study of teachers' strategies and conceptions. In: J.T. Voorbach (Ed.), *Teacher Education 10 - Research and developments on teacher education in the Netherlands.* De Lier: Academisch Boeken Centrum, 40-48.

De Jong, O., Acampo, J. & Verdonk, A. (1995). Problems in teaching the topic of redox reactions: actions and conceptions of chemistry teachers. *Journal of Research in Science Teaching, 32(10),* 1097-1110.

De Jong, O., Korthagen, F. & Wubbels, Th. (1997). Research on science teacher education in Europe: teacher thinking and conceptual change. In: K. Tobin & B. Fraser (Eds.), *International Handbook of Science Education.* Dordrecht: Kluwer Publishers.

De Vos, W. (1985). *Corpusculum Delicti.* Utrecht: Rijksuniversiteit Utrecht, dissertation.

De Vos, W. & Verdonk, A.H. (1984a). 's Rijks wegen naar een leerplan I. *NVON-maandblad, 9(2),* 35-37.

De Vos, W. & Verdonk, A.H. (1984b). 's Rijks wegen naar een leerplan II. *NVON-maandblad, 9(6/7),* 5-8.

De Vos, W. & Verdonk, A.H. (1985a). A new road to reactions, part I. *Journal of Chemical Education, 62,* 238-240.

De Vos, W. & Verdonk, A.H. (1985b). A new road to reactions, part II. *Journal of Chemical Education, 62,* 648-650.

De Vos, W. & Verdonk, A.H. (1986). A new road to reactions, part III. *Journal of Chemical Education, 63,* 972.

De Vos, W. & Verdonk, A.H. (1987a). A new road to reactions, part IV. *Journal of Chemical Education, 64,* 692-694.

De Vos, W. & Verdonk, A.H. (1987b). A new road to reactions, part V. *Journal of Chemical Education, 64,* 1010-1013.

Docters van Leeuwen, R.A.W. (1968). *De methodologische benadering van problemen op het gebied van de didactiek van de scheikunde op de middelbare school, in het bijzonder die welke het leerstofprogramma en de eindexamineertechniek betreffen.* Zeist: NIB, dissertation.

Driver, R. (1988). Changing Conceptions. *Tijdschrift voor Didactiek der β-wetenschappen, 6(1),* 161-198.

Driver, R., Asoko, H., Leach, J., Mortimer, E. & Scott, Ph. (1994). Constructing scientific knowledge in the classroom. *Educational Researcher, 23(7),* 5-12.

Driver, R. & Bell, B. (1986). Students' thinking and the learning of science: a constructivist view. *School Science Review, 67,* 443-456.

Duit, R. & Komorek, M. (1994). Constructivist informed research on students' understanding of basic ideas of chaos theory. In: H.-J. Schmidt (Ed.), *Problem solving and misconceptions in chemistry and physics.* Hong Kong: ICASE, 49-69.

Edwards, D. & Mercer, N. (1987). *Common knowledge - The development of understanding in the classroom.* London: Methuen.

Feis, R. (1976). Anode, kathode en polen; galvanische cell en stroom. *Faraday, 45,* 155-156.

Feis, R. (1977). De termen van Faraday; de misgreep van Ampère. *Faraday, 46,* 26-27.

Fellows, N.J. (1994). A window into thinking: using student writing to understand conceptual change in science learning. *Journal of Research in Science Teaching, 31(9),* 985-1001.
Finley, F.N., Stewart, J. & Yarroch, W.L. (1982). Teachers' perceptions of important and difficult science content. *Science Education, 66,* 531-538.
Flintjer, B. (1982). "Korrosion" im Unterricht der Sekundarstufe I. *Naturwissenschaften im Unterricht - Physik/Chemie, 30(8),* 307-309.
Fullan, M. (1982). *The meaning of educational change.* New York: Teachers College Press, Columbia University.
Fuller, F.F. & Bown, O.M. (1975). Becoming a teacher. In: K. Ryan (Ed.), *Teacher Education, The 47th yearbook of the NSSE, Part II.* Chicago.

Gabel, D.L. (Ed.) (1994). *Handbook of Research on Science Teaching and Learning.* New York: MacMillan.
Gabel, D.L., Samuel, K.V. & Hunn, D. (1987). Understanding the particulate nature of matter. *Journal of Chemical Education, 64(8),* 695-697.
Galili, I., Bendall, S. & Goldberg, F. (1993). The effects of prior knowledge and instruction on understanding image formation. *Journal of Research in Science Teaching, 30(3),* 271-301.
Gallagher, J.J. (1984). A study of policy and program formulation and implementation in a secondary school and science department. In: Ch.W. Anderson (Ed.), *1984 AETS Yearbook.* Columbus, Ohio: ERIC, 153-184.
Gallagher, J.J. (1991). Prospective and practicing secondary school science teachers' knowledge and beliefs about the philosophy of science. *Science Education, 75,* 121-133.
Galton, M. & Moon, B. (Eds.) (1994). *Handbook of Teacher Training in Europe.* London: David Fulton.
Garnett, P.J. & Treagust, D.F. (1992a). Conceptual difficulties experienced by senior high school students of electrochemistry: electric circuits and oxidation-reduction equations. *Journal of Research in Science Teaching, 29,* 121-142.
Garnett, P.J. & Treagust, D.F. (1992b). Conceptual difficulties experienced by senior high school students of electrochemistry: electrochemical (Galvanic) and electrolytic cells. *Journal of Research in Science Teaching, 29,* 1079-1099.
Gerhartl, F. (1976). Klare taal en tekens. *Faraday, 45,* 108-110.
Gerhartl, F. (1977). Over de betekenis van enkele elektrotechnische termen. *Faraday, 46,* 27-32.
Gottfried, S.S. & Kyle Jr, W.C. (1992). Textbook use and the biology education desired state. *Journal of Research in Science Teaching, 29(1),* 35-49.
Gramm, A. & Koch, I. (1989). Lehrervorstellungen über Chemieunterricht. *Chimica Didactica, 15,* 235-256.
Gramm, A. & Koch, I. (1991). Funktion des Experiments im Unterricht - Entwicklung und Veränderung der Vorstellungen bei Chemielehrern im Zusammenhang mit Aus- und Weiterbildung. Paper presented at the ATEE-conference, the Netherlands.
Gravemeijer, K. (1993). Ontwikkelingsonderzoek als basis voor theorievorming. In: R. De Jong & M. Wijers (Eds.), *Ontwikkelingsonderzoek - theorie en praktijk.* Culemborg: Technipress, 17-33.
Griffiths, A.K. (1994). A critical analysis and synthesis of research on students' chemistry misconceptions. In: H.-J. Schmidt (Ed.), *Problem solving and misconceptions in chemistry and physics.* Hong Kong: ICASE, 70-99.
Grob, K., Von Rhöneck, C., Völker, B. & Wettern, K. (1988). Die Gravitationsanalogie zur Einführung des Spannungsbegriffs. *Naturwissenschaften im Unterricht - Physik/Chemie, 36(31),* 14-19.
Gunstone, R.F., Gray, C.M.R. & Searle, P. (1992). Some long-term effects of uninformed conceptual change. *Science Education, 76(2),* 175-197.

Gunstone, R.F., Slattery, M., Baird, J.R. & Northfield, J.R. (1993). A case study exploration of development in preservice science teachers. *Science Education, 77(1)*, 47-73.

Haack, N.H. (1976). Slordigheden en onnauwkeurigheden II. *Faraday, 45*, 33-36.
Haertel, H. (1989). On voltage and the underlying microscopic model. Paper presented at the International Seminar: 'Relating Macroscopic Phenomena to Microscopic Particles: a Central Problem in Secondary Science Education'. Rijksuniversiteit Utrecht, the Netherlands.
Hashweh, M.Z. (1987). Effects of subject-matter knowledge in the teaching of biology and physics. *Teaching & Teacher Education, 3(2)*, 109-120.
Heap, J.L. (1985). Discourse in the production of classroom knowledge: reading lessons. *Curriculum Inquiry, 15(3)*, 245-279.
Hewson, P.W. & Hewson, M.G.A'B. (1987). Science teachers' conceptions of teaching: implications for teacher education. *International Journal of Science Education, 9*, 425-440.
Hewson, P.W. & Hewson, M.G.A'B. (1988). An appropriate conception of teaching science: a view from studies of science learning. *Science Education, 72(5)*, 597-614.
Hewson, P.W., Kerby, H.W. & Cook, P.A. (1995). Determining the conceptions of teaching science held by experienced high school science teachers. *Journal of Research in Science Teaching, 32(5)*, 503-520.
Hewson, P.W. & Thorley, N.R. (1989). The conditions of conceptual change in the classroom. *International Journal of Science Education, 11*, 541-553.
Hondebrink, J.G. (1976). Slordigheden en onnauwkeurigheden III. *Faraday, 45*, 107.
Houston, W.R. (Ed.) (1990). *Handbook of Research on Teacher Education*. New York: MacMillan.
Huibregtse, I., Korthagen, F. & Wubbels, Th. (1994). Physics teachers' conceptions of learning, teaching and professional development. *International Journal of Science Education, 16(5)*, 539-561.

Ihde, A.J. (1984). *The development of modern chemistry*. New York: Dover publications, Inc.
IUPAC (1988). *Quantities, Units and Symbols in Physical Chemistry*. Oxford: Blackwell Scientific Publications.

Jansen, W. (1975). Neues experimentelles Konzept zur Einführung in die Elektrochemie. *Mathematik und Naturwissenschaften im Unterricht, 28(5)*, 283-289.
Jansen, W., Peper, R., Fickenfrerichs, H., Bückmann, H. & Klugmann, J. (1982). Welche Vorstellungen und Modelle können dem Verständnis elektrochemische Vorgänge dienen? *Naturwissenschaften im Unterricht - Physik/Chemie, 30(8)*, 264-267.
Johnston, K. (1988). Changing teachers' conceptions of teaching and learning. In: J. Calderhead (Ed.), *Teachers' professional learning*. London: The Falmer Press, 169-195.
Johnston, K. (1991). High school science teachers' conceptualisations of teaching and learning: theory and practice. *European Journal of Teacher Education, 14(1)*, 65-78.
Joling, E., Ten Voorde, H.H. & Verdonk, A.H. (1990). Verstudieboeking: de totstandkoming van feiten beschouwd vanuit een didactische optie. *Tijdschrift voor Didactiek der β-wetenschappen, 8(3)*, 197-221.
Joling, E., Van Lierop, A., Van Soest, W., Kaper, W., Ten Voorde, H.H., De Vos, W., Mellink, E., Snel, B. & Timmer, J. (1988). *Chemie mavo: onderzoek naar het functioneren van een leergang scheikunde*. Amsterdam: SCO, SCO rapport 161.

Kerbusch, J & Biezeveld, H. (1976). Antwoord aan Feis. *Faraday, 45*, 157-158.
King, B.B. (1991). Beginning teachers' knowledge of and attitudes toward history and philosophy of science. *Science Education, 75*, 135-141.

Thorley, N.R. & Stofflett, R.T. (1996). Representation of the conceptual change model in science teacher education. *Science Education, 80(3)*, 317-339.
Treagust, D.F., Duit, R. & Fraser, B.J. (Eds.) (1996). *Improving teaching and learning in science and mathematics*. New York and London: Teachers College Press.
Treffers, A. (1993). Ontwikkelingsonderzoek in eerste aanzet. In: R. De Jong & M. Wijers (Eds.), *Ontwikkelingsonderzoek - theorie en praktijk*. Culemborg: Technipress, 35-58.

Van de Berg, G. & Van Driel, J. (1991). *Vragenlijst over het 5 VWO boek Chemie*. Delft: Wolters Noordhoff.
Van Dormolen, J. (1981). *Didactiek van de wiskunde*. Utrecht.
Van Driel, J. (1990). *Betrokken bij evenwicht*. Utrecht: Rijksuniversiteit Utrecht, dissertation.
Van Keulen, H. (1995). *Making sense*. Utrecht: Universiteit Utrecht, dissertation.
Verdonk, A.H. (1986). Basisvorming scheikunde, de noodzaak van nader onderzoek. In: A.H. Verdonk & W.M. De Jong (Eds.), *Werkdocumenten Basisvorming in het onderwijs, Wb 14, scheikunde*. 's Gravenhage: W.R.R., 1-60.
Verdonk, A.H. & Lijnse, P.L. (1993). Research in science education at Utrecht University: an outline. In: P.L. Lijnse (Ed.), *European research in science education*. Utrecht: CD-β Press, 140-145.

Wallace, J. & Louden, W. (1992). Science teaching and teachers' knowledge: prospects for reform of elementary classrooms. *Science Education, 76(5)*, 507-521.
Wester, F. (1987). *Strategieën voor kwalitatief onderzoek*. Muiderberg: Coutinho.
White, R.T. & Gunstone, R.F. (1989). Metalearning and conceptual change. *International Journal of Science Education, 11*, 577-586.
Wittrock, M.C. (Ed.) (1986). *Handbook of Research on Teaching*. New York: MacMillan, third edition
Wubbels, Th. (1992). Taking account of student teachers' preconceptions. *Teaching & Teacher Education, 8(2)*, 137-149.

Yager, R.E. (1983). The importance of terminology in teaching K-12 science. *Journal of Research in Science Teaching, 20(6)*, 577-588.
Yore, L.D. (1991). Secondary science teachers' attitudes toward and beliefs about science reading and science textbooks. *Journal of Research in Science Teaching, 28*, 55-72.

Appendices

APPENDIX A: Explanation of the manner used of rendering the transcripts

In rendering the transcripts I observed the following 'rules':
-Statements are numbered in a chronological sequence.
-Students are referred to as S1, S2 etcetera, no distinction having been made between boys or girls. Ss means more students saying something at the same time. Teachers are referred to as T1, T2 etcetera, with the same lack of distinction for men and women. My own statements and Onno De Jong's statements are referred to as TE which means teacher educator.
-Statements are represented as literally as possible. Punctuation marks are used in accordance with the used intonation. Numbers within statements are represented by figures (for example "4" in transcript where "four" is said).
-Further explanation:

... represents a short interval in a statement;

(...) means that a fragment has been left out. Sometimes this designates a mere few words. In other cases I left out one or more statements I did not consider important for the interpretation of that transcript.

APPENDIX B: Standard evaluation forms

Evaluation form concerning 'Current through Substances' 1st version

1. What were your most important experiences during this lesson?
2a. Which concepts / topics came up during this lesson?
2b. To what extent were those concepts / topics intelligible for the students?
2c. To what extent were those concepts / topics plausible for the students?
2d. To what extent were those concepts / topics applicable for the students?
3. Which suggestions do you have for improvements of the use of the concepts / topics in this lesson?

Evaluation form concerning 'Current through Substances' 2nd version

1. Mark the concepts (in bold print in the teaching material) which came up during this lesson. (here follows a list of concepts)
2a. In what way did you pay attention to making the mentioned concepts necessary for students (by means of the teaching material and, possibly, additional material)?
2b. Are you satisfied about this? Explain.
3a. In what way did you pay attention to making the mentioned concepts intelligible for students (by means of the teaching material and, possibly, additional material)?
3b. Are you satisfied about this? Explain.
4a. In what way did you pay attention to making the mentioned concepts plausible for students (by means of the teaching material and, possibly, additional material)?
4b. Are you satisfied about this? Explain.
5a. In what way did you pay attention to making the mentioned concepts fruitful for students (by means of the teaching material and, possibly, additional material)?
5b. Are you satisfied about this? Explain.
6. What would you change about your handling of the concepts (see question 1) next time?

APPENDIX C: First version of "Current through Substances"[1]

§1 Different redox reactions?
Direct and indirect redox reaction[2]; electrode; electrochemical cell; electrode reaction and cell diagram
§2 Reactions only on distance
Closed current circuit and half cell
§3 A closer look on a number of parts of an electrochemical cell
Inert electrode; salt bridge and cell diagram notation for a salt bridge
§4 Corrosion
Electrochemical background of corrosion and protection against corrosion
§5 Is it possible the other way around?
Electrolysis and electrolyte
§6 A closer look on conduction
Corpuscular model description of a current circuit
§7 Current passage and voltage
Reference half cell; voltage; potential difference; electromotive force and standard potential
§8 Again current passage and voltage
Interpreting a current-voltage graph; electrolysis voltage and counter voltage
§9 An exception to the rule
The reaction of chlorine ions at the positive electrode instead of water in an electrolysis
§10 Measuring voltage oneself
Measure potential differences, also of coupled cells
§11 Concentration cells
The influence of concentrations on potential differences and concentration cell
§12 The Nernst equation
The Nernst equation
§13 Making one's own summary
§14 Test

[1] For designing this student course material, I made use of suggestions in the following publications: Jansen, 1975; Flintjer, 1982; Jansen et al., 1982; Klugmann, 1982; Muckenfuß, 1982; Niedderer & Gohmert, 1982; Grob et al., 1988; Licht, 1990; Nolden, 1990; Sumfleth et al., 1990; Boeck, 1994a, 1994b; Rossa & Hüttner, 1994; Peterseim, 1995.

[2] The commonplace meaning of the term 'direct' fits very well into the particular meaning it has in this topic. 'Direct' means: three-dimensional contact, no intermediate step, no special set-up for the reacting substances.

APPENDIX D1: Sections 1 - 4 of 'Current through Substances' first version

§1 Different redox reactions?

EXP 1.1: *Zinc and copper separately in diluted sulphuric acid*

Requirements: zinc bar; copper bar; two beakers with diluted sulphuric acid; sandpaper

Sandpaper the zinc bar and place it in the solution of sulphuric acid.

a) Describe your observations.
b) Give the equation for the reaction.

Remove the zinc bar from the solution. Sandpaper the copper bar and place it in the second beaker with sulphuric acid solution.

c) Describe your observations.
d) Give an explanation for your observations.

EXP 1.2: *Zinc and copper together in diluted sulphuric acid*

Requirements: zinc bar; copper bar; beaker with diluted sulphuric acid; two wires with clips attached to each end; ammeter; sandpaper

Sandpaper both bars again (in order to clean them properly). Connect the zinc bar to the copper bar by means of one of the wires. Then place both bars in the solution. Take care that the bars do not touch each other.

e) Make a drawing of your set-up.
f) Describe your observations.
g) Give a possible explanation of them.

Untie the wire attached to the copper bar and connect this loose end to the ammeter with the help of a clip. Take the second wire and connect the copper bar to the ammeter in the same way. Take care that the bars do not touch.

h) Make a drawing of your set-up (an ammeter is represented by a circle with inside it a capital A; this A is for ampère).
i) Describe your observations.
j) Give an explanation for your observations.
k) Give the equations for the half reactions.
l) In which way can you proof whether the equations for the half reactions which you gave on question k are correct?
m) Do these equations tally with the direction of the current through the ammeter? Explain.
n) Give an explanation of the title of this section.

DEMO 1.3: *Making use of current*

Requirements: same set-up as in exp 1.2 (without the ammeter); a 'music card'; a lightbulb

With the set-up you built in experiment 1.2, your teacher will try to make the bulb glow. Your teacher also has the playing device from a music card. A music card is a card which you send to someone who has something to celebrate, for example a birthday. When you open a music card you can hear a birthday tune. The card's music device can play on very little current. Your teacher will also try to let the device play.

o) Give your observations. Conclusion?

Chemists call the copper and zinc bars in the set-up **electrodes**. Together with the conducting solution, these electrode form an **electrochemical cell**. Half reactions taking place at the electrodes are called **electrode reactions**.

p) May the zinc bar in set-up 1.1 be called an electrode? Explain.

To draw or describe a cell is a lot of work. That is why chemists have agreed on representing cells in the form of a diagram. For the cell of experiment 1.2 this diagram looks as follows: Zn(s) I H_2SO_4 solution I Cu(s).
The name of such a representation is **cell diagram**. The vertical line indicates an interface (in this case between liquid and solid). You could also have noted the copper electrode first. In that case the cell diagram would have looked as follows: Cu(s) I H_2SO_4 solution I Zn(s).

§2 Reactions only on distance
Suppose you want the electrochemical cell of experiment 1.2 to supply as much current as possible. This means that all electrons, which come from the zinc electrode during the reaction, should go through the wire to the copper electrode.

a) What would your set-up look like if you have to take care that all electrons would pass through the wire?

Joke and Peter do not agree on the answer their group is going to give on the previous question. Joke gives as possible set-up:

"You have to take care that H^+ cannot react directly with zinc. So, the zinc bar has to be placed in a beaker with a solution in which no H^+ is present, but which is still conducting. The copper bar still needs to be placed in the sulphuric acid solution. So a set-up with two beakers, in which the copper bar is placed in the diluted sulphuric acid and the zinc bar in another solution."

Peter agrees only partly with Joke:

"It's true that those H^+ ions may not come near zinc, because then you always get a direct reaction. But in my view, there is no reaction at all in your set-up."

b) Explain with whom you agree.

In experiment 2.1 you are going to examine whether Joke's set-up works.

EXP 2.1: *Joke's set-up*
Requirements: beaker with diluted sulphuric acid; beaker with salt solution; zinc bar; copper bar; wire with clips; ammeter

Place the zinc bar in the beaker with salt solution and the copper bar in the beaker with diluted sulphuric acid. Connect both bars with the help of the ammeter and the wire with clips.

c) Describe your observations.

d) Why is it that in this experiment no electrons go through the wire, while this did happen in experiment 1.2?

EXP 2.2: *Joke 's set-up improved?*
Requirements: the same set-up as in the previous experiment; various materials: wood, plastic, glass, metals, solid salts, sugar solution, salt solution

The objective of experiment 2.2 is to improve Joke's set-up in such a way that it can deliver current. In order to do so, you bring the solutions in both beakers into contact with each other with the help of a 'connection material'. First, make a selection from the available materials on the basis of their ability of conducting current. Choose one of the selected 'connection materials', connect the solutions with that. Answer question e. Remove the bars from the solutions and wipe them dry in such a way that possible gas bubbles are removed. Replace the tested 'connection material' by another one and place back the bars. Answer question e again. Go on like this till you tested all your selected 'connection materials'.

e) Describe your observations for each tested 'connection material'.
f) Give an explanation for your observations for each tested 'connection material'.
g) Which of the tested 'connection materials' has your preference if the cell has to be used as a current supply? Explain.

In an electrochemical cell, a solution with an electrode in it is called a **half cell**.

h) Give an explanation for the title of this section.
i) With which two set-ups of an electrochemical cell are you now acquainted?

§3 A closer look on a number of parts of a cell

EXP 3.1: *Which 'connection material' is most useful?*

Requirements: two beakers with chlorine water ($Cl_2(aq)$); empty beaker; two beakers with potassium iodide solution (with starch); four graphite bars; copper wire; tube filled with gelatine with salt solution; two wires with clips; dropper with silver nitrate solution

First, pour a little bit chlorine water in the empty beaker (in order to do a check afterwards). You will build two set-ups: A and B. Each set-up consists of a beaker with chlorine water and a beaker with potassium iodide solution (with starch). In set-up A, both solutions are connected with a copper wire and in set-up B with a tube filled with gelatine with a salt solution. Place in all four beakers a graphite bar. Connect in both set-ups the graphite bar in the chlorine water with the graphite bar in the potassium iodide solution with the help of a wire and clips. Leave the set-up for a while. In the meanwhile answer question a. Add after ten minutes to the beakers with chlorine water, two drops of silver nitrate solution. Also to the beaker with chlorine water which you kept separate.

a) Make a drawing of the set-ups and indicate all formulas of the substances.
b) Describe your observations, both for set-up A and B.
c) What differences in observations are there between set-up A and B?
d) Give for both set-ups the equations for the electrode reactions.
e) Which connection, the metal wire or the tube filled with gelatine with salt solution, has your preference for a current supplying cell? Explain.

The tube filled with gelatine with salt solution is called a **salt bridge**. In such a salt bridge ions can move. A salt bridge is represented in a cell diagram by two vertical lines (||). These indicate that two interfaces have to be crossed.

f) Give the cell diagram for set-up B.
g) Which function do the electrodes have in exp. 2.2? And in exp. 3.1?
h) How many half cells are there according to you in set-up A?

From the experiments in the first three sections, it became clear that there are electrodes which react and electrodes which do not. Electrodes which do not react themselves are called **inert electrodes**.

§4 Corrosion

Corrosion is a general name for the way materials are affected under the influence of air. For iron this process is called rusting.

EXP 4.1: *Iron and (moist) air*
Requirements: iron nail; petri dish; gelatine with a solution of table salt and two indicators

Sandpaper the nail clean. Let your teacher pour just so much liquid on the nail that it does not disappear beneath the surface. Leave the petri dish where it is (the liquid does not go fully rigid, so do not walk around with it). In the meanwhile answer question a.

a) One of the indicators is phenolphtalein. Which colour does phenolphtalein have in an acid environment and which in an alkaline environment?

The second indicator in the gelatine mixture is indicator B. This indicator reacts with Fe^{2+} ions to form a product which has a blue colour.

b) What do you observe in your dish?
c) Give the equations for the half reactions which take place at the nail (table 48 Binas).

Fighting the consequences of the rusting of iron yearly costs a lot of money. Thus much research is done into the protection of iron against rust.

EXP 4.2: *Protecting iron from rusting with the help of metals?*
Requirements: iron nail, partly wrapped in a piece of zinc; iron nail, partly wrapped in a piece of copper; petri dish; gelatine with a solution of table salt and two indicators

Place both nails, as far away from each other as possible, in the petri dish. Again ask your teacher to pour so much liquid on the nails that they are just not beneath the surface, and wait a little while. Answer in the meanwhile question d.

d) Do you expect different reactions at both nails? Explain.

Zn^{2+} ions react with indicator B to a product which has a white colour and Cu^{2+} ions react with indicator B to a product which has a brown colour.

e) Describe your observations.
f) Give the equations for the half reactions.

In situations like experiment 4.2, zinc is called a 'sacrifice metal'.

g) Explain why zinc is called this.
h) Name two other metals which instead of zinc (in experiment 4.2) may serve as sacrifice metal? Explain.
i) Would you use the term electrochemical cell in experiment 4.1? Explain.

APPENDIX D2: Sections 1 - 4 of 'Current through Substances' second version

§1 Different redox reactions?

In a previous chapter you got acquainted with redox reactions. In the following experiments you are going to have a closer look at redox reactions.

EXP 1.1: *Zinc and copper separately in diluted sulphuric acid*
Requirements: zinc bar; copper bar; two beakers with diluted sulphuric acid; sandpaper

Sandpaper the zinc bar until it is clean and place it in the solution of sulphuric acid.

a) Describe your observations.
b) Give the equation for the reaction.

Remove the zinc bar from the solution. Sandpaper the copper bar until it is clean and place it in the second beaker containing sulphuric acid solution.

c) Describe your observations.
d) Give an explanation for your observations.

EXP 1.2: *Zinc and copper together in diluted sulphuric acid*
Requirements: zinc bar; copper bar; beaker with diluted sulphuric acid; two wires with clips; ammeter; sandpaper

Sandpaper both bars again (in order to clean them properly). Connect the zinc bar with the copper bar by means of a wire and clips. Place then both bars in the solution. Take care that the bars do not touch each other in the solution.

e) Make a drawing of your set-up.
f) Describe your observations.

Release the wire at the copper bar and connect this loose end to the ammeter with the help of a clip. Take the second wire and connect the copper bar to the ammeter in the same way. Take care that the bars do not touch each other in the solution.

g) Make a drawing of your set-up (an ammeter is represented with a circle enclosing a capital A; this A is for ampère).
h) Describe your observations.
i) Give an explanation for your observations.

The sulphuric acid solution stays colourless, also when the solution is left to stand for longer than one lesson.

j) Give the equations for the half reactions.
k) In which three ways can you proof whether the equations for the half reactions which you gave on question j are correct?
l) Do these equations correspond with the direction of the current through the ammeter? Explain.
m) Give an explanation of the title of this section.

We can use the current which is supplied by the set-up of experiment 1.2, for lighting a bulb or for making a music card play, for example. A music card is a card which you send to someone who has something to celebrate, for example a birthday. When you open such a music card you can hear a (birthday) tune. The music card device can play on very little current. Your teacher will try to light the bulb and make the device play with the set-up you built (see demonstration experiment 1.3).

DEMO 1.3: *Making use of current*
Requirements: the same set-up as in exp 1.2 (without the ammeter); music card; a lightbulb

n) State your observations. Conclusion?

Your teacher will also try, with a similar set-up, to make the card's musical device play (see demonstration experiment 1.4).

DEMO 1.4: *A current supplying lemon?*
Requirements: lemon; zinc bar; copper bar; a music card; two wires with clips

o) State your observations. Conclusion?

Chemists call the zinc and copper bar in a set-up in which current passage takes place, like in the set-ups in experiment 1.2 and 1.4, **electrodes**. Half reactions taking place at electrodes are called **electrode reactions**.

p) May the zinc bar in set-up 1.1 be called an electrode? Explain.

To draw or describe such a set-up as the one in experiment 1.2 is a lot of work. This is why chemists have agreed on representing such set-ups by means of a diagram. For the set-up of experiment 1.2 this diagram is as follows: Zn(s) I H_2SO_4 solution I Cu(s).
The vertical line indicates an interface (in this case between liquid and solid). You could also have put the copper electrode first. In that case the diagram would have looked as follows: Cu(s) I H_2SO_4 solution I Zn(s).

§2 Reactions only on distance
Suppose you want the apparatus to play louder. This means that in the set-up of experiment 1.2 all electrons, which come from the zinc electrode during the reaction, should go through the wire to the copper electrode. This would mean that the current is maximized. For this a different set-up from the one in experiment 1.2 must be built.
Joke gives as a possible set-up:

> *"You have to take care that H^+ cannot react directly with zinc. So, the zinc bar has to be placed in a beaker containing a solution in which there is no H^+ present, but which still conducts. The copper bar still needs to be placed in the sulphuric acid solution. So we need a set-up with two beakers, in which the copper bar is placed in the diluted sulphuric acid and the zinc bar in another solution."*

Peter agrees only partly with Joke:

> *"It is true that those H^+ ions may not be near zinc, because then you always get a direct reaction. But in my view, there will be no reaction at all in your set-up, because in the solution in which the zinc bar is placed zinc ions will show up and then the solution will become positive and no new zinc ions will enter the solution anymore."*

a) Explain with whom you agree.

In experiment 2.1 you are going to examine whether Joke's set-up works.

EXP 2.1: *Joke's set-up*
Requirements: beaker with diluted sulphuric acid; beaker with a salt solution; zinc bar; copper bar; wire with clips; ammeter

Place the zinc bar in the beaker with the salt solution and the copper bar in the beaker with diluted sulphuric acid. Connect the bars with the help of the ammeter and the wire with clips.

b) Describe your observations.
c) Why is it that in this experiment no electrons go through the wire, whereas this did happen in experiment 1.2?

The next experiment is meant to improve Joke's set-up in such a way that it can deliver current. In order to achieve this you need to bring the solutions in both beakers into contact with each other with the help of a 'connection material'. Different 'connection materials' can be thought of, namely pieces of wood, plastic, glass, metals or glass tubes filled with a sugar or a salt solution.

d) Make a selection from the available materials on the basis of their ability of conducting (the practical realization does not need to be a hindrance).

EXP 2.2: *An improved set-up of Joke?*
Requirements: the same set-up as in the previous experiment; 'connection materials'

Choose one of the selected 'connection materials', connect the solutions with it. Answer question e. Remove the bars from the solutions and wipe them dry, in such a way that possible gas bubbles are removed. Replace the tested 'connection material' with another one and place the bars back. Answer question e again. Go on like this until you have tested all your selected 'connection materials'.

e) Describe your observations for each tested 'connection material'.
f) In which cases did it succeed to let the set-up supply current, while zinc did not react directly with H^+?
g) Which of the tested 'connection materials' has your preference if the cell has to be used as a current supply? Explain.

A set-up, with electrodes and positioned in between conducting substances, in which current passage takes place is called an **electrochemical cell**. In an electrochemical cell, a combination of an electrode and a current conducting substance is called a **half cell**. A diagram, as described in §1, of an electrochemical cell is called a **cell diagram**.

h) Give an explanation for the title of this section.
i) With which two set-ups of an electrochemical cell are you now acquainted?

When you look at the equations for the electrode reactions, which take place in the electrochemical cell of experiment 2.2, then you can deduce from these equations that electrons go from the zinc electrode via the connecting wire to the copper electrode. We call the zinc electrode **negatively charged with respect to** the copper electrode. And the copper electrode **positively charged with respect to** the zinc electrode.
Electrochemical cells which supply maximally current you know from daily practice, namely in the form of batteries and accumulators in cars.

§3 A closer look on cells
In this section, you are going to build two other cells to become more acquainted with electrochemical cells. In the first experiment, you will build a cell with two identical electrodes and you will work out whether this cell can supply current.

EXP 3.1: *A cell with two graphite electrodes*
Requirements: beaker with bromine water ($Br_2(aq)$); empty beaker; beaker with potassium iodide solution (with starch); two graphite bars; copper wire **or** tube filled with gelatine with salt solution; wire with clips; dropper with silver nitrate solution

First, pour a little bit bromine water in the empty beaker (in order to do a check afterwards). You will build a set-up which consists of a beaker with bromine water and a beaker with potassium iodide solution (with starch). Place in both beakers a graphite bar. Connect the graphite bar in the bromine water with the graphite bar in the potassium iodide solution with the help of a wire and clips. Connect both solutions with a copper wire or a tube filled with gelatine with salt solution. Leave the set-up for a while. In the meanwhile answer question a. Add after 5 minutes a few drops of silver nitrate solution to the beakers with bromine water solution.

a) Make a drawing of the set-up and indicate all formulas of the substances.
b) Describe your observations.
c) Give the equations for the electrode reactions at the graphite electrodes.
d) Argue which charge the electrodes get with respect to each other with the help of the equations for the electrode reactions.
e) Which function do the graphite electrodes have in exp. 3.1? Which difference is there according to you with the electrodes in exp. 2.2?
f) How many half cells are there in the set-up you built in exp. 3.1? Explain.

In the next experiment, you will build another electrochemical cell, this time with two different electrodes.

EXP 3.2: *A cell with a graphite and an iron electrode*
Requirements: beaker with bromine water; beaker with table salt solution (with indicator B); graphite bar; iron bar; copper wire **or** tube filled with gelatine with salt solution; wire with clips; dropper with silver nitrate solution

Place the iron bar in the beaker with table salt solution and the graphite bar in the beaker with bromine water. Connect the two bars with the help of a wire with clips. Also in this set-up you connect the solutions with either a copper wire or the tube filled with gelatine with salt solution. Did you choose in exp. 3.1 for the copper wire, then take now the other connection material (or vice versa of course). Leave the set-up for a while. In the meanwhile answer question g. Add after 5 minutes a few drops silver nitrate to the beaker with bromine water.

g) Make a drawing of the set-up and indicate all formulas of the substances.
h) Describe your observations (indicator B reacts with Fe^{2+} ions to form a product with a blue colour).
i) Give the equations for the electrode reactions at the graphite and iron electrode.
j) Argue which charge the graphite and the iron electrode get with respect to each other with the help of the equations for the electrode reactions.
k) Which two functions has the iron electrode in exp. 3.2?
l) How many half cells are there in the set-up you built in exp. 3.2? Explain.

The tube filled with gelatine with salt solution is called a **salt bridge**. In a salt bridge ions can move. A salt bridge is represented in a cell diagram with two vertical lines (||). These indicate that two interfaces have to be crossed.

m) Give the cell diagrams for the set-ups you have built in exp. 3.1 and 3.1.

From the experiments in the first three sections, it became clear that there are electrodes which react and electrodes which do not. Electrodes with do not react are called **inert electrodes**.

§4 Affecting of metals and protection against it

Some metals are being affected when they are exposed to a combination of oxygen and water. In fact you see this around you daily. Think of the affecting of metals on your bike, of cars, bridges and ships. This affecting, which comprises redox reactions, in actual life takes place in rather a complicated manner. In the next experiments you will get acquainted with this.

EXP 4.1: *Iron, zinc and copper and (moist) air*
Requirements: iron nail; piece of zinc; piece of copper; petri dish; gelatine with a solution of table salt and two indicators

Sandpaper the three pieces of metal until they shine. Place the nail, the piece of zinc and the piece of copper next to each other in the petri dish. Take care that they do not touch each other. Let your teacher pour so much liquid on the metals that they barely stick out from beneath the surface. Leave the petri dish where it is (the liquid does not get fully rigid, so do not walk around with it). In the meantime answer question a.

a) One of the indicators is phenolphtalein. Which colour does phenolphtalein have in an acid environment and which in an alkaline environment?

The second indicator in the gelatine mixture is indicator B. This indicator reacts with different metal ions to form into different products which each have a specific colour.

metal ion	colour metal ion/indicator complex
Fe^{2+}	blue
Zn^{2+}	white
Cu^{2+}	brown

b) What do you observe in your dish? Look at the dish against a light and a dark background and make a drawing.
c) Give the equations for the half reactions, when they take place, at the three metals (table 48 BINAS).
d) Why is table salt added to the gelatine with two indicators?
e) Would you call the nail in gelatine with a solution of table salt and two indicators an electrochemical cell? Explain.

The general name for the affecting of metals through a combination of water and oxygen is **corrosion**. In experiment 4.1, you have seen some examples of corrosion. For the corrosion of iron a special term exists: **rusting**. Because the metal iron is so often used, you will be told more of the process of rusting in this section. In experiment 4.1, you saw that through the action of moist air, blue and red areas arose at the nail. The ions are moving towards each other in the liquid and will react with each other.

f) Give the equation for the reaction which occurs if the arisen ions meet each other.

The solid substance which arose reacts further with moist air to form a substance iron(III)hydroxide (most important constituent of iron rust).

g) Give the equation for this reaction.

In general the rusting of iron is an unwanted process. Each year in the Netherlands alone, a loss of a thousand million guilders is suffered by the rusting of cars, bridges etcetera. That is why a lot of research is being done into the protection of iron with the help of another metal. The question is which metals are suitable for this. You are going to sort this out in the next experiment.

EXP 4.2: *Protecting iron from rusting with the help of metals?*
Requirements: iron nail, partly wrapped in a piece of zinc; iron nail, partly wrapped in a piece of copper; petri dish; gelatine with a solution of table salt and two indicators

Place both nails, as far away from each other as possible, in the petri dish. Again ask your teacher to pour so much liquid on the nails that they barely stick out from beneath the surface, and wait a little while. In the meantime answer question h.

h) Do you expect different reactions at both nails? Explain.

i) Describe your observations. Look at the dish against a light and a dark background and make a drawing

j) Give the equations for the half reactions.

In situations like experiment 4.2, zinc is called a **sacrifice metal**.

k) Explain why zinc is called this.

l) Name two other metals which can serve as sacrifice metal instead of zinc (in experiment 4.2)? Explain.

m) Would you call the nail with zinc in gelatine with a solution of table salt and two indicators an electrochemical cell? Explain.

APPENDIX E1: Section 6 of 'Current through Substances' first version

§6 A closer look at conduction

DEMO 6.1: *Conduction in a cell*

Requirements: two beakers with potassium bromide solution with phenolphtalein; two graphite bars; salt bridge; wires with clips; current supplying apparatus

A cell is built on the demonstration table in the classroom. In this cell a graphite bar is placed in a potassium bromide solution. This graphite bar is connected with a current supplying apparatus which is also connected with another graphite bar that is also placed in a potassium bromide solution. The solutions in the two beakers are connected by a salt bridge. This salt bridge is a tube with gelatine with two salt solutions. The salt solution in the middle of the 'bridge' has a green colour and has as its proportion formula: $Cu(NH_3)_4CrO_4$. The other salt is potassium chloride. The current circuit is closed. It takes about ten minutes before something can be seen in the salt bridge. In the meantime answer questions a and b.

a) Make a drawing of the set-up (see table 91b BINAS for the symbol of a battery).
b) Give the cell diagram.
c) Describe your observations.
d) Give the equations for the electrode reactions.
e) Which ions are moving in the salt bridge (see table 65 BINAS)?
f) Indicate the movements of electrons and ions with the help of arrows in the drawing (in the whole set-up).

The movements of ions in the solution and in the salt bridge are called **migration**.

APPENDIX E2: Section 7 of 'Current through Substances' second version

§7 A closer look at conduction

In sections 2 and 3 you have concluded that a (half) noble metal and a salt bridge are both suitable to be used as connection material between electrolytes. The question is, however, whether they are both equally suitable. In this section you are going to sort out whether or not that is the case.

DEMO 7.1: *Conduction in a cell*

Requirements: four beakers with potassium iodide solution with phenolphtalein and starch; four graphite bars; salt bridge; copper wire; wires with clips; two current supplying apparatus

Two cells are built on the demonstration table in the classroom. In cell A, a graphite bar is placed in a potassium iodide solution. This graphite bar is connected with a current supplying apparatus which is also connected with another graphite bar that is also placed in a potassium iodide solution. The solutions in the two beakers are connected by a copper wire.
Cell B is built in the same way as cell A. But here the solutions are connected by a salt bridge. This salt bridge is a tube with gelatine with two salt solutions. The salt solution in the middle of the 'bridge' has a green colour. This salt has as its proportion formula: $Cu(NH_3)_4CrO_4$. The other salt is potassium chloride. The current circuit of cell A and cell B is closed and the current supplying apparatus are turned on. It takes about ten minutes before something can be seen in the salt bridge. In the meantime answer questions a and b.

a) Make a drawing of set-up A and set-up B.
b) Give the cell diagrams.
c) Describe your observations.
d) Give the equations for the reactions at the graphite electrodes.
e) Give the equations for the reactions at the copper wire.
f) Indicate the movements of electrons and ions in the drawing of set-up A with the help of arrows (in the whole current circuit).
g) Which ions are moving in the salt bridge (see table 65 BINAS)?
h) Indicate the movements of electrons and ions in the drawing of set-up B with the help of arrows (in the whole current circuit).

Because of the electrode reactions which take place, the electrolytes get somewhat positively or negatively charged. However, an electrolyte should always be **electrically neutral**. In order to take care that the electrolytes stay electrically neutral, **charge transport** takes place within the connection material. In the salt bridge, charge transport takes place in the form of ion transport. These ions are chosen in such a way that they do not react with the ions present in the solutions of the cell. In the copper wire, charge transport takes place in the form of electron transport. Because of this, half reactions take place at the extremities of the copper wire.

i) Why do chemists often prefer a salt bridge as connection material to a copper wire?

APPENDIX F1: Section 7, 10 and 11 of 'Current through Substances' first version

§7 Current and voltage

In the electrochemical cell of experiment 5.1, you have seen that two batteries do not always give the same result, due to the fact that the batteries differ in power. On the label of a battery it is indicated 'how strong' such a battery is. The power (expressed in volt) is also called: **voltage** or **potential difference**. You can measure a potential difference (symbol ΔV) with a voltmeter. A battery which you buy in the shop is not built in a diagrammatically different way from the cells you yourselves have built until now.

a) How much volt is indicated on the batteries A and B?

b) With which of the two batteries did no reaction take place in the cell? Explain why.

Of the cells you have built yourselves potential differences can be measured. The potential difference the voltmeter indicates if there is no current passage in the cell is called **electromotive force** (V_{bron}). Only potential differences can be measured. Chemists all over the world have agreed to use one certain half cell as 'count-off point'. Potentials of other half cells are measured with respect to this half cell. The potential of this half cell, also called reference cell, is set on zero volt. As reference cell is chosen for the H^+/H_2 half cell. A cell is built which has the following cell diagram:

$Cu(s)$ | $CuSO_4$ solution (1M) || H_2SO_4 solution (0,5M) | $H_2(g;10^5Pa)$ | $Pt(s)$

The electromotive force of this cell amounts to 0,34 volt. According to the general agreement, the potential of the right hand half cell amounts to 0,00 volt.

c) State the value of the Cu^{2+}/Cu-half cell potential with respect to the reference cell?

The potential of a half cell is called **standard potential** (V^0) if the concentrations of the reacting particles are 1 M and the pressure of the gases 10^5 Pa.

d) Give the equations of the electrode reactions as the electrodes in the above-mentioned cell are connected to each other so as to conduct current.

e) Which charge do the electrodes get with respect to each other?

You can find the values for the standard potentials in table 48 of BINAS.

§10 Measure voltage yourselves

In the sections 7 and 8, you got acquainted with the concept of voltage. In this section you are going to measure potential differences between different combinations of half cells.

EXP 10.1: *Three different combinations*

Requirements: copper, zinc and lead bars; tubes with porous bottoms, filled with copper, zinc and lead salt solutions respectively (1M); petri dish with gelatine with salt solution; voltmeter (represented in a drawing by a circle containing a V); wires; clips

Place a tube with salt solution, containing a bar of the same metal, on top of the gelatine with salt solution. Place a second one next to it. Attach a wire to each bar with the help of a clip. Stick the other extremity of each wire into an entrance of the voltmeter.

a) Which connection wire should go into the 'plus-entrance' of the voltmeter? Explain.

b) Measure the electromotive force for each combination.

c) Give the cell diagram for each combination.

d) Calculate the electromotive force for each combination (with the help of table 48).

c) Give some reasons for possible differences between the measured and calculated values of the electromotive forces.

As you already knew, it is possible to measure potential differences between half cells. It would be interesting to know whether potential differences can be measured between cells.

EXP 10.2: *Two electrochemical cells connected to each other*
Requirements: the same materials as in experiment 10.2; a spatula

Make a groove in the middle of the bottom of gelatine with the help of the spatula. At the left side of the groove place the copper half cell and one of the lead half cells. At the right hand side of the groove place the zinc half cell and the other lead half cell (it does not matter in what sequence). Connect the half cells to each other in pairs (see the drawing beneath[3]).

f) Give the cell diagram for the (coupled) cell you have built now.
g) Measure the electromotive force.

Also another sequence of half cells is possible. Build this (coupled) cell as well.

h) Give the cell diagram for the (coupled) cell you have built now.
i) Measure the electromotive force.

You have now measured a number of potential differences, also of coupled cells. In real life, a lot of coupled cells occur, for example the lead accumulator in a car.

§11 Concentration cells

In this section a potential difference is measured of a cell which is built from two almost identical half cells. Both half cells contain a solution of the same substance, only the ion concentrations differ. Such a cell is called a **concentration cell**.

DEMO 11.1: *Influence of concentration on voltage*
Requirements: two beakers with potassium permanganate solution; two graphite bars; siphon with distilled water; stirrer; salt bridge; wires; clips; voltmeter

Each graphite bar is placed in a beaker with potassium permanganate solution. Both potassium permanganate solutions have the same molarity. The solutions are connected via a salt bridge. Both graphite bars are connected via a voltmeter. The potential difference is measured.

a) Write down the measured potential difference.

To one of the two potassium permanganate solutions a bit of distilled water is added. Again the potential difference is measured. This is repeated a number of times.

b) Write down the potential difference each time.
c) In which case is the voltage smallest?
d) Give an explanation for your answer to question c.
e) If your teacher diluted the other potassium permanganate solution (in the same way), what do you expect will happen to the value of the potential difference? Explain.
f) Do you expect that adding some solid potassium permanganate to one of the solutions has an influence on the potential difference? Explain.

[3] This drawing is not included in this dissertation.

In this section you have seen that the concentrations of the reacting particles in the half cells influences the potential difference between those half cells. Knowledge of the influence of concentrations can be of importance for building cells with a certain voltage.

APPENDIX F2: Section 8, 9 and 11 of 'Current through Substances' second version

§8 Measure voltage yourselves

Well-known examples of electrochemical cells are batteries. Until now you have been familiar with current supply by batteries. On the label of batteries you can buy in the store, there is no indication of current intensity. What is indicated most of the time is 'how strong' such a battery is. This power (expressed in volt) is also called: **voltage or potential difference**. You can measure a potential difference (symbol ΔV) with a voltmeter. Of course, from other cells than batteries potential differences can also be measured. The potential difference the voltmeter indicates if there is no current passage in the cell is called **electromotive force** (V_{bron}). The voltmeter has a high internal resistance as a result of which currentless can be measured.
In the next experiment, you are going to measure potential differences of different cells.

EXP 8.1: *Voltage of different cells*

Requirements: tubes with bottoms of gelatine with a salt solution, filled with copper, zinc and lead salt solutions respectively (1M); one copper, one zinc and two lead bars; petri dish with gelatine with salt solution; voltmeter (represented in drawing by a circle containing a V); wires; clips; plastic holder with 4 holes

Place the plastic holder on the petri dish (see drawing[4]). Place the four tubes, each filled with salt solution, into a hole in such a way that they stand upright on the gelatine in the petri dish. Place a bar into the accompanying salt solution (e.g. copper bar into copper salt solution). Attach a wire to the copper bar and one to the zinc bar with the help of clips. Stick the other extremity of each wire into an entrance of the voltmeter.

a) Which connection wire should go into the 'plus-entrance' of the voltmeter? Explain.
b) Measure the electromotive force for this combination.
c) Then measure the electromotive force for each other possible combination.
d) Give the cell diagram for each combination.

In the previous experiment you measured potential differences of three combinations of half cells. You could also have measured the potential difference of only two combinations and predict from this the potential difference of the third combination. For example, measure the combinations "zinc/lead" and "copper/lead" and predict from this the combination "zinc/copper". This is based on the fact that you always measure with respect to one and the same half cell (in this case the Pb^{2+}/Pb-half cell). Such a half cell is called a reference half cell.

e) A student has done measurements with the following three combinations: iron/<u>lead</u>: 0,31V, zinc/<u>lead</u>: 0,63V and <u>copper</u>/lead: 0,47V. The underlined half cell is the half cell connected with the 'plus-entrance' of the voltmeter. Argue, using these measurements, from which cells the electromotive force can be predicted through calculations.

It is convenient to always measure with respect to one and the same half cell. Chemists have agreed on the H^+/H_2-half cell as reference half cell. Potentials of other half cells are measured <u>with respect to</u> this half cell. The potential of this half cell is set on zero volt. A cell is built which has the following cell diagram (see also figure 8.1[5]):

Cu(s) | $CuSO_4$ solution (1M) || HNO_3 solution (1M) | $H_2(g;p^0)$ | Pt(s)

f) Why has a line been drawn in the cell diagram between the nitric acid solution and the hydrogen gas?

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4 This drawing is not included in this dissertation.
5 This figure is not included in this dissertation.

g) Give the equations for the electrode reactions as the electrodes in the above-mentioned cell are connected to each other in such a way as to conduct current.
h) Argue which charge the electrodes get with respect to each other with the help of the equations for the electrode reactions .

The electromotive force of the cell from figure 8.1 amounts to 0,34 volt. According to the general agreement, the potential of the right hand half cell amounts to 0,00 volt.
i) Give the value and the sign of the potential of the Cu^{2+}/Cu-half cell with respect to the reference half cell?

If the concentrations of the reacting particles are all 1 M, if the pressure of the gases is the standard pressure (p^0) and if the temperature is 298 K, then the potential of a half cell is called the **standard potential** (V^0).
You can find the values for the standard potentials in table 48 of BINAS.
j) Calculate the electromotive force for each cell you have built in experiment 8.1 (with the help of table 48).
k) Give some reasons for possible differences between the measured and calculated values of the electromotive forces.

§9 Coupled cells
In section 8, you yourselves measured voltages of electrochemical cells. In real life you often use more than one electrochemical cell. On the electrical devices for which two (or more) batteries are needed, such as a walk man or a flashlight, the way the batteries should be placed is most of the time indicated by a + and -. If this is not done in the indicated way, the device often does not operate. In the next experiment, you are going to examine what influence the sequence of coupling of cells has on the magnitude of the voltage.

EXP 9.1: *Two electrochemical cells connected to each other*
Requirements: the same materials as in experiment 8.1; a spatula

Remove the four tubes carefully from the plastic holder and remove the holder from the petri dish. Make a groove down to the bottom of the petri dish with the help of the spatula in the middle of gelatine with salt solution (see drawing beneath[6]). Place the holder back again and place the copper half cell and one of the lead half cells at the left side of the groove. Place the zinc half cell and the other lead half cell at the right hand side of the groove (it does not matter in what sequence). Connect the inner half cells across the groove with a wire and two clips. Connect the outer half cells with the voltmeter.
a) Give the cell diagram for the (coupled) cell you have built now.
b) Measure the electromotive force.

Another sequence of half cells is also possible. Build this (coupled) cell as well.
c) Give the cell diagram for the (coupled) cell you have built now.
d) Measure the electromotive force.
e) Which of the two coupled cells represents the situation in which the batteries should be coupled in electrical devices? Explain.

You have now measured a number of potential differences of coupled cells. In real life, a lot of use is made of coupled cells, for example in the lead accumulator in a car.

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[6] This drawing is not included in this dissertation.

§11 The Nernst equation

In the next experiment the potential difference is measured of a cell which is built from two identical half cells. During the experiment, the concentration of one of the electrolytes is changed. You are going to sort out whether this has any influence on the potential difference to be measured.

DEMO 11.1: *Influence of concentration on voltage?*
Requirements: two beakers with lead nitrate solution; two graphite bars; salt bridge; wires; clips; voltmeter; sodium sulphate

Each graphite bar is placed in a beaker with lead nitrate solution. Both lead nitrate solutions have the same molarity. The solutions are connected via a salt bridge. Both graphite bars are connected via a voltmeter. The potential difference is measured.

a) Write down the measured potential difference.

To one of the lead nitrate solutions sodium sulphate is added. Again the potential difference is measured.

b) Write down the potential difference again.
c) In which case is the voltage smallest?
d) Give an explanation for your answer to question c.
e) If your teacher added (as much) sodium sulphate to the other lead nitrate solution, what do you expect will happen to the value of the potential difference? Explain.
f) Do you expect that diluting one of the lead nitrate solutions will have an influence on the potential difference? Explain.

Both half cells contained a solution of the same substance, but its concentrations were different. Such a cell is called a **concentration cell**. In the experiment you have seen that the concentrations of the reacting particles in the half cells influence the potential difference between those half cells. From this it can be deduced that the potential of a half cell depends on the concentration of the reacting particles. The potential depends on more factors, but here we do not go into this here. (Then the Nernst equation follows with some examples)

Subject index

(A reference concerns the page where the meaning of the term is described for the first time)

Samenvatting

Dit proefschrift beschrijft een onderzoek dat plaatsvond van 1991 tot 1996 aan de Faculteit Scheikunde van de Universiteit Utrecht. Ik heb een chemiedidactisch onderzoek uitgevoerd naar het onderwijzen en leren met betrekking tot het onderwerp elektrochemische cellen in het voortgezet onderwijs. Chemiedidactiek onderzoekt scheikunde-onderwijs en stelt daarbij de inhoud centraal, in dit geval schoolchemie ten aanzien van elektrochemische cellen. Het gaat hierbij om de relatie tussen onderwijzen en leren. Enerzijds, wat is het dat docenten en leerboeken leerlingen aanreiken dat hen tot begrijpen brengt en anderzijds, wat is het dat leerlingen uiten dat docenten tot onderwijzend handelen en veranderingen daarin brengt.

Terugkijkend kan dit proefschrift in twee delen worden opgesplitst:
- de hoofdstukken 1 tot en met 5, welke handelen over de ontwikkeling van het onderzoeksterrein, de onderzoeksvragen en de onderzoeksmethoden. Dit exploratieve gedeelte van mijn onderzoek is uitgevoerd door middel van het beschrijven van belangrijke concepten, het analyseren van bestaand onderwijsmateriaal en onderwijs op secundair niveau, en het ontwikkelen van een kader voor het beschrijven en ontwerpen van nieuw onderwijs in elektrochemische cellen.
- hoofdstuk 6 tot en met 8, waarin de resultaten worden weergegeven van mijn ontwikkelingsonderzoek betreffende de vragen over concepties van docenten en onderwijsproblemen. Deze hoofdstukken betreffen het construeren van corpusculaire redeneringen over stroomdoorgang in een elektrochemische cel en het construeren van corpusculaire, meet- en rekenredeneringen over de karakteristiek potentiaalverschil van een elektrochemische cel.

Wanneer dergelijk ontwikkelingsonderzoek productief leren en onderwijzen als empirisch resultaat heeft, kan voor het onderwijzen een *didactische structuur* geformuleerd worden.

In ***hoofdstuk 1*** worden het object en de relevantie van het onderzoek belicht. Hierbij wordt beschreven dat het onderwerp elektrochemie als moeilijk wordt beschouwd door zowel leerlingen als docenten. Na een beschrijving van het onderwerp elektrochemie in het leerplan, wordt de keuze om *concepties betreffende het onderwerp elektrochemische cellen* te bestuderen op basis van inhoudelijke redenen gemaakt.

Het hoofdonderzoeksdoel is bijdragen aan *twee* didactische structuren:
- een didactische structuur van elektrochemische cellen en
- een didactische structuur van het creëren van condities voor het leren van elektrochemische cellen.

In deze paragraaf wordt de keuze voor in-service nascholing gemaakt als een chronologische combinatie van leerling- en docentcursus.

In ***hoofdstuk 2*** startte ik met het selecteren van een aantal belangrijke elektrochemische concepten, namelijk *elektrolyt, elektrode, elektrodereactie* en *potentiaalverschil* als karakteristieken van elektrochemische cellen.

Voor het wetenschaps-historische domein heb ik de contexten waarin de concepten zijn ontwikkeld geanalyseerd en vervolgens beschreven en benoemd. Vijf contexten resulteerden:
- *de fenomenologische context,* die ook de *meetcontext* omvat,
- *de corpusculaire context,* die ook de *corpusculair-elektrostatische context* omvat en
- *de chemisch-thermodynamische context.*

Hierbij kon ik ook *contextvolgordes* aangeven. De ontwikkeling van de concepten elektrolyt, elektrode en elektrodereactie bleek van een hoofdzakelijk fenomenologische context naar een hoofdzakelijk corpusculaire context plaats te hebben gevonden. Voor het concept potentiaalverschil bleek de contextvolgorde van een voornamelijk meetcontext naar een voornamelijk chemisch-thermodynamische context verlopen te zijn.

Voor het tertiaire onderwijsdomein werd duidelijk dat ik de benoemde contexten kon gebruiken voor het analyseren van de vier concepten in een fysische-chemie studieboek en een elektrochemie studieboek. De corpusculair-elektrostatische context kon ik niet aanwijzen. In aanvulling op contextvolgordes, kon in dit domein ook *contextmenging* worden aangewezen.

Voor de concepten elektrolyt en elektrode kon een mix van de fenomenologische en de corpusculaire context worden aangewezen. Voor het concept elektrodereactie bleek de contextvolgorde veranderd ten opzichte van die in het vorige domein: in de studieboeken bleek de volgorde van een corpusculaire context naar een meetcontext in plaats van andersom. Voor het concept potentiaalverschil kon een mix van de meetcontext en de chemisch-thermodynamische context worden aangewezen.

Voor het secundaire onderwijsdomein kon ik de benoemde contexten ook gebruiken voor de analyse van de vier concepten in twee algemeen gebruikte leerlingboeken. Ik kon contextvolgordes en contextmenging aanwijzen. Weer kon ik de corpusculair-elektrostatische context niet aangeven. Wel kon een nieuwe context, *de elektrochemische rekencontext* betreffende potentiaal-concentratie relaties, worden aangewezen.

Voor de concepten elektrolyt en elektrode kon een mix van corpusculaire en fenomenologische context worden aangewezen, zoals ook het geval was in het tertiaire onderwijsdomein. Voor het concept elektrodereactie bleek een mix te ontbreken, in tegenstelling tot de andere concepten. Dit concept bleek hoofdzakelijk te worden beschreven in een corpusculaire context zonder verwijzingen naar een

fenomenologische context. Voor het concept potentiaalverschil kon een mix van meetcontext en elektrochemische rekencontext worden aangegeven.
Ten slotte kon ik in het secundaire onderwijsdomein geen contextvolgordes aanwijzen omdat er óf contextmenging kon worden aangewezen óf er was slechts één context waarin het concept wordt beschreven.

In ***hoofdstuk 3*** ga ik in op *huidig onderwijs* betreffende het onderwerp *elektrochemische cellen* om mogelijke problemen die bepaald contextgebruik met zich meebrengt aan te wijzen. Onderwijsproblemen zijn door mij gedefinieerd als het gebruik van contexten door docenten, dat conceptuele moeilijkheden voor leerlingen veroorzaakt. De volgende onderwerpen konden verbonden worden met deze onderwijsproblemen: elektronenoverdracht op afstand, ionentransport, zoutbrug, corrosie, de Nernstvergelijking en het berekenen van de bronspanning.
Het bestuderen van het gebruik van contexten door docenten en conceptuele moeilijkheden van leerlingen in relatie met deze onderwerpen gebeurde op empirische wijze. Door middel van geluidsopnamen werden lessenseries over elektrochemische cellen bij twee docenten geregistreerd. Deze geluidsopnamen werden uitgeschreven tot protocollen. Vervolgens werden deze protocollen geanalyseerd om onderwijsproblemen te kunnen beschrijven. Gedurende en na afloop van de lessenserie werden ook interviews met de docenten gehouden om onduidelijkheden voor mij in hun onderwijzen op te helderen en om concepties van docenten ten aanzien van de aangegeven onderwijsproblemen te verkrijgen. De interviews werden ook opgenomen en de geluidsbanden hiervan uitgeschreven tot protocollen welke vervolgens geanalyseerd werden.
Drie soorten onderwijsproblemen konden worden aangegeven: *het benadrukken van een bepaalde context, het mengen van contexten* en *het construeren van contexten door de docenten zelf.* De onderwijsproblemen worden besproken aan de hand van twee perspectieven: het expert-novice perspectief en het top-down onderwijsperspectief.
Onderwijsproblemen traden op bij een aantal elektrochemische concepten, die *sleutelconcepten* genoemd worden. Deze concepten veroorzaakten moeilijkheden voor zowel docenten als voor leerlingen. Sleutelconcepten bleken *elektronenoverdracht, elektronentransport, ionentransport* (deze drie worden gesitueerd in een corpusculaire context) en *potentiaalverschil* (dit kan worden gesitueerd in een meetcontext, een chemisch thermodynamische context of een elektrochemische rekencontext).
Het gebruik van contexten zal een criterium zijn voor het ontwerpen van zowel docent- als leerlingcursussen.

In ***hoofdstuk 4*** beschreef ik het kader voor het beschrijven en ontwerpen van een docentcursus over het onderwijzen van elektrochemische cellen. Voor de hoofdstructuur van de docentcursus, waar de leerlingcursus deel van uitmaakt, heb ik gekozen voor sociaal constructivisme, dat geconcretiseerd wordt door docenten

mogelijkheden te bieden voor het opdoen van sociale en fysieke ervaringen in alle drie de fasen van de docentcursus: introductie op, realisatie en evaluatie van de leerlingcursus. Gedurende deze fasen kunnen docenten zich bewust worden van hun onderwijskader. In deze cursus vroeg ik de docenten om te letten op concepten, op het gebruik van contexten, en op leerlingactiviteiten. Ik lette op hetzelfde maar dan voor zowel docenten als leerlingen (spreken/luisteren, schrijven/lezen, observeren/ interpreteren). Voor de inhoud van de cursus koos ik voor drie categorieën van kennis zoals beschreven door Shulman:
* *content knowledge* (de vier sleutelconcepten en het contextgebruik in leerboeken),
* *pedagogical content knowledge* (docentgebruik van contexten en het creëren van leercondities) en
* *knowledge of students* (bestaande leerlingconcepties en ontwikkeling van leerlingconcepties).
Voor de drie corpusculaire sleutelconcepten is de keuze om te starten vanuit de fenomenologische context van belang, voor het concept potentiaalverschil de keus om te starten vanuit de meetcontext.
De leercondities worden geformuleerd volgens Posner's model van leren, te weten noodzakelijkheid, plausibiliteit, begrijpelijkheid en vruchtbaarheid. Voor structurering van de leerlingcursus koos ik de onderwijsfasen van Van Dormolen, te weten oriëntatie, ontwikkeling en applicatie. De relatie van deze fasen met het gebruik van contexten en Posner's model kan als volgt beschreven worden:
- de noodzakelijkheid is verbonden met contextintroductie in de oriëntatiefase,
- de begrijpelijkheid en de plausibiliteit zijn verbonden met contextuitbreiding en contextkoppeling in de ontwikkelingsfase,
- de vruchtbaarheid is verbonden met contextapplicatie in de toepassingfase.

Hoofdstuk 5 begin ik met een beschrijving van het ontwerp van de *cycli van mijn ontwikkelingsonderzoek*. Eerst worden de centrale onderzoeksvragen beschreven. Deze betreffen concepties van docenten die deelnemen aan een in-service cursus die het gebruik van het nieuwe leerlingcursusmateriaal over elektrochemische cellen omvat, en onderwijsproblemen die aangewezen kunnen worden gedurende het onderwijzen met dit nieuwe materiaal. Vervolgens komen de onderzoeksmethodes aan de orde:
- *de cyclische methode* waarin cycli van onderzoek van docentcursussen worden beschreven en
- *protocolanalyse*, waarvan de voor- en de nadelen worden beschreven.
Daarna wordt het ontwerp van de twee achtereenvolgende docentcursussen beschreven. De hoofdstructuur van de docentcursus is een introductie op het nieuwe leerlingcursusmateriaal, gevolgd door een realisatie van het onderwijzen met dit materiaal en evaluatie hiervan. De hoofdstructuur van de leerlingcursus is van een

fenomenologische naar een corpusculaire context en van een meetcontext naar een elektrochemische rekencontext.

In ***hoofdstuk 6*** presenteer ik concepties van docenten en onderwijsproblemen betreffende het *onderwijzen* van de sleutelconcepten *elektronenoverdracht* en *elektronentransport.* Deze sleutelconcepten zijn verbonden met de concepten elektrodereactie en elektrode.
Ten eerste konden *docentconcepties* worden aangewezen betreffende de *objectkarakteristiek* van een elektrode en de *lokatiekarakteristiek* van een elektrodereactie. *Onderwijsproblemen* konden worden aangewezen betreffende deze laatste karakteristiek in het geval van het onderwijzen en het leren van het onderwerp corrosie (putcorrosie). Docentactiviteiten betroffen het tellen van halfreacties in een corpusculaire context. Leerlingen bleken moeilijkheden te ervaren in het begrijpen dat twee verschillende halfreacties die aan elkaar gerelateerd zijn op twee (of meer) lokaties van hetzelfde voorwerp kunnen plaatsvinden. Deze introductie van corrosie wordt door mij gezien als *introductie van een nieuwe corpusculaire context van elektrode.*
Ook konden *docentconcepties* betreffende de *proceskarakteristiek* van een elektrodereactie worden aangewezen. Dit waren voornamelijk corpusculaire concepties.
Docentconcepties van de *functie van een elektrode* in een elektrochemische cel bleken zowel fenomenologisch als corpusculair, te weten fenomenologisch gezien als deel uitmakend van een stroomcircuit, en corpusculair gezien als een combinatie van elektronenoverdracht en elektronentransport.

Docentconcepties betreffende *Posner's leerconditie van noodzakelijkheid* kunnen worden aangewezen voor zover het het concept van elektrode betreft. In voorgaand onderwijs leren leerlingen directe redoxreacties corpusculair te beschrijven met behulp van aanwijzingen van de docent en het leerboek. In het onderwerp elektrochemische cellen treedt de noodzakelijkheid op voor docenten om een staaf een elektrode te noemen op basis van hun observaties van twee ruimtelijk gescheiden en te onderscheiden (half)reactie identiteiten.

In ***hoofdstuk 7*** presenteer ik docentconcepties en onderwijsproblemen betreffende het *onderwijzen* van het sleutelconcept *ionentransport* in een elektrochemische cel.
Vier docentconcepties betreffende een corpusculaire beschrijving van stroomdoorgang in een elektrochemische cel konden worden aangegeven.
Ten eerste konden *docentconcepties* betreffende een *incomplete corpusculaire context* worden aangewezen. Deze concepties worden incompleet genoemd omdat geïdentificeerd ionentransport niet aan alle ionen in de zoutbrug wordt toegekend.

Ten tweede konden *docentconcepties* betreffende een *corpusculaire contextuitbreiding* worden aangewezen. Deze concepties waren beperkt tot interpretaties voor de zoutbrug en betroffen niet de elektrolyten.
Ten derde konden *docentconcepties* betreffende een *corpusculaire contextapplicatie* worden aangegeven. Hierbij worden identiteit, transport en richting van ionen en elektronen toegekend aan andere delen van de cel, namelijk elektrolyten, elektroden en draden.
Ten vierde konden ook *docentconcepties* worden aangewezen die beschouwd kunnen worden als een *complete corpusculaire context* van een elektrochemische cel, namelijk het beschrijven van elektronenoverdracht, elektronentransport en ionentransport in samenhang als beschrijving van stroomdoorgang. Er konden ook *onderwijsproblemen* betreffende het *bereiken van een complete corpusculaire context* voor stroomdoorgang worden aangegeven. De docenten verwezen niet naar de fenomenologische context van het experiment of de combinatie van experimenten (bijvoorbeeld het 'koperbrug' en het 'gedeeltelijk gekleurde zoutbrug' experiment). De conceptuele moeilijkheden van de leerlingen betreffen het niet kunnen beschrijven van ionentransport, elektronenoverdracht en elektronentransport in samenhang.

Ook konden *docentconcepties* betreffende de *contextvolgorde* van *fenomenologisch* naar *corpusculaire* context worden aangegeven.
Verder kunnen *docentconcepties* betreffende de *dominantie* van of hun *benadrukken* van de *corpusculaire context* in relatie met de fenomenologische context worden aangewezen en het *construeren van contexten door docenten zelf.* In relatie met deze concepties konden *onderwijsproblemen* worden aangegeven. Docentactiviteiten betreffen het geen aandacht schenken aan voorkennis en bestaande leerlingconcepties. Bovendien bleek dat docenten leerlingen geen mogelijkheden boden voor contextconstructie. De conceptuele moeilijkheden van leerlingen betreffen, ondermeer, stroomdoorgang in de elektrolyt in de vorm van elektronentransport.

Als laatste konden er ook *docentconcepties* betreffende *de vier leercondities van Posner* worden aangewezen. Bijvoorbeeld, aan de leerconditie van noodzakelijkheid werd de betekenis van samenhangende corpusculaire redeneringen van stroomdoorgang toegekend, en aan de leerconditie van plausibiliteit een betekenis van observaties en metingen.

In ***hoofdstuk 8*** beschrijf ik docentconcepties en onderwijsproblemen betreffende het *onderwijzen* van het sleutelconcept *potentiaalverschil* van een elektrochemische cel.
Docentconcepties betreffende de *corpusculaire context* konden worden aangewezen. Betreffende deze concepties interpreteer ik dat er of een koppeling met de meetwaarden voor potentiaalverschillen is (meetcontext), of met de getabelleerde waarden voor potentiaalverschillen (chemisch thermodynamische context).

Ook konden *docentconcepties* worden aangewezen betreffende *verschillen tussen potentiaalverschilwaarden*, in ieder geval voor gekoppelde elektrochemische cellen maar waarschijnlijk ook voor afzonderlijke. Verschillen tussen gemeten waarden van potentiaalverschillen en getabelleerde waarden voor potentiaalverschillen van elektrochemische cellen, als ook verschillen tussen de gemeten waarden van potentiaalverschil van gekoppelde cellen en berekende waarden hiervoor met behulp van gemeten waarden van potentiaalverschillen van afzonderlijke elektrochemische cellen werden opgemerkt.
Docentconcepties betreffende het *berekenen van potentiaalverschillen* waren corpusculaire concepties of rekenconcepties. Regels voor potentiaalverschilberekeningen worden aangekondigd zonder terug te gaan naar de waarde en het teken van het gemeten potentiaalverschil. *Onderwijsproblemen* betreffende *leerlingen die de rekencontext niet zelf construeren* konden worden aangegeven: de docenten verwezen niet naar de fenomenologische context. De conceptuele moeilijkheden van leerlingen betreffen het begrijpen van deze rekenregels. Niet verwijzen naar de fenomenologische context was ook het geval bij de leerconditie van begrijpelijkheid betreffende de corpusculaire context van stroomdoorgang.

Docentconcepties betreffende *Posner's leerconditie van vruchtbaarheid* konden worden aangewezen. Betreffende deze concepties worden de meetwaarde en het teken van potentiaalverschil van afzonderlijke elektrochemische cellen als delen van gekoppelde cellen toegepast in het voorspellen van de waarde en het teken van het potentiaalverschil van deze gekoppelde cellen. Deze vruchtbaarheid wordt door mij gezien als *contextapplicatie.*

Het *ontbreken van docentconcepties* betreffende de *elektrochemische reken-*, de *chemische thermodynamische* en de *meetcontext*, al dan niet in samenhang met elkaar zou onderwerp kunnen zijn van verder onderzoek.

In ***hoofdstuk 9*** wordt eerst een Engelse samenvatting van de eerste acht hoofdstukken van dit proefschrift gegeven.
Vervolgens wordt een didactische structuur van elektrochemische cellen beschreven, dit betreft elektrochemische concepten en hun volgorde. Deze structuur ziet er als volgt uit: elektrodereactie, elektrode, elektrolyt, de combinatie van de concepten elektronenoverdracht, elektronentransport en ionentransport, corrosie, teken en meetwaarde van potentiaalverschil, concentratieafhankelijke waarde van potentiaalverschil en potentiaalverschil als getabelleerde waarde. Ook worden er voorstellen voor het leerplan beschreven. Deze betreffen de plaats van het onderwerp elektrochemische cellen in het curriculum en het verwijderen van de Nernstvergelijking uit het curriculum. Voorstellen voor onderwijs betreffen het beginnen van het onderwijs in elektrochemische cellen met het concept

stroomdoorgang in plaats van het concept potentiaalverschil, en een keuze voor het onderwijzen in een begeleidingskader.
Hierna wordt een didactische structuur van het creëren van condities voor het leren van elektrochemische cellen beschreven. Deze structuur ziet er als volgt uit: concept, context, sleutelconcept, gebruik van contexten, Posner's leercondities en het creëren van leercondities. Ook worden er voorstellen voor docentcursussen gedaan. Deze betreffen het belang van concepten, contexten en leercondities.
Het hoofdstuk sluit af met een evaluatie van dit onderzoek en een aantal aanbevelingen voor vervolgonderzoek.

Nawoord

"Teaching is a vital profession and a fascinating experience: if you really want to learn a subject, teach it"

Een proefschrift schrijf je nooit alleen, integendeel, soms leek het wel of ik bij elke pagina mensen om hulp moest vragen. Daarom wil ik hier de kans benutten om allen te bedanken die op een of andere manier een bijdrage hebben geleverd en hun ervaringen met mij hebben gedeeld. Zij hebben voor mij het doen van onderzoek plezierig gemaakt en het proces van schrijven minder eenzaam. Een aantal personen wil ik met name noemen.

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Curriculum vitae

Jeannine Acampo werd geboren op 12 juli 1967 te Maastricht. Zij bezocht het Sintermeertencollege te Heerlen, waar zij in 1985 haar diploma VWO β behaalde.

Aansluitend begon zij aan de studie scheikunde aan de Rijksuniversiteit Leiden. Het propaedeutisch examen werd afgelegd in februari 1987.
Het afstudeeronderzoek vond plaats in de Vakgroep Eiwitbiosynthese onder begeleiding van Dr. J.P. Abrahams, Dr. B. Kraal en Prof. dr. L. Bosch. In deze periode werd onderzoek verricht naar de affiniteit van het eiwit EF-Tu voor aa-tRNA. Het doctoraalexamen werd afgelegd in januari 1990.

In januari 1990 begon zij aan de tweede fase opleiding tot scheikundedocent bij de Universitaire Leraren Opleiding aan de Rijksuniversiteit Leiden. Haar eerstegraads lesbevoegheid behaalde zij in januari 1991.

In januari 1991 trad zij in dienst van de Faculteit Scheikunde van de Universiteit Utrecht, om bij de Vakgroep Chemiedidactiek het onderzoek te verrichten waarvan in dit proefschrift verslag wordt gedaan. Naast haar wetenschappelijk onderzoek, verrichtte zij diverse onderwijstaken in de Faculteit Scheikunde, zoals op practica voor biologiestudenten. Zij gaf een aantal lezingen over haar werk in binnen- en buitenland, onder andere in Essen, Dortmund en Thessaloniki.

Sinds december 1992 is zij redactrice scheikunde voor het NVOX (voorheen NVON-Maandblad), een maandblad voor docenten natuurwetenschappen in het voortgezet onderwijs.
Sinds januari 1994 is zij lid van de voorbereidingscommissie die jaarlijks de Woudschotenconferentie voor scheikundedocenten organiseert.
Van oktober 1994 tot oktober 1996 is zij als medewerkster van één van de pedagogische centra (KPC) betrokken geweest bij de vernieuwingen in het voortgezet onderwijs (de nieuwe Tweede Fase).
Vanaf maart 1996 is zij betrokken bij huiswerkbegeleiding zoals dat plaatsvindt in buurthuizen in Utrecht.
Als vervangster gaf zij les in het schooljaar 1996-1997 op het Sint Bonifatiuscollege te Utrecht. Aan deze school is zij vanaf augustus 1997 verbonden als docente scheikunde.