Contingency in high-school students’ reasoning about electrochemical cells

Opportunities for learning and teaching in school science

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Till Leena
Abstract

The thesis takes its departure from the extensive literature on students’ alternative ideas in science. Although describing students’ conceptual knowledge in many science areas, the literature offers little about how this knowledge enters into the science learning process. Neither has it focused on how particulars and contingencies of curricular materials enter into the learning process. In this thesis I make high-resolution analyses of students’ learning in action during school science activities about real or idealized electrochemical cells. I use a discursive mechanism of learning developed to describe how students become participants in new practices through slow changes in word use. Specifically, I examine how alternative and accepted scientific ideas, as well as curricular materials, enter into students’ reasoning. The results are then used for producing hypotheses over how a teacher can support students’ science learning. Alternative ideas in electrochemistry did not necessarily interfere negatively with, and were sometimes productive for, students’ reasoning during the activities. Students included the particulars and contingencies of curricular materials in their reasoning not only when interacting with a real electrochemical cell but also in a more theoretical concept mapping activity about an idealized cell. Through taxonomic and correlational investigations students connected the particulars and contingencies of the real electrochemical cell to the generic knowledge of electrochemistry. When actively introduced by the researcher, such investigations had consequences for how single students framed their explanations of a real electrochemical cell. The results indicate ways in which teachers may encourage the productive use of contingencies to promote learning within the science classroom. However, this may require consideration of what students say in terms of consequences for their further learning rather than in terms of correct or incorrect content.

Keywords: electrochemistry; laboratory work; concept mapping; high-school; learning; teaching; pragmatism; practical epistemology analysis; contingency; discourse; misconceptions; alternative ideas; curricular materials.
List of papers

This thesis is comprised of a summary of four papers, which are referred to by their Roman numerals:


III  Hamza, K. M., & Wickman, P-O. Students’ interactions with curricular materials and scientific ideas in two different school science activities. *Submitted manuscript*.

IV  Hamza, K. M., & Wickman, P-O. Moving beyond a focus on conceptual difficulties to support students’ learning in science *Submitted manuscript*.

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Preface

There are two parts of this preface. The first one is in Swedish and is an effort to express my acknowledgements to those who have been around for me during these five years one way or another. The second part is in English and provides some brief guidelines to the reader on how to approach the thesis.

Någon gång i oktober 2004 fick jag ett e-mail som löd:

Hej.
Vi fick pengar. Kul va?
/P-O

Utöver att han lyckades skriva en så stilig ansökan att den tog sig igenom vetenskapsrådets nålsögon och därmed beredde mig möjlighet att påbörja forskarstudier, har P-O Wickman varit avgörande på många sätt under de här fem åren. Här vill jag särskilt lyfta fram min uppskattnings känsla i våra (handlednings-) samtal som P-O alltid har visat – försiktigt stödande när jag har haft (någorlunda…) flyt, och ett rejält gemensamt tag när det emellanåt gått trögare. Tack P-O, jag har lärt mig oerhört mycket av dig och hela tiden känt att jag haft ditt stöd och förtroende!

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En viktig förutsättning för att forskarstudierna ska bli en god erfarenhet är att undervisningsdelen av tjänsten fungerar väl. Lotta Lager-Nyqvist, och sedermera Martin deRon, har verkligen sett till att hitta goda lösningar för att få undervisning och forskarstudier att löpa smidigt sida vid sida. Lotta, som för övrigt var min handledare under lärarutbildningen, var också den som läste och kommenterade min första trevande forskningsplan. Lotta, jag minns att dina kommentarer var nyttiga, men framför allt att de var av sådan art att jag blev stärkt i känslan av att det här var något jag skulle kunna fixa.


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milärare och alla de gymnasieelever som tyvärr måste förbli anonyma. Utan er – ingen avhandling.

Slutligen vill jag tacka min familj som på olika sätt stöttat mig, inte bara under dessa fem speciella år. Tack mamma, pappa, mormor, morfar, Per-Åke och Frank för att ni alltid trott på mig. Tack Adam och Alex, ni betyder mer för mig än vad ni kanske inser. Tack Leena, du vet att jag tidigt utnämnde dig till min inofficiella bihandledare, och det har du verkligen varit under dessa fem år. Du är klippan på vilken min tillvaro vilar.

Finally, a note on how to approach the summarizing chapter (in Swedish called “Kappan”). To begin with, this is a compilation thesis of four papers that I have been struggling with for four and a half years. The summarizing chapter is precisely what it says, a summary of these four papers. Consequently, I have omitted all the excerpts and thick descriptions which constitute such an extensive part of the individual papers. Moreover, I have created a somewhat different logic for the presentation of the results, in an effort to integrate them more fully. For instance, results and discussions of the results of the four studies are presented together. Moreover, I have extracted the implications for teaching discussed in each paper into a separate section consisting of a set of tentative hypotheses for science teaching more generally. In two other respects, however, I have retained the logic of the papers. Thus, the reader will search in vain for a separate section on issues of validity, reliability, and generalizability. Instead, I treat such issues in the contexts in which they arise. I have also retained the ambition from the four papers of justifying the theoretical framework underpinning my studies in strictly operational terms, that is, in close connection to the purposes and specific needs of the empirical investigations conducted.
Introduction

Details are all that matters: God dwells there, and you never get to see Him if you don't struggle to get them right.¹

This thesis presents results on students’ learning in action during school science activities. Through detailed analyses of students’ moment-by-moment learning during activities covering real or idealized electrochemical cells, I examine how ideas and curricular materials present in the activities enter into students’ reasoning. From these results I produce tentative hypotheses over how a teacher can support students’ science learning.

Ever since the rediscovery that students bring a significant amount of experience to the science classroom, rather than entering it empty-handed (Driver & Easley, 1978; Fensham, 2004, p. 137), a central focus of science education research has been on the content and change of students’ ideas in science (Erickson, 2000; Taber, 2006). An extensive body of research provides evidence that students display a wide variety of alternative ideas in clinical interviews and paper-and-pencil tests (comprehensively compiled by Duit, 2009). The central theoretical term for the alternative ideas which are identified in such studies continues to be “misconceptions”² (diSessa, 2006; Smith, diSessa, & Roschelle, 1993). Because they appear both before and after science instruction, these misconceptions seem to be highly resistant to

² Although other terms have also been used to describe the alternative scientific ideas that students express in interviews and written tests, a search in ERIC between 1990 and 2009 reveals that the term “misconceptions” continues to dominate the field. A search for [“misconceptions” AND “science” AND “students” NOT (“alternative” OR “intuitive” OR “framework”)] resulted in 597 hits in peer-reviewed journals. A search for [“alternative conceptions” OR “alternative frameworks” OR “intuitive theories”) AND “science” AND “students”], on the other hand, resulted in 113 hits altogether (i.e., 16 percent of the total number of hits). Thus, findings covering students’ alternative scientific ideas are still rendered primarily as “misconceptions” in the science education literature. Moreover, the particular interview studies about students’ understanding of electrochemistry use the word “misconceptions”. Therefore, I use the two terms “alternative (scientific) ideas” (which I prefer) and “misconceptions” (which is the dominating term) interchangeably throughout the thesis, without any differences in connotation between the terms. I likewise use the term “accepted scientific ideas” to refer to those compatible with the accepted knowledge of the science area in question.
change (Duit & Treagust, 2003; Scott, Asoko, & Leach, 2007; Vosniadou, 2001). Moreover, a central conclusion from research into students’ alternative ideas is that misconceptions, identified in interviews and written tests, can also interfere with learning the correct scientific ideas and concepts in other settings (Groves & Pugh, 2002; Gunstone & White, 2000; Novak, 2002; Songer & Mintzes, 1994; Taber, 1995; Özmen, 2004). Remarkably enough, we lack direct empirical evidence to show what part these ideas, alternative as well as accepted ones, play in the science learning process as they enter into students’ reasoning in different school science activities (diSessa, 2006; Hammer, 2000; Smith et al., 1993). Yet, the need to determine how misconceptions work in action and how they interact with instructional practices was noted early on in the history of research on students’ ideas in science (Driver & Erickson, 1983).

Studies of students’ ideas in science have generally paid little or no analytic attention to how the particular features of questions or materials used in interviews (such as pictures or real examples of natural phenomena) enter into their reasoning (Roth & Hwang, 2006; Welzel & Roth, 1998). The questions and probes used are mostly considered to elicit the general beliefs held by the student rather than simply elicit temporary on-the-hoof explanations (Taber & Watts, 2000). Moreover, if an influence of context is recorded then it is treated as a methodological problem of discriminating between students’ contextual choices as opposed to their actual conceptions (Duit & Treagust, 2003). Thus, much of what we know about students’ reasoning in science is framed in terms of generic ideas that students are considered to possess, and whose content can be compared to the theoretical knowledge within a certain area of science (Taber & Watts, 2000). The few interview studies where particular features of questions and materials have been included in the analysis present inconclusive evidence concerning the consequences for students’ reasoning in science. Some studies demonstrate reasoning to be both coherent and stable across contexts (Ioannides & Vosniadou, 2002; Taber, 2000; Watson, Prieto, & Dillon, 1997; Vosniadou, Skopeliti, & Ikospentaki, 2005). Whilst other studies indicate that particular features of questions and materials used have significant consequences for what students say during an interview (diSessa, Gillespie, & Esterly, 2004; Schoultz, Säljö, & Wyndhamn, 2001a, 2001b; Tytler, 1998; Welzel & Roth, 1998).

Whereas scholars argue about the importance of particular features of the materials used in interviews for students’ reasoning (diSessa et al., 2004 vs. Ioannides & Vosniadou, 2002; Schoultz et al., 2001b vs. Vosniadou et al., 2005), it is well established that the materials present during laboratory work play complex and important parts for promoting or confounding students’ learning (Lunetta, Hofstein, & Clough, 2007). Often the particular features of the materials for the activity may dominate students’ reasoning too extensively at the expense of engagement in the relevant scientific ideas (Hodson, 1993; Hofstein & Lunetta, 2004; Kirschner & Huisman, 1998; Lunetta,
1998; Molander, Halldén, & Pedersen, 2001). At the same time, interactions with curricular materials of laboratory work constitute unique opportunities to establish links with the relevant scientific ideas (Millar, 1998; White, 1991). Close analyses of how students act in order to further learning situations, consistently reveal that encounters with particular features of the materials used will frame their reasoning in unique ways (Hwang & Roth, 2007; Jiménez-Aleixandre & Reigosa, 2006; Kelly & Crawford, 1997; Kelly, Crawford, & Green, 2001; Wickman, 2004; Wickman & Östman, 2002a; von Aufschnaiter & von Aufschnaiter & von Aufschnaiter, 2007). The results from such studies indicate that generic descriptions of the content and changes in students’ ideas appearing in interviews or written tests, do not constitute sufficient accounts of the processes of learning science in more authentic, and often more complex, settings, in which the whole array of curricular materials and other artifacts of most school science activities are present. Just as descriptions of expert knowledge also reveal it to include embodied, local, and contingently emerging practices which involve concrete materials (Goodwin, 1994; Lynch, Livingstone, & Garfinkel, 1983), the particular features of curricular materials cannot be neglected in analyses of students’ learning during school science activities (Brown, Collins, & Duguid, 1989; Hwang & Roth, 2007; Kelly et al., 2001; Wickman & Östman, 2002b).

Scott et al. (2007) argued that science education research needs to be able to make some kind of recommendations for teaching, based on the results it produces. The actions that teachers regularly take to support students’ continual learning in the classroom have been carefully described by a number of researchers (e.g., Chin, 2007; Kelly, Brown, & Crawford, 2000; Lidar, Lundqvist, & Östman, 2006; Ritchie, 1998; Sharpe, 2006; Wells, 1996). Teachers regularly make use of a variety of scaffolds, strategies, and moves in order to, for instance, keep students on a certain track, help them decide which aspects of the activity are worth paying attention to, or encourage them to extend their reasoning. A central conclusion from the extensive research on the content and change of students’ ideas in science, is that teachers need to identify and directly address misconceptions in order to facilitate learning (Donovan & Bransford, 2005). Various ways of taking students’ alternative ideas as the basis for teaching have been suggested and implemented in carefully sequenced intervention studies (Andersson & Bach, 2005; Leach & Scott, 2002; Meheut, 2005). An equally central conclusion from research on student learning in settings in which they interact with curricular materials and equipment, primarily in laboratory work, is that the teacher needs to minimize focus on the particulars of the materials used and instead encourage students to engage in the relevant scientific ideas (Lunetta et al., 2007). Here too, laboratory tasks which focus more on ideas and less on the messy contingencies of the real world have been suggested and implemented (Kirschner & Huisman, 1998; Shiland, 1999). Yet, concern is recurrently expressed that teachers do not incorporate results from science
education research into day-to-day practice (Duit & Treagust, 2003; Gunstone & White, 2000). Indeed, despite extensive and detailed knowledge of students’ conceptual starting points, of their various problems of interacting with materials in the laboratory, as well as of teachers’ regular actions to help students in the classroom, there is still a gap between this knowledge and our capacity to construct reliable approaches to instruction (Hofstein & Lunetta, 2004; Lijnse, 2000; Scott et al., 2007).

It is possible that one aspect of this problematic situation is that research has tended to divide the study of learning and teaching into students’ and teachers’ actions, on the one hand, and students’ knowledge as a result of these actions, on the other (for some recent examples, see Abrahams & Millar, 2008; Andersson, Bach, Hagman, Olander, & Wallin, 2005; Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001). In this thesis, I take a pragmatist approach to knowledge as a mode of action (Dewey, 1925/1996, p. 324, 1929/1996, p. 86) and, therefore, of learning as a matter of acquiring habits of action for coping with reality (Rorty, 1991; Wickman, 2006, p. 51). In this pragmatist approach, rather than being studied separate from the actions of learning and teaching in the classroom as subsequent changes in students’ knowledge, learning is here studied in action through descriptions of changes in the ways that students cope with different situations. Leach and Scott (2003) noted there is a marked need for studies describing how students act in authentic learning situations. DiSessa (2006) stressed that we need descriptions of the slow processes by which students’ reasoning changes. Moreover, both DiSessa (2006) and Halldén (1999) argued that contextual features should be made a central concern in studies of how students’ ideas change during instruction. Lunetta and Hofstein (2004) noted that research is needed into how teachers can help students interact intellectually as well as physically during practical learning activities.

Together, these suggestions indicate a need for science education to focus on the processes by which students learn certain science content as they interact with the various constituents of whole situations. Specifically, there seems to be a need for more detailed studies of how students’ alternative scientific ideas, as well as the accepted scientific ideas on offer in the classroom, enter into the learning process. Such studies may constitute a complement to the extensive descriptions of the content of students’ alternative ideas at a particular moment in time made through interviews or written tests. Moreover, the abundance of generic descriptions of students’ ideas in science may need to be complemented with moment-by-moment analyses of how students connect their ideas to the particular aspects of curricular materials involved in a science learning activity. Indeed, studies of the moment-by-moment processes by which students come to reason in certain ways during the course of science learning activities, and through interactions with both ideas and materials, are increasing in number (Jakobson & Wickman, 2007a, 2007b; Jiménez-Aleixandre & Reigosa, 2006; Kelly, 2004; Magnus-
son, Templin, & Boyle, 1997; Wickman, 2006; von Aufschnaiter & von Aufschnaiter, 2007). With an increasing supplement of such studies, we should be in a better position to produce hypotheses for teaching, which are empirically grounded in both the content and processes of students’ learning in science.
Aim of the thesis

The overall aim of this thesis is to make detailed, moment-by-moment analyses of students’ reasoning in school science activities, and to use these analyses to suggest hypotheses about what a teacher may need to consider in order to support students’ learning in the science classroom. I used high-school students’ reasoning about real or idealized electrochemical cells in school science settings as the model system. The analyses specifically focused on how students’ reasoning developed in encounters with the alternative and accepted scientific ideas that students came up with during the activities, as well as in encounters with the curricular materials present in the activities. I analyzed conversations between pairs of students working without help from the teacher as well as conversations between the researcher (myself) and individual students. I addressed the following two broad research questions:

1. How do scientific ideas and curricular materials enter into students’ reasoning about a real or idealized electrochemical cell during a school science activity?
2. What opportunities for learning and teaching school science may be inferred from detailed analyses of how ideas and materials enter into students’ reasoning?

I address the first research question empirically, through detailed descriptions and analyses of how students furthered the school science activities in which they engaged. I address the second research question through an interpretation of what these empirical data suggest in terms of possible actions a teacher may take to support students’ moment-by-moment learning in science. Through the second research question I thus generalize my detailed analyses of one particular study system (i.e., reasoning about electrochemical cells), and do this by producing tentative hypotheses about science teaching and learning which may then be tested in future studies.
Rationale of the studies

Here I provide a short rationale of the four studies included in this thesis, together with the specific research questions of each study. However, the research questions presented have been slightly modified in order for them to be understood prior to the reader being introduced to the theoretical approach of the thesis.

Paper I deals with what consequences different encounters have on students’ reasoning during a school science activity on electrochemical cells. During the analysis of the data I specifically came to focus on what consequences encounters with alternative ideas had, when compared to other aspects of the activity. Previous research has produced detailed lists of students’ misconceptions of electrochemical cells (Garnett & Treagust, 1992b; Sanger & Greenbowe, 1997) on the basis of student responses to questions in interviews. I therefore asked

1. To what extent do encounters with common misconceptions described in the literature influence students’ reasoning during a practical on electrochemistry?
2. To what extent do encounters with other aspects of the activity influence students’ reasoning during the practical?

Paper II builds on the same empirical material as, and analytically constitutes a logical continuation of, paper I. The results of paper I showed that encounters with particulars and contingencies of the real electrochemical cell were significant for how students’ reasoning developed. Therefore, I became interested in making a systematic description of how these particular and contingent aspects of science learning situations form part of a student’s scientific accounts, as a complement to previous descriptions of students’ understanding of the generalized knowledge of this area. I asked

3. What is it, more than the theoretical and generalized knowledge statements of the area, that students need to learn in order to reason scientifically in encounters with an electrochemical cell?
4. To what extent can we systematically characterize the knowledge/learning required to reason scientifically in encounters with the particulars and contingencies of a specific problem?
Paper III was motivated by the results from paper I and II, in that I wanted to (a) extend the study of students’ reasoning about electrochemical cells also to a more theoretical activity than laboratory work, and (b) study how students interact with scientific ideas and curricular materials (i.e., the two focuses of paper I and II, respectively), and do this in activities that lie rather far apart on the theory – practice scale. Therefore I asked

5. How do students interact with scientific ideas and curricular materials to further a concept mapping (i.e., more theoretical) activity and a lab work (i.e., more practical) activity about electrochemical cells?

In paper IV, I wanted to further extend the study to also include interactions with a more knowledgeable person. At the same time, I was interested in the consequences of actively introducing new students to some of the elements that my previous studies (primarily paper II) had shown to be significant for other students’ reasoning. This interest was both instructional (Are students’ own ways of reasoning, demonstrated in my previous studies, relevant in other school science settings?) and methodological (Can we devise a heuristic for making detailed and descriptive studies in science education relevant also to school science practice?). Paper IV, then, is an effort to synthesize some of the results from my three previous studies, both from an instructional and a methodological point of view. I asked

6. In what ways do taxonomic and correlational investigations become part of students’ reasoning about a real electrochemical cell when these are actively introduced into the conversation by a researcher?
Observing students’ learning in action, as they interact with different parts of a school science activity, places a number of requirements on the operationalization of learning. First, I wanted to follow the moment-by-moment processes of science learning during the activity. Therefore, learning needed to be described and analyzed directly in terms of changed action, rather than indirectly in terms of changed cognition. Describing changes in students’ cognition indirectly through interviews or written tests, would have destroyed the conditions for following learning as it developed in the course of a particular activity, through substituting a different activity for the one for which I wanted to describe students’ science learning processes (Greeno, 1997). Second, I wanted to examine how ideas and materials entered into the learning process without privileging one over the other. Therefore, these different parts of the activity needed to be analyzed on equal terms. More specifically, in my analyses of student action, I needed to avoid treating alternative and accepted scientific ideas as more significant parts of the learning process than particular aspects of the materials involved in the activity, as well as the other way around.

To accommodate these requirements I used a theoretical mechanism of learning developed by Wickman and Östman (2002b). This approach was developed to enable high-resolution descriptions and subsequent analyses of students’ learning processes, rendered as moment-by-moment changes in word use slowly enabling students to become participants in new practices (Wickman & Östman, 2002b). The unit of analysis is situated human action, that is, what students do and say as part of furthering activities having purposes (Wickman, 2006, p. 53). Being operationalized on a discursive level, students’ moment-by-moment learning is thus tantamount to the continual development of their reasoning during the activity. Other authors have argued that learning should be construed in terms of people’s conversations and actions which can be directly observed, rather than through cognitive entities or processes which cannot (Lave, 1993; Lemke, 1990; Säljö, 2002; Wertsch, del Río, & Alvarez, 1995). Such arguments do not need to imply that cognitive entities and processes do not exist, but simply that it will make sense to operationalize the phenomena and processes studied in terms of the type of data obtained (Button, 2008; Säljö, 1999). After all, even data from in-depth interviews and psychological experiments will consist of records of people’s actions in the form of conversations or other social behavior, and
not of cognitive entities or processes per se (Lemke, 1990, p. 193; Säljö, 1997, 2002).

Because in the mechanism used in this thesis, the unit of analysis is action situated in an activity, students’ interactions with ideas during the learning process are described in relation to their interactions with other parts of the learning situation. These may include recollections of previous experiences both in and out of school, natural phenomena, or physical artifacts (Wickman, 2004). This approach, to study how scientific knowledge and ideas are intertwined with physical artifacts and other materials present as people engage in furthering whole activities, is consistent with other studies of both expert practices and student learning (reviewed by: Greeno, 2006; Kelly, 2004; Lynch et al., 1983; Roth & McGinn, 1997). In particular, the mechanism used here assigns different parts of a learning situation to the same descriptive (viz., discursive) level (Wickman, 2006, p. 53). It is thus especially suited for addressing questions of how discursive encounters between the teaching content, the physical world, and students’ prior knowledge will result in learning in situ within the science classroom (Wickman & Östman, 2002b).

The mechanism of learning used here operationalizes learning as a series of transformations of experience (Dewey, 1938/1996, p. 59). Such a transformation of experience occurs as people establish continuity between previous experiences and the present one. The process may be seen as a continuous rhythm of construing relations between the past and the present, in order to take the experience forward (Wickman, 2006, pp. 72-73). It could be argued that the minimal requirement for learning to take place is that some kind of relationship between prior and present experience is established by the participants in a learning situation. It is this minimal requirement that the theoretical mechanism which is used here will employ. It thus constitutes a way of minimizing the risk of overlooking instances of learning, as well as parts of a situation that may participate in the learning process, simply because they were not included in the definition of learning from the outset. Just as actions for coping with real-world situations are not restricted to manipulating and testing statements according to their truth value, a student trying to further a science learning activity will use any results from prior experiences that will help her give meaning to the present experience (Brown et al., 1989; Dewey, 1933/1996, p. 241; Wickman, 2006, p. 42). Kelly, Chen, and Crawford (1998) made a similar argument: what counts as science in the classroom is an empirical, contingent question that needs to be subject to descriptive investigations rather than being theoretically defined in advance. Thus, in this thesis learning is operationalized generously and inclusively in order to be able to make empirical descriptions and analyses, rather than normative assessments, of the science learning process.

Taking transformation of experience rather than, for instance, transformation of conceptual frameworks as a basis for an operational mechanism of
learning thus amounts to extending the possible ways in which learning can be studied empirically (Wickman, 2006, p. 42). This implies, however, that experience is treated from a Deweyan pragmatist perspective. The Deweyan pragmatist conception of human experience does not posit it as a purely psychological or private phenomenon (Dewey, 1925/1996, p. 179; Garrison, 1995; Wong & Pugh, 2001). Rather, it involves those parts that people happen to use – scientific ideas, aesthetic judgments, physical artifacts – in the transactions which make up a particular experience (Biesta, 1994). No method of studying learning has access to anything beyond what people say and do in particular situations. The mechanism used here confines the description and analysis of learning to those parts of an experience which come into question in the activity, while avoiding any inferences about experiential processes not accessible to observation. Indeed, as people act in whole situations there is rarely reason or opportunity to divide the experience into separate realms. Various distinctions, such as those between ideas and materials made in this thesis, are the result of later reflection made for certain purposes (Dewey, 1916/1996, p. 173; Gee & Green, 1998; Kruckeberg, 2006; Rockwell, 2001; Wickman, 2006, p. 69). Working with Dewey’s concept of experience means resetting all different modes of human action to the same ontological level (Dewey, 1925/1996, p. 19, 1929/1996, p. 175; Koschmann, Kuutti, & Hickman, 1998), without privileging one mode (e.g., use of conceptual knowledge) over another (e.g., aesthetic judgments or taxonomic investigations). This makes possible an analysis of how different aspects of a situation enter into the experience and consequently, into the learning process.

Any operational mechanism of learning needs to account for the continuous (prior knowledge and experiences), situational (elements of the present experience), and transformational (change of experience) aspects of learning (Wickman, 2006, p. 53). The continuous and situational aspects are operationalized in the two concepts of encounter and stand fast (Wickman & Östman, 2002b). An encounter is an operationalization of the parts in a learning situation which are seen to meet as they appear in student talk and action during an activity. Encounters occur between individuals as well as between individuals and curricular materials such as instructions, natural phenomena, or physical artifacts. Moreover, acting with language requires some words to be already familiar in the sense that their use in a particular encounter is not questioned by the participants. Such words are said to stand fast, which means simply that the words are observed to work as temporary points of departure for furthering the activity, in whichever direction it may take. An encounter involves prior knowledge and other previous experiences (continuous aspect), as well as new and unique elements of the present experience (situational aspect). Likewise, the words that stand fast represent both the continuous (the word is familiar from a previous experience) and situational (the word is used in relation to the elements of the present experi-
ence) aspect. Through these two concepts it is therefore possible to describe, among other things, how alternative and accepted scientific ideas meet with particular aspects of the curricular materials used.

The transformational aspect (i.e., the process) of learning is operationalized in the two concepts of gap and relation (Wickman, 2006, pp. 53 and 56; Wickman & Östman, 2002b). Gaps are noticed in encounters with, for example, instructions, utterances, artifacts, or natural phenomena. To be able to continue the activity students need to fill the gaps by construing relations to what stands fast in the encounter. If they are unable to construe any relations the gap is said to linger. This has as a consequence that the activity momentarily stops and subsequently takes a new direction as students notice new gaps in new encounters. Thus, learning is operationalized generously and inclusively, since any relation construed to establish continuity between students’ prior experiences and the various other parts of a new situation is included in the definition. With the addition of these two concepts it is possible to analyze how alternative and accepted scientific ideas, as well as particular aspects of the materials used, transform the experience and, therefore, how they enter into the learning process during a school science activity.

Descriptions of the ways in which students cope with different situations in the course of an activity constitute the practical epistemologies emerging in the classroom, that is, how students themselves use knowledge as well as their ways of establishing new knowledge in order to proceed with an activity that has certain purposes (Wickman, 2004). People learn constantly as they move from one situation to the next (Dewey, 1938/1996, p. 26; Lave, 1993). In Dewey’s terms they “carry over from prior experience factors which modify subsequent activities” (Dewey, 1916/1996, p. 51). A practical epistemology analysis is precisely an operational mechanism for describing how people establish such continuity between prior and present experiences. In the long run, this process slowly and gradually changes people’s habits (Dewey, 1916/1996, p. 51; Wickman, 2004). In this respect, a practical epistemology analysis also represents a mechanism for analyzing the habits emerging during an activity, that is, how people cope with various activities in repeatable patterns (Wickman, 2006, p. 58).

I will illustrate how a practical epistemology analysis can be used to describe and analyze the science learning process during a certain activity, as well as the habits emerging across encounters within or across student groups, by reviewing an authentic transcript taken from one of my studies (but not presented in the papers). In the example transcript, Gary and Fred are reasoning about the bubbling occurring in the magnesium half cell (Figure 1a), involving another group (Simon and Sean) in their reasoning. The theoretical mechanism of learning outlined above keeps the description and subsequent analysis of student action within the confines of the purpose of the activity. One of the explicit assignments in the instructions is that stu-
dents should “discuss and try to explain what chemical reactions take place”. The practical epistemology analysis is conducted in view of that purpose.

Example transcript

1 Gary: No but… which gas is it?
2 Fred: Right… what on earth can it be? Have you figured it out?
   Simon! Do you know which gas is forming?
3 Simon: Well, I suppose it’s hydrogen gas, don’t you think so?
4 Fred: Where would the hydrogen come from?
5 Gary: Right. [everybody’s laughing]
6 Simon: No actually I’ve no idea.
7 Sean: Uhmm, what could it be?
8 Gary: It’s got to be some kind of oxide.
9 Fred: I think it’s, yeah…
10 Sean: Some oxide, yeah, from magnesium.
11 Fred: Exactly.
12 Gary: Cause we’ve got… we’ve got magnesium, in solid form.
13 Fred: Exactly.
14 Gary: And we’ve got magnesium…
15 Fred: … -sulfate
16 Gary: Yes.

To begin with, the encounter with the electrochemical cell gives rise to the gap “Which gas is it?” (Turn 1). The students construe three relations in order to fill this gap: “it – hydrogen gas” (Turn 3), “it – some oxide” (Turn 8) and “oxide – from magnesium” (Turn 10). Moreover, the first of these relations gives rise to another gap: “Where would the hydrogen come from?” (Turn 4). This second gap lingers for the moment (Turn 5 – 6). Following the reasoning in turn 1 – 11, Gary and Fred also construe the relations “we have – magnesium – in solid form” and “we have – magnesium sulfate” (Turn 12 – 16), which fill the (implicit) gap “What do we have in the cell?” Note that the operational definition of students noticing a gap is that they actually construe one or several relations. Noticing a gap does not in itself imply any particular difficulty that students may have. Even though students will certainly notice some gaps that they are unable to fill with relations, this is not the definition of the process of noticing gaps but only one possible outcome of it. Moreover, in this particular case all of the words that students use stand fast, that is, they are used without the students questioning what the words mean. Aspects of the situation which are seen to meet in students’ reasoning are (1) the bubbling occurring in the magnesium half cell, (b) the constituents of the cell, and (3) ideas of possible gases. Here, then, is a moment-by-moment description of students’ learning in action during an activity, rendered as the gaps and relations being construed in the encounter, as well as aspects of the situation involved in that learning.
We may now analyze what students learn as a consequence of how they cope with this encounter in relation to the purpose of the activity. Besides, the analysis may focus on different aspects of the activity. For instance, we could analyze what direction students’ reasoning takes in this particular encounter. We may then conclude that in the example, students’ reasoning is leading in an unwanted direction in relation to the purpose of learning what chemical reactions take place. Here the students learn that the bubbles are probably not hydrogen gas but rather some oxide, and probably magnesium oxide (Turn 3 – 10). We could then take this analysis as a basis for a more specific description of the subsequent relations that these students construe (to bubbles) in new encounters with their real electrochemical cell. An analysis of all such relations would reveal, among other things, that Gary and Fred changed their reasoning several times over which gas they were dealing with during the activity, as a consequence of focusing on different aspects of the encounters with the real electrochemical cell (paper I). We may also analyze what consequences particular relations (or absence thereof) have for learning taking a certain direction. Here students learn that the bubbles are not hydrogen gas because there is no obvious source of hydrogen (Turn 4 – 6). The fact that they do not acknowledge the presence of hydrogen (-ions) in the solutions makes them dismiss, at the time, the possibility that the bubbles could be hydrogen gas. We could hypothesize that helping them with this issue may have set off the learning process in another direction (paper IV). On the other hand, it is possible to analyze how certain gaps or relations, which are construed in this encounter, are used by the students later during the activity. This requires a new set of descriptions which focus particularly on how relations from this encounter recur in students’ subsequent reasoning, together with analyses of the consequences of construing these relations in new encounters. In this particular case, such an analysis shows that the faulty relations to magnesium oxide as a possible gas (Turn 8 – 11), when returned to at a later moment, lead to finer distinctions concerning the constituents of the cell (e.g., that oxygen atoms in the sulfate ions have to be distinguished from oxygen present in the solutions). Finally, we may analyze more specifically how the students cope with the main gap (Turn 1) in this encounter. To fill that gap they also need to fill another gap concerning the constituents of the cell. So in the course of learning what gas is being produced they also learn that solid magnesium and magnesium sulfate is present in the cell (Turn 12 – 16), and do so by engaging in a short investigation concerning some of the constituents of the cell. Such an analysis may show that students regularly use certain approaches (e.g., making taxonomic investigations; paper II, III, and IV) in order to further the purpose of the activity, while other possible habits of action for coping with certain situations are absent.

To summarize, a practical epistemology analysis situates the accounts of what and how students learn within an activity that has certain purposes. It is
an effort to begin the study of human action in general, and student learning in particular, in those parts of an experience which become explicit and visible in action during an activity. Descriptions and analyses of these experiences are made through operationally defined concepts (Wickman & Östman, 2002b). The results of these analyses may be converted into tentative hypotheses which can be tested in other settings, for example involving a teacher. The interpretation of these experiences provides material for new descriptions and analyses of students’ learning, which may in turn be taken further by introducing them into new settings and so on. By this process of generalization in the Deweyan sense (Wickman & Östman, 2002a), we may make claims about learning and teaching in science as having increasing warranted assertibility (Hickman, 1998), because the claims are continuously being tested in new settings in the light of previous experiences. The approach is inspired by Dewey’s empirical method. This means beginning inquiry by describing human experience (i.e., those parts of the experience possible to observe in talk and action) and analyze the descriptions with operationally defined and carefully delimited analytic concepts (Dewey & Bentley, 1949/1996). The results are then returned to the experiences that contributed with the initial problems to be solved, in order to begin a modified inquiry (Dewey, 1925/1996, pp. 11-26; Hickman, 1998). The theoretical mechanism of learning which has been outlined above is therefore well suited for the overall aim of this thesis. Namely to produce detailed descriptions of student learning of science content in different settings, analyze these descriptions in relation to the purpose of the activity, and produce tentative hypotheses over how to support students’ learning. Thereby, in the long run, identifying how to support the gradual change of students’ habits of action for coping with various situations.
Study system: Reasoning about electrochemical cells

The phenomena of redox reactions and electrochemistry are all around us (Zumdahl & Zumdahl, 2003). We encounter them more or less overtly as we burn fossil fuels, use digital watches and other portable electric devices, or curse our rusting car. Although less evident, life itself can be considered a gigantic redox reaction with its massive charge and subsequent release of electrons in photosynthesis and respiration, respectively. Electrochemistry also has a close connection to physics concepts such as energy and voltage, and practical applications of electrochemistry are countless. In particular, electrochemical cells, or batteries, of various kinds are pervasive in our society (Zumdahl & Zumdahl, 2003). They may be disposable or rechargeable, be a couple of micrometers thick or weigh as much as 80 tons, and represent either serious environmental hazards (e.g., Ni–Cd-batteries) or hold promise of more or less clean energy sources (e.g., fuel cells in cars). Redox reactions also constitute a theoretically important category of chemical reactions (Petrucci, 1989). Taken together, the topic of students’ reasoning about electrochemical cells represents a relevant choice of study system because it constitutes part of students’ everyday experiences as well as of their experiences during high-school chemistry courses.

There are also more specific reasons for choosing electrochemical cells as a model system for the purposes of studying the processes by which ideas and materials enter into students’ reasoning. Redox reactions and electrochemistry constituted one of the six main topics reviewed concerning student misconceptions in chemistry (Garnett, Garnett, & Hackling, 1995). Three interview studies have produced detailed records of high-school and college students’ misconceptions about electrochemical cells in Australia and the USA (Garnett & Treagust, 1992a, 1992b; Sanger & Greenbowe, 1997), and these misconceptions were also confirmed in a study from South Africa (Huddle, White, & Rogers, 2000). Moreover, Garnett and Treagust (1992b) provided a comprehensive list of propositional and conceptual statements required to explain an idealized electrochemical cell (see Table 1 of paper II). It is also acknowledged that processes of electrochemistry are complex and difficult for students to understand from real experiments with, for instance, electrochemical cells. Also, there are a number of studies in which various idealized models have been used instead of real electrochemical cells.
in order to facilitate conceptual change in electrochemistry (Huddle et al., 2000; Sanger & Greenbowe, 2000; Yang, Andre, & Greenbowe, 2003). All of the studies cited above agree that students alternative ideas (rendered primarily as misconceptions) constitute serious obstacles to learning about electrochemical cells, and some provide explicit advice for teaching. For example, it is suggested that teachers should regularly diagnose misconceptions before teaching (Garnett & Treagust, 1992b), use electrochemistry words and terms in exact ways (Garnett & Treagust, 1992b; Sanger & Greenbowe, 1997), and avoid confusing students with more than one explanatory model when presenting content on redox reactions and electrochemistry (Garnett & Treagust, 1992a). Common to these suggestions is the assumption that teachers should primarily address students’ conceptual difficulties by dealing more directly and more carefully with conceptual issues in the classroom. Moreover, the suggestions for what to do in the science classroom are inferred from interviews and written tests. The study system therefore also fits the additional purpose of this thesis: to instead suggest tentative hypotheses for teaching electrochemistry on the basis of detailed analyses of students’ moment-by-moment learning in action within the science classroom.

Finally, the study system (reasoning about electrochemical cells) is representative for student learning in school science more generally, because results and conclusions concerning alternative ideas, problems of interacting with materials in laboratory work, as well as suggestions for teaching align well with those of many other school science areas (cf., Lunetta et al., 2007; Taber, 2006). Thus, the study system does not stand out as being unusually difficult or confusing to students, although it would have most likely been possible to find a less complex activity than a real copper–magnesium cell (perhaps one in which no bubbles of hydrogen gas were produced; Figure 1a). On the other hand, it would have been easier still to find even more complex, yet regular, school science activities for students to interact with, for instance in biology. After all, as science educators, we want students to be able to use their knowledge in authentic interactions with the real world (Mintzes, Wandersee, & Novak, 2001). Such use necessarily implies encounters with the messy contingencies of the real world which so often cause uncertainty or even perplexity, irrespective of whether they are encountered, for instance, while reading a newspaper article about fuel-cells or while figuring out how to safely recharge the car battery.

School science activities

High-school students (Grade 10, Age 16-17) engaged either in a practical involving a real electrochemical cell (paper I, II, III, and IV) or in constructing a concept map of an idealized cell (paper III). Figure 1 illustrates and briefly explains the specific electrochemical cell used throughout all studies.
in this thesis. The overall and explicit purpose in all activities was that the
students should reason about how a current can be produced in the electro-
chemical cell and thus drive an electric motor or LED. In other words, the
explicit purpose of both the lab work and concept mapping activity was tan-
tamount to the “correct explanations” curriculum emphasis (Roberts, 1994).
Even though I wrote the specific instructions for all activities, they were
checked and approved by the teachers in advance. Moreover, the activities
fitted into the current curriculum in such a way that either (a) they would
have been conducted anyway in a similar form according to the regular
teachers (lab work activity of paper I, II, and III) or (b) the regular teachers
considered the activity a relevant contribution to the curriculum (concept
mapping activity of paper III; lab work activity of paper IV). In all studies
the students had already been introduced to the concepts of redox reactions
in the previous semester. At the time of the studies they were either in the
middle of working with a unit on electrochemistry and other energy conver-
sions or were engaged in reviewing the entire basic chemistry course before
the final test.

Lab work activity (paper I, II, III, and IV).

Students were briefly introduced to the lab work activity by the researcher.
They were given a lab sheet which provided details of how to construct the
cell and instructions to (a) observe what happened to the cell and the electric
motor/LED, (b) look closely at the metal strips (i.e., electrodes) after ten
minutes, (c) measure the voltage, and (d) connect the motor/LED to the real
battery (dry cell, 1.5V). Moreover, at the end of the instructions three ques-
tions asked the students to “discuss and try to explain” (a) how a current can
occur in the cell, (b) what chemical reactions take place, and (c) what role
the “porous white glass wall” (paper I and II)/the “glass filter” (paper III and
IV) at the bottom of the U-tube has. All necessary materials and equipment
were provided on a prepared tray so that the students would stay near the
audio recording equipment.

Figure 1a illustrates some of the processes which could be observed in the
real electrochemical cell the students constructed (paper I, II, III, and IV). As
can be seen, the students were able to observe the magnesium electrode turn-
ing dull (as it was oxidized) and a layer (of copper) forming on the copper
electrode. Additionally, the students frequently observed bubbles being pro-
duced in the magnesium sulfate solution as soon as the magnesium electrode
was immersed. These bubbles of hydrogen gas are produced when magne-
sium reduces hydrogen ions in the magnesium sulfate solution, which is
acidic (pH 4).
Figure 1. The specific electrochemical cell used throughout the studies in this thesis was the copper–magnesium cell \([\text{Mg}(s) \mid \text{Mg}^{2+} (1.0 \text{ M}) \mid \text{Cu}^{2+} (1.0 \text{ M}) \mid \text{Cu}(s)]\). Provided that the electrodes are clean of layers of oxide, this cell provides enough voltage and current to drive a small electric motor or light-emitting diode (LED). Ideally, what happens in the cell is the following. When the circuit is closed, the magnesium electrode begins to oxidize. Electrons lost by the magnesium atoms pass through the leads, through the electric motor or LED, and end up by reducing copper ions in the copper sulfate solution. The copper ions gaining electrons turn into copper that is precipitated on the copper electrode. As the magnesium atoms lose electrons they turn into magnesium ions that enter into the magnesium sulfate solution. To complete the circuit, positive ions (e.g., magnesium ions and protons) move through the glass filter into the copper sulfate solution while negative ions (e.g., sulfate ions) move through the filter into the magnesium sulfate solution. (a) A schematic representation of the electrochemical cell that students set up in the lab work activities (paper I, II, III, and IV), together with illustrations of what could be observed to happen. The instructions did not contain any representation of the cell. It was possible to observe the magnesium electrode turning dull (as it oxidized) and a layer (of copper) forming on the copper electrode. On the magnesium side a bluish precipitation (most likely of copper magnesium hydroxide) and bubbles (of hydrogen gas) formed. Some leakage of copper sulfate solution through the glass filter could be observed. The electric motor could be connected either way, but sometimes students failed to make it work (because they had too small a surface area on the anode). The light-emitting diode had to be connected to the correct terminals. The voltmeter gave a positive or negative reading of voltage depending on which terminals it was connected to. (b) The picture of an idealized electrochemical cell given to the students in the concept mapping activity (paper III).

Moreover, there was a slight leakage of copper sulfate solution through the glass filter. Therefore, as the pH increased around the magnesium electrode as a result of the reduction of hydrogen ions, a visible precipitation\(^3\) (probably magnesium copper hydroxide, Lars Eriksson, personal communication, December 1, 2009) formed in the magnesium half cell. The students were also able to observe that the LED worked only when connected to the termi-

\(^3\) X-ray diffraction indicates that the precipitate is essentially composed of a solid solution of copper hydroxide and magnesium hydroxide, \((\text{Mgx,Cu1-x})(\text{OH})_2(\text{H}_2\text{O})_y\). I am indebted to Dr. Lars Eriksson at Stockholm University for performing these analyses and interpreting the results.
nals in a certain manner. Similarly, they occasionally received a negative reading on the voltmeter which depended on how they connected it to the cell. Finally, the electric motor moved considerably faster when connected to the real battery than to their electrochemical cell (because of the stronger current), even though the voltage of the real battery was somewhat lower.

The instructions fell between 0 and 1 in terms of the degree of openness (Herron, 1971). The problem was clearly stated as one of “reasoning about and trying to explain how your electrochemical cell can produce current” and methods were described in a traditional cook-book style typical of most school laboratory work (Domin, 1999). The main outcome (i.e., that the cell would drive the electric motor or light the LED) was anticipated in the instructions, whereas all the other outcomes listed above (Figure 1a) were not mentioned. Finally, no answers to the questions were given. Thus, the instructions fell somewhere between an expository and discovery approach to instruction (as defined by Gyllenpalm, Wickman, & Holmgren, in press). These two approaches to laboratory work are the ones most commonly employed in secondary school science (Domin, 1999).

Concept mapping activity (paper III).

Students were briefly introduced to the concept mapping activity by the researcher. I stressed that I wanted their concept maps not only to contain terms connected in certain ways but also to have words or sentences associated with the links between terms. To illustrate how to construct the concept map I provided an example map (about the structure of the atom) on the back of the instructions sheet. The written instructions asked students to reason about the idealized drawing of the copper–magnesium cell (Figure 1b) and construct a concept map from 23 different terms4 provided on pieces of paper. They could also add their own terms by using post-it notes. Moreover, at the end of the instructions there were three questions (identical to those of the lab work activities) which asked the students to “discuss and try to explain” (a) how a current can occur in the cell, (b) what chemical reactions take place, and (c) what role the glass filter at the bottom of the U-tube has. I decided on which terms to provide on the basis of my knowledge of students’ reasoning about the real electrochemical cell (paper I and II). Also, I chose to provide the students with as many as 23 terms so the concept mapping activity would require a similar amount of time to that of the lab work activity, which turned out to be a good estimate.

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4 The 23 electrochemistry terms provided were half cell, electrode, plus terminal, minus terminal, glass filter, current, voltage, circuit, charges, electrons, ions, positive ions, negative ions, oxidation, oxidize, reduction, reduce, noble, electronegative, chemical reaction, redox reaction, chemical energy, electric energy.
Study settings, data collection, and data processing

The main data for all analyses come from audio recordings of student conversations as they worked (a) in pairs with a practical activity on electrochemical cells (paper I, II, and III), (b) in pairs with a concept mapping activity on electrochemical cells (paper III), or (c) alone with a practical activity on electrochemical cells with the researcher (me) as a partner instead of a peer (paper IV). In the concept mapping activity I supplemented the audio recordings with video data of their manipulation of the concept maps. Only the hands of students, together with the emerging concept map, were caught on video tape. In the lab work activities it was mostly evident from the audio recordings alone what the students were doing. However, data was supplemented with notes and sketches of the cell made by the students in the course of the activity. When needed, I used these to confirm certain actions in the audio recorded material. Recordings were between 28 and 61 minutes long.

I recorded 12 pairs (24 students) completing the lab work activity (paper I, II, and III) and 4 pairs (8 students) completing the concept mapping activity (paper III) in two high-schools from two different municipalities in the Stockholm area, Sweden. All students attended the Science Program. One of the schools (paper I and II) harbored mostly high-achieving students as judged from the required marks for entry to the school, whereas the other school (paper III) required considerably lower marks for entry. In addition, I recorded conversations between eight individual students and myself (researcher) in two other high-schools from two additional municipalities in the Stockholm area (paper IV). One of the schools (five students from the Technical Program) harbored medium achieving students as judged from the required marks for entry, whereas the other school (three students from the Science Program) required lower marks, on par with the school in paper III. I transcribed the entire sessions verbatim. Students in paper I and II, and three of the students of paper IV, used one textbook (Andersson, Sonesson, Stålhandske, & Tullberg, 2000), whereas students in paper III, and five of the students in paper IV, used a different textbook (Henriksson, 2006).

When students worked in pairs during the lab work activities (paper I, II, and III) or the concept mapping activity (paper III), I briefly introduced the activity to them by explaining the safety issues and reiterating some of the special research conditions. These were (a) that the students could speak freely because their regular teacher would not gain access to the recordings, (b) that I was not interested in how well they understood electrochemistry but rather in the different ways they would proceed with the activity, and (c) that unlike an ordinary lab work session they would receive minimal help from both the researcher (me) and the teacher (paper I, II, and III). However, the regular teachers were sometimes unable to keep from responding to the students’ requests with somewhat more help than I had intended. Even on
those rare occasions, however, it is clear from the recordings that both teachers (paper I and II, and III, respectively) provided a minimum of help compared to what would have been likely in a regular lab work activity.

Likewise, when students worked alone during the lab work activity, with the researcher as a partner (paper IV), I also began by introducing the conditions for the activity. These were similar to (a) and (b) above, but I also asked each student to continuously talk about what they were doing during the activity. Moreover, in contrast to when students were working in pairs (paper I, II, and III), here (paper IV) I stressed that they could ask me for as much help as they wanted, although I would decide in what form the help would come. I emphasized to the student that the support I gave would be based on some ideas of how to help students reason about electrochemical cells which I had got from my earlier studies.

One important difference between this and previous studies of students’ reasoning in electrochemistry is the way in which they were situated (another one being the way in which learning was operationalized, as described above). Previous studies primarily observed students as they were reasoning about idealized cells in clinical interview situations. Here, on the other hand, I observed students as they engaged in reasoning about real or idealized cells in activities that were deemed by the teachers to fit well into the curriculum.

At the same time, all four studies drew their data from the talk and action of either two students or one student and the researcher (i.e., dyads) jointly furthering the activities. Because learning is here operationalized as changes in students’ moment-by-moment reasoning during an activity, one important requirement of my settings was simply to arrange for situations in which students communicated in a reasonably authentic manner, and the dyad is arguably the smallest unit from which authentic conversations can be recorded. Moreover, pairs of students, as in paper I – III, constitute a common unit of classroom activities, especially with respect to laboratory work. Although prolonged interactions between a more knowledgeable person (teacher or researcher) and single students concerning certain science content, as in paper IV, are not particularly common in school science activities, the dyad is a classic interactional unit in studies of how to support children’s and students’ learning (e.g., Wood, Bruner, & Ross, 1976). Moreover, the primary purpose of paper IV was not to determine the effects of interventions from the researcher, but to examine the consequences for learning about electrochemical cells of introducing some of the ways in which students in my previous studies had coped with similar situations. Thus, there was a point in preserving the dyad as the interactional unit throughout the four studies of this thesis. Also, as the interactions with the students in paper IV relied on close acquaintance with the results from my previous studies (particularly paper II), at this stage it was deemed necessary that the researcher was also the one who interacted with the students in the new settings.
Analytic approach

Examining how scientific ideas enter into students’ reasoning

In order to examine how alternative scientific ideas in electrochemistry enter into students’ moment-by-moment reasoning during a school science activity, I audio recorded pairs of students as they engaged in building and explaining a real electrochemical cell (paper I). I took my departure from the three main interview studies identifying misconceptions of electrochemistry (Garnett & Treagust, 1992a, 1992b; Sanger & Greenbowe, 1997). I went through the transcripts extensively and located all instances where students construed relations touching upon a misconception of electrochemistry previously recorded in the literature. In other words, I did not try to identify misconceptions in terms of internal conceptual structures or mental models of the learners, as is usually done (e.g., Duit & Treagust, 2003; Vosniadou et al., 2005). Instead, since I was interested in examining how misconceptions work in action (Driver & Erickson, 1983), I identified encounters with misconceptions through the relations students construed to cope with new situations during the activity. I then analyzed how students construed other relations to fill the gaps noticed in these encounters. Specifically, I examined whether the encounter with a known misconception interfered negatively with how students filled gaps or whether the encounter was rather neutral (i.e., having no observable consequences for their further reasoning) or even generative (i.e., having positive consequences for their further reasoning) of how the students were able to continue the activity.

In order to examine how ideas of electrochemistry more generally (i.e., accepted as well as alternative ones) enter into students’ reasoning in two different (lab work vs. concept mapping) settings, I audio recorded four pairs (8 students) completing the lab work activity on a real electrochemical cell and audio and video recorded four pairs (8 students) completing the concept mapping activity about an idealized electrochemical cell (paper III). I operationalized interactions with ideas of electrochemistry as all relations constituting part of an explanation to one of the three questions provided in the instructions. An important part of this analysis was the extent to which ideas of electrochemistry entered into students’ reasoning separate from or in connection to the curricular materials of each activity, respectively. Therefore, I extensively described how students sequentially, and moment-by-moment, construed relations to scientific ideas and curricular materials, and analyzed how one followed on another. In that way, I was able to characterize ways in which students furthered the two activities (lab work and concept mapping) through interacting with either ideas or materials, and through doing this either separately or in coordination.
Examining how curricular materials enter into students’ reasoning

In order to examine how particular and contingently occurring features of the real electrochemical cell entered into students’ reasoning, I audio recorded pairs of students as they engaged in building and explaining a real electrochemical cell (paper II). I took my departure from the study of Garnett and Treagust (1992b) in which they comprehensively outlined the generic statements – drawn from senior chemistry textbooks – needed to explain an electrochemical cell (see Table 1 of paper II). I treated any feature brought out in student discourse as a particular if it had something to do with the specific electrochemical cell the students were working with (e.g., copper electrode, initial blue color of copper solution, LED, or electric motor). I treated an occurrence noted in an encounter with the electrochemical cell not only as a particular but also as a contingency if it did not necessarily need to happen (e.g., LED or electric fan working or not, or negative reading on the voltmeter) or if it could vary between groups depending on what they paid attention to (e.g., precipitation of copper on copper electrode or bubbles in the magnesium sulfate solution). I went through the transcripts extensively and marked all encounters which contained particulars and contingencies of the real electrochemical cell, and in which the construed relations, at the same time, connected to any of the generic statements in Garnett and Treagust’s (1992b) list. In that way, I was able to analyze what more went into students’ accounts of a real electrochemical cell than producing generic statements of the accepted scientific knowledge of the topic.

I also examined how curricular materials, present in either a lab work activity containing a real electrochemical cell or a concept mapping activity containing an emerging concept map, entered into students’ reasoning (paper III). Of course, some curricular materials were common to both activities, for instance textbooks and parts of the instructions. But because I was interested in a comparison between these two activities I focused only on the curricular materials characteristic of each activity. I operationalized interactions with curricular materials in either activity as all relations pertaining to interactions with the real electrochemical cell or the physically emerging concept map. An important part of this analysis was the extent to which these materials entered into students’ reasoning separately, or in connection with, the ideas of electrochemistry, respectively. Therefore, I extensively described how students sequentially, and moment-by-moment, construed relations to materials and ideas, and analyzed how one followed on another. In that way, I was able to characterize ways in which students furthered the two activities (lab work and concept mapping) through interacting with either materials or ideas, and through doing this either separately or in coordination. As can be seen, this procedure is equivalent to that concerning students’ ideas as described above (paper III).
Finally, I examined how particulars and contingencies of a real electrochemical cell entered into students’ reasoning if actively introduced to the student (paper IV), rather than being noticed by the students themselves (as was the case in paper II and III). Moreover, I introduced ways of coping with those particulars and contingencies observed to be important for students themselves when they worked in pairs without any help from a teacher (paper II). In other words, I introduced some aspects of previously described practical epistemologies for dealing with certain curricular materials of an activity, in this case a real electrochemical cell, into new school science settings, and examined the consequences for the students’ further reasoning (paper IV). Here, then, was an attempt at transforming detailed analyses of students’ learning processes, within a particular science area, into tools for helping other students experiencing similar situations. Thus, the analysis of paper IV is an investigation both of (a) how students deal with the particulars and contingencies of a real electrochemical cell in another setting (i.e., with a more knowledgeable person instead of a peer), and (b) how detailed analyses of students’ learning processes can be converted into suggestions for action in order to support other students’ reasoning in similar activities.

Ethical considerations

I personally visited all four classes and informed them of the research project. This met the requirement for informed consent (Hermerén, 1996) as I informed the students about the background to the project and the area I was interested in studying. In short, I informed the class that even though we know quite a lot about how students understand school science, we know considerably less about how they go about learning the things they are expected to learn. I also told them that I would like to study this by recording their different ways of coping with a school science activity. Thus, I made it clear I was not interested in what they already knew about electrochemistry, but how their reasoning developed in the course of the activity. I also informed them they would be kept entirely anonymous, even to me; because I would directly substitute any names mentioned in the recordings and would not reveal the name of the school or the teacher. Moreover, I informed them that no one but I would be able to access the original recordings unless, in the future, someone wanted to check my results by returning to the original recordings (Hermerén, 1996, requirements for confidentiality and restricted use). Finally, I made it clear that the results from the study would be published in international journals and in a doctoral thesis. After giving this information, I handed out written forms with similar information as well as contact information, and asked the students to bring them home and show their parents. However, because the students were older than 15 years, I only requested their signature and not their parents’. Before the studies began I
stressed they should feel free to interrupt their participation whenever they wanted; no student did this, however.
Results and discussion

In this section I present a summary of the results of the four studies in four subsections. The first two subsections address the first research question of this thesis: “How do scientific ideas and curricular materials enter into students’ reasoning about a real or idealized electrochemical cell during a school science activity?” The third subsection is an effort to draw together some of the most salient results of the four studies into possible patterns concerning students’ habits of action for coping with the activities. Finally, the fourth subsection addresses the second research question: “What opportunities for learning and teaching school science may be inferred from detailed analyses of how ideas and materials enter into students’ reasoning?”

The results of this thesis are primarily produced through what may be labeled thick descriptions (Geertz, 1973) of student talk and action during the activities. This was accomplished through the use of the practical epistemology analysis which was presented in the theoretical approach section. In other words, I conducted detailed analyses of student talk and action using strictly operationalized analytic concepts, and situated the analyses in the context and purpose of the activity. In paper I – IV these thick descriptions (excerpts and subsequent analyses) are extensively presented to the reader in an effort to provide transparent analyses. The reader may refer to paper I – IV for access to these thick descriptions of the data collected.

How alternative and accepted scientific ideas entered into students’ reasoning

I recorded encounters with three misconceptions (i.e., alternative scientific ideas) of electrochemistry identified in the literature (Garnett & Treagust, 1992a, 1992b; Sanger & Greenbowe, 1997) as students were reasoning about a real electrochemical cell (paper I, Table 1). None of these encounters with misconceptions interfered negatively with students’ subsequent reasoning during the practical. Garnett and Treagust (1992b) predicted that misconceptions of electrochemistry demonstrated in interviews will adversely affect students’ subsequent learning. Other studies have reported that misconceptions previously recorded in interviews are not possible to detect when students are reasoning in other contexts (Jakobsson, Mäkitalo, & Säljö, 2009;
Klaassen & Lijnse, 1996; Schoultz et al., 2001b). My results indicate that students may indeed touch upon such misconceptions even in other settings than clinical interviews (paper I). However, these alternative ideas may have significantly different consequences when set in motion for furthering a more complex and more authentic activity than answering questions during an interview. The misconceptions that the students encountered were either neutral (i.e., lacked observable consequences) or, in fact, generative (i.e., had positive consequences) with respect to the students’ possibilities of furthering the activity (paper I). Smith, diSessa, and Roschelle (1993) and Hammer (1997) presented results indicating that simpler and more primitive aspects of scientific conceptions may constitute resources for students’ as well as experts’ reasoning in physics depending on the context in which they are used. On the basis of their findings, Smith et al. (1993) concluded that the extent to which a certain aspect of a conception will constitute a hindrance or a resource for students’ learning is contingent on the contextual features of the situation.

With the exception of one instance, encounters with alternative ideas entered into students’ reasoning as possibilities or alternatives (the remaining encounter nevertheless constituting a marked resource; paper I). This also means that students readily changed their reasoning in the course of the activity. Many studies have shown students’ alternative ideas to be deeply entrenched, difficult to change through instruction, and stable across contexts (Ioannides & Vosniadou, 2002; Watson et al., 1997; Vosniadou & Ioannides, 1998). Some interview studies, however, support the results presented here, by demonstrating that students’ reasoning may vary considerably both within and across contexts (diSessa et al., 2004; Tytler, 1998; Welzel & Roth, 1998). Moreover, Hogan, Nastasi, and Pressley (1999) found that although middle-school students invoked well-known alternative ideas about the nature of matter during peer discussions, they grappled with these ideas rather than offering them as fixed explanations.

Alternative ideas thus formed part of the practical epistemologies emerging as students furthered the lab work activity. But rather than determining how students coped with situations during the activity they entered as one of several contingencies leading up to a certain line of reasoning (paper I). So the alternative scientific ideas identified in interview situations could be said to appear, not as misconceptions but as potential relationships in the more complex activity of reasoning about a real electrochemical cell. In action, that is when set in motion to accomplish something, the worth of these potential relationships depended on their consequences for students’ further reasoning rather than on their agreement with the accepted science.

Scientific ideas more generally entered into students’ reasoning for furthering both a lab work activity containing a real electrochemical cell and a concept mapping activity about an idealized cell (paper III). Students interacted with ideas both separate from and in coordination with the curricular
materials (i.e., the real electrochemical cell or the physical concept map) which were present in the activity (paper III, Table 2). Several studies demonstrate a weak connection between students’ engagement with scientific ideas and their manipulation of the materials present in school laboratory work (Hofstein & Lunetta, 2004). Although concept mapping is generally considered to readily engage students’ ideas about a certain science area (e.g., Nicoll, Francisco, & Nakhleh, 2001; Odom & Kelly, 2001; Wandersee, 2000), there have been indications that students may not reach the explanatory level even in such conceptually explicit activities (van Boxtel, van der Linden, Roelofs, & Erkens, 2002). The students studied here, however, extensively invoked scientific ideas for furthering the construction of their concept map, and less extensively for furthering the construction and observations of the real electrochemical cell (paper III, Table 3). Possibly, this was due to the fact that both the lab work and the concept mapping activity had explicit assignments for interacting with materials as well as with ideas (cf., paper III, Table 1). Wickman (2004) illustrated how encounters with written instructions influenced the practical epistemologies emerging during a university lab work activity. Abrahams and Millar (2008) showed that explicitly making secondary students aware of the underlying scientific ideas made them engage in these as part of the lab work activity. And explicitly requesting that students engage in explanations made them talk more about multiple kinds of relationships while making a concept map (van Boxtel et al., 2002).

In order to investigate if encounters with misconceptions had different consequences when entering into students’ reasoning during a more theoretical activity (i.e., concept mapping), I analyzed the data collected for paper III in the same way as those of paper I (this analysis is not presented in paper III, however). The analysis indicates a difference between the way encounters with misconceptions entered into students’ reasoning in the lab work activity (which was virtually identical to the activity in paper I) and the concept mapping activity. In the lab work activity I found no instance where an encounter with misconceptions interfered with students’ reasoning, similar to the results from paper I. All eight encounters with misconceptions were either neutral or, in one case, generative of students’ further reasoning. In the concept mapping activity encounters with misconceptions more or less interfered with students’ reasoning six times, whereas they were neutral or constituted resources for students’ reasoning four times (i.e., ten encounters with misconceptions altogether). Thus, students encountered misconceptions equally often in both activities (8 times vs. 10 times). But it seems as if students were more likely to simply construe a certain relation without questioning it or suggest alternatives in the concept mapping activity, rather than construe the potential relationships characteristic of the lab work activity (cf., paper I). This in turn, may partly be due to the fact that actions on the real electrochemical cell had observable consequences that students could
choose to include in their reasoning. The emerging concept map could not as clearly provide such responses, as it were, to students’ actions. Indeed, we should expect the lab work activity to contain a larger number of contingencies to which students may respond and thereby change their reasoning. Thus, it is possible that alternative ideas are less important for how students’ reasoning develops in a more practical activity (such as laboratory work on electrochemical cells) than in a more theoretical one (such as constructing a concept map about an idealized cell).

Taken together, the results indicate that in use and in ongoing activity, the relevance for the learning process of the ideas students come up with is not only a function of their content, that is, whether the ideas are correct or incorrect with respect to the accepted scientific knowledge. The content of the ideas that students expressed at one moment in time during a school science activity with the purpose of reasoning about a natural phenomenon underdetermined what students’ reasoning about that phenomenon looked like at a later moment during the same activity (paper I). Moreover, the consequences of encountering a misconception varied between different types of activities. These results support the contention that the significance of alternative ideas for students’ learning is dependent on the particular contextual features of the situation in which the ideas are drawn on for furthering the activity (Smith et al., 1993; Wong, 1996; paper I). As Smith et. al. (1993, p. 153) remarked, even “simple shifts in application context can turn wrong answers into productive ideas”. This implies that the educational worth of the various ideas students come up with during a science learning activity may depend more on the consequences of the acts to which the ideas lead, rather than on how they match with the accepted scientific ideas (Dewey, 1929/1996, p. 109; Wickman, 2004; Wong & Pugh, 2001).

How curricular materials entered into students’ reasoning

Students interacted extensively with the curricular materials of the activity not only when they were building and observing a real electrochemical cell (paper I, II, and III) but also when they engaged in constructing a concept map about an idealized cell (paper III, Table 2). Although widely acknowledged in school laboratory work (Hofstein & Lunetta, 2004), to my knowledge there are no previous studies showing that students focus extensively on manipulating materials in allegedly more theoretical activities (such as concept mapping; paper III). Indeed, laboratory work has often been considered to present teachers and students with unique problems of handling the messy contingencies of materials and equipment (Hodson, 1993; Kirschner & Huisman, 1998; Nott & Wellington, 1997; Osborne, 1998).
Students invoked the real electrochemical cell but never the physical concept map for furthering their explanations of how an electrochemical cell works (paper III, Table 3). In other words, the curricular materials of the concept mapping activity formed part of the practical epistemologies for building a concept map but never for producing explanations of an idealized electrochemical cell (paper III). The real electrochemical cell, on the other hand, entered into students’ reasoning both as a product to be assembled and as a resource for furthering their explanations of the cell (paper III and cf., paper I). Indeed, students recurrently changed their reasoning during the same activity as a consequence of new encounters with the real electrochemical cell (paper I). Together with encounters with misconceptions, encounters with the curricular materials of the activity thus entered as another, and potentially more important, contingency in students’ reasoning (paper I).

In encounters with the real electrochemical cell students displayed two additional knowledge interests to that of producing correct explanations of how the cell worked (paper II). I labeled these a taxonomic and a measurement (correlational) interest (paper II) and further referred to these actions as either taxonomic or correlational investigations engaged in by the students (paper III and IV). The taxonomic interest (Schwab, 1978) manifested itself as a need to make distinctions as well as to recognize and name both particular parts of the cell and observable products of the reactions taking place (paper II and III). The measurement (correlational) interest (Schwab, 1978) was seen as students engaged in discussions about reasonable interpretations of measurements and correlations applying to their cell (paper II). Students needed to fill the gaps concerning these two knowledge interests in order to make the encounters with the particulars and contingencies of their real electrochemical cell continuous with the content of the generic knowledge statements which Garnett and Treagust (1992b; paper II, Table 1) considered necessary to explain an electrochemical cell.

The results confirm the importance of learning discursive norms for what counts as science, and what does not count as such, within a certain community of practice (Bergqvist & Säljö, 1994; Goodwin, 1993; Kelly & Crawford, 1997; Lidar et al., 2006); in that the students needed to decide on the relevancy of distinctions, observations, and measurements for the purpose of providing a scientific account of their cell (paper II). At the same time, the results show that students made some of the contingencies of the actual practice relevant parts of the practical epistemologies emerging in order to provide an account of the electrochemical cell, irrespective of whether an expert would count that particular contingency as a relevant part of the account or not (paper II). For example, bubbles and a precipitation in the magnesium half cell, and possible correlations between voltage and time, became important parts of students’ reasoning (paper II). Students thereby extended what goes into a scientific account of a certain electrochemical cell by including
some of the particulars and contingencies of the situation in their account (cf., Kelly et al., 2000).

It may be significant that the particulars and contingencies of the lab work activity constituted such a salient and important part of students’ learning even though the instructions were characterized by a low level (0 – 1) of openness and fell into an expository or discovery approach to instruction (cf., Gyllenpalm et al., in press; Herron, 1971). It is reasonable to assume that a more open-ended task, for instance one in which the methods for setting up the cell were not given, would lead to an even more pronounced need for students to learn relevant ways of coping with various contingencies for furthering the activity. It is commonly assumed that closed, cook-book style laboratory instructions are not conducive to students’ possibilities of engaging in meaningful learning. For instance, Domin (1999, p. 544) claimed that in these types of activities students are not given opportunity to “integrate new experiences with prior knowledge, establish a context for the purpose of the laboratory activity, and determine the activity’s relevance to themselves”. However, these points seem to be precisely the types of things that students in this study were engaged in, through the taxonomic and measurement interests they displayed. So, despite the many givens present in the lab work instructions, students still needed to engage in a type of open-ended process of generalization in action, in which they expanded their repertoire of talking and acting in encounters with particular and contingent aspects of the real world (cf., Halliday, 1993; Wells, 2008; Wickman & Östman, 2002a).

The practical epistemologies for dealing with the particulars and contingencies of a real electrochemical cell described in paper II (i.e., making taxonomic and correlational investigations) were important also when introduced to single students in conversations with the researcher (paper IV). The students included certain distinctions in their subsequent explanations, and excluded others, as a consequence of making taxonomic and/or correlational investigations (paper IV, Table 1). Likewise, they included some of the correlations in extended accounts of their cell (paper IV, Table 1) much like in paper II. Another consequence of making taxonomic investigations was that students learned to make new connections between the macroscopic and submicroscopic levels of chemical representation (paper IV, Table 1). Treagust, Chittleborough, and Mamiala (2003) demonstrated that the ability to move between the different levels of chemical representation was a significant factor for students’ possibilities of making use of explanations in chemistry. The authors suggested that instruction should allow students the opportunity to explicitly discuss these relationships (Treagust et al., 2003). My results indicate there are also more indirect ways in which students can begin to learn to make some of these connections.

These results (paper IV) are intriguing because students were able to modify or extend their explanations by being directed towards particular and
contingent aspects of their real electrochemical cell, rather than by focusing more closely on the conceptual content of their attempted explanations. In other words, there was no direct relationship between the content of a particular line of student reasoning about a scientific phenomenon and the content of the learning needed to subsequently expand or change that reasoning (paper IV). In a recent review, Scott et. al. (2007) recommended a closer analysis of the various learning demands – conceptual, epistemological, or ontological – tied to particular concepts that are known to be difficult for students (e.g., the concept of energy). My results (paper II and IV) indicate that this recommendation may need to be extended beyond such an analysis of certain scientific concepts, to include also difficulties with setting the concepts in motion (i.e., make the concepts do work) as students deal with whole situations involving, among other things, the particulars and contingencies of the curricular materials present.

When students engaged in interactions with the curricular materials of the lab work or concept mapping activity, taxonomic investigations – in the general sense of agreeing on the use of words (i.e., make distinctions and name things) – helped further the activities by linking up with the relevant chemistry to be learned (paper III). Moreover, in both activities students often needed to orient themselves in the conditions and rules for the activities (paper III). As Schwab (1978) pointed out, every science requires a taxonomy specifying how to divide and name the world for its particular purposes. Taxonomic science thus constitutes a basis for other types of scientific work, such as that of creating relational systems of increasing explanatory power (Schwab, 1978). In light of this it is quite reasonable, although rarely emphasized, that students need to come to terms with a variety of taxonomic issues as exemplified primarily in paper II; and that these investigations have consequences for students’ possibilities of furthering the activity of providing a scientific account of a real or idealized electrochemical cell (paper II, III, and IV). Other studies confirm that students need to deal with many aspects of a learning experience beyond material evidence or theoretical explanations in order to learn how to go on with the activity (Ekström, Lindwall, & Säljö, 2009; Lindwall & Lymer, 2008; Wickman, 2004; Wickman & Östman, 2002b).

Habits of action

In summary, the results indicate some regularities which are indicative of possible habits of action for coping with scientific ideas and curricular materials in two different school science activities. (1) Students regularly engaged in, rather than ignored, the particulars and contingencies of the curricular materials which formed part of the activity (paper I, II, III, and IV). Particularly in lab work, this habit seems to have led to their reasoning being fluid.
and dependent on the contingencies of the situation rather than fixed and
dependent on alternative ideas (paper I). Accordingly, (2) students displayed
habits of construing potential relationships rather than expressing entrenched
misconceptions in encounters with the real electrochemical cell (paper I). (3)
Students regularly engaged in interacting with curricular materials without
coordinating these actions with the relevant scientific ideas in both the lab
work and the concept mapping activities (paper III). (4) Students habitually
neglected to use the physical product resulting from the concept mapping
activity (i.e., the concept map) to further the activity (paper III). That is, they
did not make use of the links they had already established between electro-
chemistry terms in the emerging concept map as resources for their further
reasoning during the activity. However, (5) students displayed a distinctive
habit of invoking taxonomic investigations for coping with the particulars
and contingencies of the curricular materials of the activities (paper II, III,
and IV). Through this habit, students managed to connect the particulars and
contingencies of the curricular materials that were present in the activity to
the general knowledge of electrochemistry (paper II and III).

Hypotheses of how to support students’ science learning

The purpose of this thesis was to (a) make detailed descriptions and analyses
of students’ moment-by-moment learning of school science content, particu-
larly with respect to how they interact with ideas and materials present in the
activities, and (b) use the results about students’ idiosyncratic ways of cop-
ing with a school science activity to suggest tentative hypotheses over how
to support their learning. The results in this thesis have a number of possible
consequences for teachers’ interactions with students in the science class-
room. Below I use the main findings of the thesis to suggest tentative hy-
potheses about what a teacher may need to consider in order to help students
further an activity with the purpose of learning school science content. The
hypotheses are framed as possible consequences for students’ learning from
a teacher taking certain actions to attain particular purposes in the science
classroom. Therefore, they constitute a type of generalization over the results
of this thesis. Yet, the hypotheses should be considered in the prospective
sense of the word, as suggestions about possible connections having been
inferred from detailed descriptions and analyses of a particular study system.
The justification for producing these hypotheses is to frame the empirical
results of this thesis, limited as they are to a certain study system and to par-
ticular settings, in such an explicit way that their relevance for teaching and
learning school science may be clearly and directly tested in new studies.

My results (especially paper I, II, and IV) suggest that students’ learning
in science may be characterized as an ongoing achievement, emerging out of
interactions between different contingencies of learning situations and in
relation to the particular purposes of the activity; something which has also been pointed out by other authors to various degrees (Gee & Green, 1998; Hwang & Roth, 2007; Kelly et al., 2000; Wickman, 2004; Wickman & Östman, 2002a). Thus, a teacher may consider making use of these contingencies to achieve different purposes related to supporting students’ learning of school science content.

A teacher could take the contingency of students’ reasoning into account by using encounters with both alternative ideas and the particular features of materials present in the activity, as a means for achieving the objective of learning a correct scientific explanation. Encounters with misconceptions during the learning activity sometimes had productive consequences for students’ further reasoning (paper I). And actively directing attention, not towards more refined theoretical explanations but towards taxonomic or correlational investigations in encounters with the curricular materials of the activity, sometimes had consequences for students’ possibilities of giving a more correct scientific explanation of the natural phenomenon in question (paper IV). The teacher could thus consider what students are saying at a particular moment during the activity, not primarily as reports of their cognitive states but as contributions made by the students in order to further the activity for a particular purpose.

The activities studied in this thesis all fell within the correct-explanations curriculum emphasis (sensu Roberts, 1994). In other words, the students’ reasoning was part of an activity with the purpose of arriving at the correct explanation for how an electrochemical cell works. Yet, I analyzed their reasoning in terms of how it contributed to how students were able to cope with this activity, and not in terms of whether their reasoning reflected knowledge of the correct explanation. What students were saying in the encounters at particular moments during the activity either contributed to or restricted the activity of producing such explanations (paper I, II, and III). Accordingly, instead of acting on the content of such encounters per se, the teacher may consider possible consequences of the encounters for achieving a certain purpose. Some authors have suggested that teachers consider students’ partial and contingently emerging conceptions as possible resources for learning physics depending on the learning situation as a whole (diSessa, 2006; Hammer, 2000). Other authors have pointed to the importance of acknowledging aspects of classroom situations other than purely conceptual ones for the promotion of conceptual learning in science. For instance, it has been suggested that both aesthetic experiences and metaphors, emerging in response to the contingencies of a learning situation, may be actively used by teachers to support conceptual learning in primary school children as well as university students (Jakobson & Wickman, 2007a, 2007b; Wickman, 2006).

In addition to using the contingency of students’ reasoning as a means for supporting their learning, a teacher could encourage students to freely include the particulars and contingencies of encounters with curricular materi-
als in their reasoning as an end in itself. After all, students spontaneously displayed an interest to address not only conceptual issues but also issues concerning the particulars and contingencies of the real electrochemical cell as they strived to provide a scientific account of it (paper II and IV). Allowing encounters which students themselves perceive as important to become valued parts of their own reasoning may thus render the school science experience more meaningful from the students’ point of view; irrespective of its perceived relevance from the teacher’s point of view or from that of the correct scientific explanation. Some previous studies have presented results which may support this idea. For instance, Jakobson and Wickman (2007b) demonstrated how primary children’s spontaneous metaphors during a science activity enlivened and humanized the subject and thus helped the children make their school science experiences continuous with their out-of-school experiences. Lundegård and Wickman (2007) demonstrated the importance of attending to value judgments as a prerequisite for attending to facts in education for sustainable development. Also, Wickman (2006) demonstrated how university students’ aesthetic judgments during a science activity made their experiences more significant, thereby furthering the activity.

Furthermore, the teacher could use knowledge of which contingencies of a learning experience are relevant from the students’ point of view (paper II), in order to continuously extend or revise the content of the regular school science account of the phenomenon in question. This would be a matter of supplementing the theoretical analysis of the content to be taught (Lijnse, 2000; Scott et al., 2007; Tiberghien, 2000) by deciding what content should be included also on empirical grounds. Moreover, it would amount to an analysis of the school science content that rested not only on the generic properties of scientific concepts of a science topic, but also on how this knowledge is used in action and in relation to particulars and contingencies of real practice. In fact, Aikenhead (2000) asserted that there is always a potential for the teacher and students to renegotiate what counts as science in school. However, even though decisions of content may have a number of different rationales (Fensham, 2000), they have not included students’ own contingent choices of such content.

Yet, because students’ reasoning in science can be described as a contingently developing achievement, the separation between means and ends is analytic rather than ontological. Consequently, using a certain contingency as a means for helping students modify their explanation will constitute, in effect, a qualitatively different experience from helping them arrive at the explanation by some other means. So it is not simply a question of which means is most effective for achieving the same end (e.g., either directing the student’s attention towards a taxonomic investigation involving the curricular materials of the activity (cf., paper IV) or providing the conceptually relevant support), but rather what parts of the entire situation are important
for making the learning experience more significant (cf., Wickman & Östman, 2002b).

On the other hand, making the encounter with, and subsequent reasoning about, a certain particular or contingency an end in itself is dependent on the ultimate purpose of the activity. In the activities studied in this thesis the purpose was for students to provide a scientifically correct account of a real or an idealized electrochemical cell. In order to make that account meaningful, however, students may sometimes need to be encouraged to include certain contingencies for their own sake, rather than learn to exclude them.

Finally, students sometimes had difficulties coping with the particulars and contingencies of curricular materials without assistance from the teacher (paper II and III). Thus, a teacher may consider helping students learn appropriate ways of coping with the particulars and contingencies of the materials present, in order to further practical as well as more theoretical school science activities. Other authors have demonstrated the central role of the teacher in helping students learn discursive ways of acting and perceiving within a certain school science practice (Kelly et al., 2000; Kelly & Crawford, 1997; Lidar et al., 2006; Säljö & Bergqvist, 1993). However, these considerations have been limited to practical work in school science.

In summary, the results from this thesis suggest that the contingency of students’ reasoning during a school science activity may be productively dealt with by either (a) harnessing the contingent aspects of encounters with alternative ideas and curricular materials for the purpose of helping students arrive at the correct explanations; (b) allowing the contingencies of encounters with curricular materials to become valued parts of the scientific account; or (c) helping students learn which contingencies are relevant and which are not within the scientific practice in question. Hypothesis (c) has been identified in several studies, both as a necessary aspect of learning science and as a regular move that teachers make in their interactions with students (Kelly & Crawford, 1997; Lidar et al., 2006; Säljö & Bergqvist, 1993). Hypothesis (a) has been indicated in the literature as far as alternative ideas are concerned (Hammer, 2000; Smith et al., 1993). For materials present in a school science activity, Nott and Wellington (1995) suggested that contingencies leading to teacher demonstrations “going wrong”, as it were, may be used as resources for learning about the nature of science. In this thesis, I further suggest that encounters with messy and problematic contingencies of the real world may actually constitute resources also for arriving at the correct explanation of the phenomena in question. Finally, hypothesis (b) seems to be lacking in the literature. Using detailed analyses of students’ own moment-by-moment choices of what to include in their accounts of scientific phenomena as hints to what should be included in the school science account seems to be a new idea generated from the results of this thesis.

In a general sense, Kelly (2004) argued that ethnographic and sociolinguistic studies of the discourse processes of science classrooms provide us
with resources of demystifying school science and of broadening our notion of what counts as science. At the same time he warned against interpreting such empirical and descriptive studies normatively. To be sure, descriptions of “how things are” in the classroom cannot unreservedly be taken as grounds for deciding “how things ought to be” (Biesta, 2007). On the other hand, Schofield (1990/2007) suggested that one aspect of generalizing from qualitative educational research may be to combine descriptions of “what is” with analyses of and suggestions for “what could be”. Thus, detailed empirical studies of “how things are” as students themselves engage in making sense of a school science activity may be one way for students to have a say over how to frame a school science activity and its content. In other words, such studies may allow empirical data to be represented in the discussion of what to include as canonical school science, as a complement to theoretical and normative considerations made by policy makers, researchers, and teachers. Brown et al. (1989) noted that schooling tends to disregard students’ own inventive heuristics for solving problems in the classroom. As suggested in this thesis, the influence of students’ own ways of coping with a school science activity may be accomplished both (a) in the moment-by-moment development of the curriculum during a lesson and (b) by later reflection by teachers or researchers (as in this thesis) over what content some students chose to include, as they were in the middle of furthering a particular school science activity.
Concluding remarks

Taken together, the results from this thesis indicate that it may be productive to subject to renewed empirical scrutiny some of the tenets constituting hard core assumptions of the still dominant constructivist research program in science education; for example the tenets that models of learners’ conceptual structures meaningfully explain their difficulties of learning science, that students’ existing ideas play a primary part in science learning, and that effective science teaching, therefore, first of all needs to take learners’ existing ideas and understanding of concepts into account (Erickson, 2000; Taber, 2006). Here, I investigated in close detail how some previous and generally accepted results in science education applied when students’ learning processes were described and analyzed in action, as students engaged in relevant school science activities. Specifically, I asked what role alternative and accepted scientific ideas, as well as the particular features of certain curricular materials, have in the learning process. On the basis of detailed analyses of the practical epistemologies emerging in the course of students’ reasoning, the thesis makes some anomalous, and perhaps even counterintuitive, claims concerning how these parts of school science activities enter into students’ science learning processes.

1. Alternative ideas need not constitute hindrances to, and may sometimes be productive for, students’ learning in science (paper I).
2. Students extensively deal with particular and contingent features of the curricular materials of a science learning activity, through taxonomic and measurement (correlational) investigations, which connect these particulars to the generic knowledge of the topic (paper II and III).
3. The particular and contingent features of the curricular materials of a learning activity which students choose to include in their reasoning (i.e., the taxonomic and measurement interests that students display) thus constitute potentially significant parts of the scientific accounts that students are expected to learn (paper II and IV).
4. Students’ idiosyncratic practices for coping with the curricular materials of a learning situation can be used as potential tools for teaching (paper IV).

It is possible that previous studies of, for instance, students’ reasoning about electrochemical cells during interviews, have made unwarranted assump-
tions about the extent to which the results will apply to other settings as well. The hypotheses that I suggest, on the basis of the results of this study, should not be interpreted as assuming this type of generalization to other settings. Learning operationalized as a continuous change of experience implies that subsequent learning is potentially contingent on all those elements which make up both previous experiences and present ones (Wickman, 2006). As indicated by the results of this thesis, what types of consequences these different elements have for how the experience changes is an empirical question. It is some of these contingencies of science learning – specifically how students deal with alternative ideas and the particulars of curricular materials – whose consequences I have described and converted into tentative hypotheses for teaching. These hypotheses are of little use if they are taken as generalizations in the retrospective sense of summarizing results already obtained. Their primary justification for science education lies in suggesting and delineating, in more detail, paths for future studies, in which the results of this thesis may be tried out in new, different, and more authentic school science settings. Surely, there will never be a formula to predict which particular action a teacher should take in a particular situation (Lidar et al., 2006; Wickman, 2004). But results such as those of this thesis may help teachers become sensitive to a wider range of opportunities for teaching which may arise in encounters with different features of a classroom activity. In the end, the reason why a teacher is always needed as a partner to help students learn science, and the reason why efforts to reduce pedagogical noise and other potential distractions are futile or even unfortunate, may well be that there are always some new, contingently emerging, and potentially relevant elements in every new situation, and in the course of even the most carefully planned school science activity.
References


Svensk sammanfattning

Enskildheter och tillfälligheter i gymnasieelevers resonemang om galvaniska element – Möjligheter för lärande och undervisning i naturvetenskap


Tidigare forskning om lärande i naturvetenskap

Det finns en omfattande konstruktivistisk forskning om elevers förståelse av naturvetenskapens fenomen, begrepp och teorier. Denna forskning visar att elever, i intervjuer och skriftliga test, ofta uppvisar alternativa idéer om hur världen fungerar, d v s idéer som inte stämmer med de naturvetenskapliga förklaringarna. När eleverna intervjuas igen efter att ha fått undervisning, fortsätter många ändå att uppvisa samma idéer som tidigare. Utifrån sådana intervjustudier har den konstruktivistiska forskningen dragit slutsatser om vilka svårigheter elever har när de försöker lära sig naturvetenskap i klassrummet. En slutsats från denna forskning är att elevernas alternativa idéer utgör avgörande hinder för deras möjligheter att lära sig skolans naturvetenskap. En annan slutsats är att undervisningen i första hand bör inriktas på att identifiera och förändra elevernas alternativa idéer, för att på så sätt få eleverna att resonera i enlighet med de accepterade naturvetenskapliga förklaringarna.

Att studera lärande i handling
Vanligen har frågor om hur elever gör för att lära sig naturvetenskap undersökt genom att beskriva deras handlingar i klassrummet. Detsamma gäller studier av hur lärare gör för att hjälpa elever att lära sig naturvetenskap under en aktivitet. Vad eleverna lär sig under dessa aktiviteter har däremot studerats genom att placera eleverna i helt andra aktiviteter, såsom intervjuer eller skriftliga test. Lärandet har med andra ord oftast studerats indirekt, efter att undervisningen har upphört. Den här uppdelningen mellan hur elever och lärare handlar i klassrummet å ena sidan, och vad elever lär sig å den andra, gör att vi i själva verket vet ganska lite om vilken roll naturvetenskapliga idéer, liksom det undervisningsmateriel eleverna möter, spelar för hur deras resonemang utvecklas under en klassrumsaktivitet. Det är också glest med studier som kan peka på samband mellan särskilda aspekter av en klassrumsaktivitet och elevers lärande av ett visst innehåll.

I den här avhandlingen studerade jag elevernas lärande i handling, dvs medan det pågick i klassrummet. Jag studerade alltså både vad eleverna lärde sig, och hur de gjorde för att lära sig, medan de faktiskt var engagerade i en naturvetenskaplig klassrumsaktivitet. Jag gjorde detta genom att beskrIVA och analysera hur deras resonemang utvecklades under aktiviteten, framför allt i möten med alternativa och accepterade naturvetenskapliga idéer samt undervisningsmaterialet.

Betydelsen av alternativa idéer för elevernas resonemang
frågor, och eleverna ändrade sina resonemang upprepade gånger under aktiviteten. I enstaka fall utgjorde möten med alternativa idéer till och med resurser snarare än hinder för deras fortsatta resonemang. Resultaten motsäger därmed de förutsägelser om hur alternativa idéer inverkar på elevers lärande som gjorts utifrån intervjustudier. Men när jag gjorde motsvarande analys på elevernas resonemang medan de konstruerade en begreppskarta, visade det sig att möten med alternativa idéer i något större utsträckning utgjorde hinder för lärandet (data från paper III, men inte redovisade där).

De här resultaten tyder på att betydelsen av alternativa idéer för elevers lärande kan bero på i vilka situationer de blir aktuella som delar av elevernas resonemang. Hur möten med alternativa idéer inverkar på elevernas fortsatta lärande verkar inte enbart bero på i vilken utsträckning idéerna överensstämmer med accepterad naturvetenskap, utan också på vilka konsekvenser de får i aktiviteten. Dessa konsekvenser kan uppenbarligen variera mellan till exempel en laboration och en mer teoretisk aktivitet, som att t ex bygga en begreppskarta.

**Betydelsen av enskildheter och tillfälligheter för elevernas resonemang**

Utifrån samma empiriska material undersökte jag på motsvarande sätt vilken betydelse möten med det riktiga galvaniska elementet fick för elevernas resonemang (paper I och II). I dessa möten blev en mängd enskildheter och tillfälligheter som rörde det galvaniska elementet aktuella för eleverna. Exempel på enskildheter är att just detta element innehöll koppar- och magnesiumelektroder, eller att det bildades bubblor och en fällning i magnesiumsulfaten. Exempel på tillfälligheter är att elmotorn ibland inte snurrade eller att lysdioden ibland inte lyste, liksom att eleverna uppmätte negativ eller avtagande spänning i elementet.


För att kunna resonera om det galvaniska elementet behövde eleverna således inte bara lära sig naturvetenskapliga begrepp och idéer, utan även att göra distinktioner och mätningar rörande elementet. I vissa fall verkar det som om eleverna främst behövde lära sig vilka enskildheter och tillfälligheter som var relevanta, och vilka som kunde uteslutas, i ett naturvetenskapligt
resonemang om hur ett galvaniskt element kan generera ström. Men i andra fall är det tydligt att det fanns aspekter i mötena med elementet som en erfaren läraware eller kemist skulle betrakta som irrelevanta, men som ändå utgjorde viktiga delar av elevernas naturvetenskapliga resonemang. Utan dessa enskildheter och tillfälligheter, som eleverna alltså spontant inkluderade i sina resonemang, är det möjligt att resonemangen skulle blivit mindre relevanta och mindre intressanta för dem. Dessa resultat möjliggör för lärare och beslutsfattare att reflektera över vad som utgör viktiga delar av ett naturvetenskapligt innehåll, inte enbart utifrån vad som är accepterad naturvetenskaplig kunskap utan även utifrån vilka delar av en lärandesituation som blir väsentliga för eleverna själva, medan de faktiskt engagerar sig i detta lärande.

**Lärande i två olika aktiviteter**

Jag jämförde också fyra par elever som arbetade med en laboration om galvaniska element med fyra par som arbetade med att bygga en begreppskarta utifrån en teckning av samma element (paper III). Syftet med studien var att undersöka på vilka sätt, och i vilken utsträckning, elever interagerar med naturvetenskapliga idéer och det särskilda undervisningsmaterialet i praktiskt (laborationen) och mer teoretiskt (begreppskarteövningen) inriktade aktiviteter. Här visar mina resultat att eleverna i båda aktiviteterna främst ägnade sig åt elementet eller begreppskarten utan att göra direkta kopplingar till naturvetenskapliga idéer. Att elever inte kopplar samman undervisningsmaterialet med de naturvetenskapliga idéerna tycks således inte bara vara ett fenomen som är begränsat till praktiskt arbete i laborationer. Mina resultat visar att även en mer teoretisk uppgift kan innebära att elever i första hand ägnar sig åt andra delar av aktiviteten än de naturvetenskapliga idéerna.


Det är därför möjligt att betrakta olika naturvetenskapliga aktiviteter i skolan som komplementära, när det gäller hur elever lär sig att interagera med naturvetenskapliga idéer och med det undervisningsmaterial som förekommer. Resultaten tyder på att man bör vara försiktig med att anta vilka möjligheter och problem för lärande som en viss aktivitet erbjuder enbart med utgångspunkt från dess form. Detaljerade studier som denna, där elevernas interaktioner med olika delar av en aktivitet analyseras tillsammans med deras lärande medan verksamheten faktiskt pågår, behövs för att mer i
Fokus på enskildheter och tillfälligheter

Resultaten från mina två första studier (paper I och II) antydde att de enskilda detaljerna och de tillfälliga inslagen i elevernas möten med det galvaniska elementet är viktiga för lärandet. Möten med alternativa idéer var däremot inte automatiskt avgörande för vad eleverna lärde sig, särskilt inte i laborationen. Vidare hade jag beskrivit två sätt, utöver att ta till generella kunskaper i elektrokemi, som eleverna använde för att resonera om sitt galvaniska element, nämligen taxonomiska utredningar samt utredningar om mätningar och korrelationer i elementet. I min sista studie (paper IV) undersökte jag därför vilka konsekvenser det fick för enskilda elevers resonemang kring ett galvaniskt element, om jag i samtal med dem (a) riktade deras uppmärksamhet mer mot enskildheter och tillfälligheter i elementet än mot de generella naturvetenskapliga förklaringarna, samt om jag (b) riktade deras uppmärksamhet mer mot utredningar om taxonomi och korrelationer i elementet än mot mer begreppsliga utredningar.

Jag fann tre olika typer av konsekvenser för elevernas resonemang. Utredningarna fick konsekvenser för elevernas möjligheter att (1) förklara hur elementet fungerar, (2) göra kopplingar mellan olika beskrivningsnivåer i kemi (t ex mellan makroskopiska och submikroskopiska beskrivningar) samt (3) uppfatta vad som skedde i elementet. Det verkar som om elevers svårigheter med att förklara ett naturvetenskapligt fenomen inte alltid, eller enbart, beror på svårigheter med de begrepp och idéer som ingår i dessa förklaringar. Mina resultat visar att elever kan utveckla sina förklaringar av galvaniska element även genom att göra utredningar som inte är direkt kopplade till dessa förklaringar. På ett mer allmänt plan tyder studien på att det kan vara möjligt för en lärare att använda sig av analyser av hur vissa elever går tillväga för att lära sig ett naturvetenskapligt innehåll, som en möjlig grund för interaktioner med andra elever.

Tre hypoteser för att stödja lärande i skolans naturvetenskap

Utifrån resultaten av de fyra studierna (paper I – IV) formulerade jag tre hypoteser om hur lärare kan stödja elevers lärande i naturvetenskap. Hypoteserna är relaterade till det viktigaste resultatet i avhandlingen, nämligen att enskildheter och tillfälligheter spelade en väsentlig roll i elevernas resonemang om galvaniska element. Jag föreslår därför att lärare i naturvetenskap kan ta hänsyn till detta i sina interaktioner med elever i klassrummet, genom att (1) använda enskildheter och tillfälligheter som medel för att hjälpa elever att lära sig förklara fenomen mer naturvetenskapligt, (2) använda enskildheter och tillfälligheter som mål i sig själva, d v s låta dem inkluderas som relevanta delar av elevernas resonemang, samt (3) lära eleverna att handskas kompetent med enskildheter och tillfälligheter i olika situationer.
Dessa hypoteser är inte generaliseringar i den bemärkelsen att de uttrycker mönster som gäller allmänt för elevers lärande i naturvetenskap. Istället utgör de formuleringar av möjliga konsekvenser för elevers lärande av att lära sig formulera möjliga konsekvenser för elevers lärande av att lära sig med elever på specifika sätt i olika naturvetenskapliga klassrumsaktiviteter. Som sådana utgör de förslag till nya studier, där dessa konsekvenser kan undersökas inom andra ämnesområden i skolans naturvetenskap, liksom i andra undervisningssammanhang (t ex helklass).

Avslutning
Sammantaget pekar resultaten i den här avhandlingen på hur de enskildheter och tillfälligheter som blir aktuella i en aktivitet, på olika sätt utgör väsentliga delar av elevers resonemang i skolans naturvetenskap. Generella beskrivningar av hur elever resonerar om ett naturvetenskapligt fenomen i intervju-situationer, utgör inte tillräckligt underlag för att förstå vilka problem eleverna behöver lösa medan de är i färd med att lära sig ett naturvetenskapligt innehåll i klassrummet. Inte heller är det tillräckligt att eleverna lär sig de accepterade naturvetenskapliga idéerna för att de ska kunna responera kompetent i olika situationer. För att mer allsidigt beskriva lärandet i klassrummet behöver vi ta hänsyn även till de enskildheter och tillfälligheter som eleverna möter i en situation. Eleverna behöver också lära sig att handskas med dessa enskildheter och tillfälligheter, antingen genom att se hur de faktiskt kan inkluderas i ett naturvetenskapligt resonemang, eller genom att se vilka delar som är relevanta att inkludera eller utesluta ur en naturvetenskaplig synvinkel. Slutligen är det inte självklart att lärare i naturvetenskap i första hand ska identifiera och förändra elevernas alternativa idéer. Vid sidan av dessa idéer spelar enskildheter och tillfälligheter en viktig roll i elevers resonemang, och utgör därmed kompletterande och potentiellt produktiva resurser som en lärare kan använda för att stödja elevers lärande i naturvetenskap.

Tack P-O och Leena för värdefulla synpunkter på den här sammanfattningen.