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Sensemaking in chemistry at upper secondary school

Ylva Hamnell-Pamment

Lund Studies in Educational Sciences 20

Lund Studies in Educational Sciences

This is a thesis about how students at upper secondary school in Sweden attempt to make sense of chemistry, and how chemistry teachers can help with student sensemaking. Learning and making sense of chemistry has long been known to be problematic for students, which is a large concern for educators, especially as many problems with making sense of chemistry persist for students at university level and beyond.

In the thesis, Ylva Hamnell-Pamment reformulates current theories about chemistry learning in order to provide a theoretical lens through which to connect teacher–student interaction with sensemaking and chemistry learning. In four articles, she studies how students and teachers at five schools in Sweden make sense of chemistry phenomena. With the aim to increase knowledge about how students make sense of chemistry phenomena at upper secondary school, and how teachers can help them learn, Ylva Hamnell-Pamment shows the importance of student language use, student previous achievement level, and teacher guidance and support.

Ylva Hamnell-Pamment is an upper secondary school teacher in chemistry and biology with a licentiate degree in biochemical toxicology. She currently teaches about learning in science at PLUS, the Lund University Faculty of Science pedagogical unit, and at the Supplementary Teacher Education programme at the Department of Educational Sciences, Lund University.

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SENSEMAKING IN CHEMISTRY AT UPPER SECONDARY SCHOOL

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PREFACE

I could not have finished this thesis without the support of many people. Thank you to all the teachers and students who allowed me access to their classrooms and learning journeys. I would also like to thank the Faculty of Science for funding my PhD project.

Thank you, Roger, for your endless support and confidence in me, and for always helping me find a way forward through the ups and downs. To Susanne, thank you for all your support as a supervisor, and especially for always having time to read my texts and help me with my writing. I thank Marie and Sophie at the Chemistry Department for their support across the science–humanities boundary, always reminding me to think of the audience for my articles. Finally, I would like to thank Vesa for patiently (and enthusiastically!) helping me make sense of conversation analysis.

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There have been many PhD students whom I have shared a journey with, but some of them have been by my side throughout. Tina, you have been an amazing friend and colleague, thank you for always being there. Helena, thank you for your endless support in helping me solve problems, big and small. Emil, thank you for all the conversations and the good laughs, I have learnt so much about both humanities and ethics from you. Jonatan, thank you for asking the difficult questions and opening up for new perspectives. Paul, thank you for the cheerful company during both days and evenings. Colin, thank you for always sharing your boundless enthusiasm. Lee, thank you for nice conversations, support during hard times and for helping me and the girls find an apartment in Lund.

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I am very grateful to the friends that have given me companionship and encouragement throughout my life, and especially Björn and Margré Edholm for your never-ending support during the 30 years we have known each other.

To my sister Carin … thank you for all your support and all the long conversations about both big and small things in life. Mum and dad, I miss you and think of you with love.

Dearest Christoffer, thank you for always being there for me, you enrich my life in so many ways.

Finally, I would like to thank my daughters, Audrey and Katie, for filling my life with happiness and meaning, knowing you has taught me so much and I dedicate this thesis to you.

Lund, September 2023

To Audrey and Katie

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Paper II

Hamnell-Pamment, Y. (2023). Scientific language use and sensemaking in concept maps: Interaction between concept systems, scientific concepts and everyday concepts. *Knowledge Management & E-Learning*, 15, 448–467. https://doi.org/10.34105/j.kmel.2023.15.026

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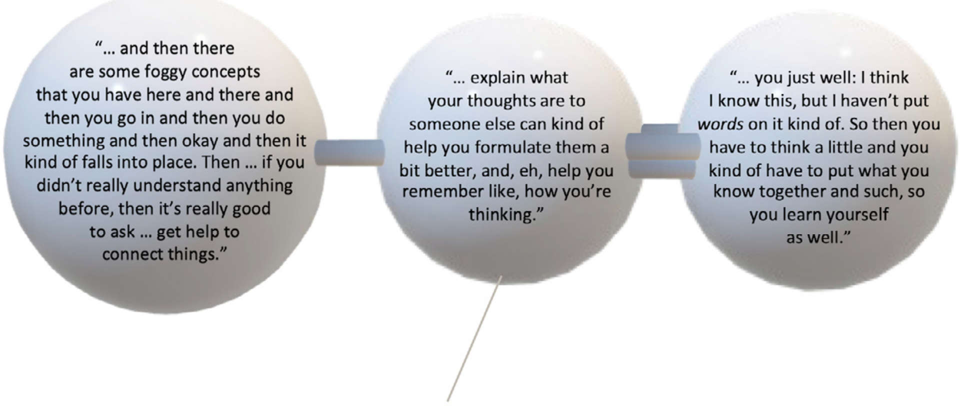
Hamnell-Pamment, Y. (2023). *Making sense of chemical equilibrium: Productive teacher–student dialogues as a balancing act between sensemaking and managing tension* [Revised manuscript submitted for publication]. Department of Educational Sciences, Lund University.



"… and then there are some foggy concepts that you have here and there and then you go in and then you do something and then okay and then it kind of falls into place. Then … if you didn't really understand anything before, then it's really good to ask … get help to connect things."

"… explain what your thoughts are to someone else can kind of help you formulate them a bit better, and, eh, help you remember like, how you're thinking."

"… you just well: I think I know this, but I haven't put *words* on it kind of. So then you have to think a little and you kind of have to put what you know together and such, so you learn yourself as well."

(The solution is colourless, but it is not water. A molecule that can cause consternation for students studying shift in chemical equilibrium.)

1 INTRODUCTION

This thesis contains an ethnographic aspect; namely, the researcher as an interpreter of data collected from different chemistry teaching and learning contexts. These contexts carry inherent meaning to the participating actors and to those whose background helps them understand what is being talked about and acted upon. Because of this, reflexivity – that is, who the researcher is and the researcher's position in relation to the research – becomes important for understanding both the focus of the research and how the data is interpreted (Cohen et al., 2018, pp. 302–303). Students' thoughts on learning in the laboratory, such as those shown above (quotes from focus groups conducted for the thesis, unpublished data), can be interpreted differently by different researchers from different backgrounds. What for me (the researcher) illustrates the fascinating process of sensemaking in chemistry might illustrate something else for someone with a different background, focus and life experience. Therefore, I will begin this thesis by introducing myself, my background and my motivations for the thesis.

Throughout the text I will sometimes write in the first person because, although I take an interpretative stance, science education research is a research field with cultural norms stemming from the science field, and the researcher-as-person is normally absent in publications in the field. The shift in language use between the first person and the objective observer reflects the fact that the thesis is situated on the threshold between the humanities and science traditions.

1.1 My motivations for this PhD thesis

I first became fascinated with chemistry learning at Stockholm University, where I was part of a research group focused on protein folding equilibria between 2007 and 2012. In 2009, I taught at a 10-week biochemistry course to molecular biologists, for the second time. I had grown tired of the endless stream of lab report returns the previous year (approximately seven returns per student) and the ineffectiveness of the laboratory lectures that we held in terms of helping the students understand basic concepts necessary to interpret their data. In 2009, to prepare, I spent a lot of time trying to help the students based on literature in chemistry education that I found during my courses in university pedagogy for the natural sciences. I organised their studies through the use of preparatory exercises with explicit page referencing for reading in the lab compendium and conceptual questions on troublesome aspects of the theory. I started each lab with group discussions about the conceptual questions and ensured that each group arrived at the desired answer. Then the students were given a point-by-point overview of the procedure, from start to finish, and I also handed out a printout of the overview to everyone. I planned discussion sessions during the lab whenever there was a break, to answer the question 'what is going on here?', and discussed the results with the students at the end of each lab. During these sessions, the students who finished first were asked to do their calculations and present their results on the board, and then we looked at them together as a group to discuss what they meant. I felt I had done everything I could to help the students connect theory and practice.

However, there was one student that I could not help. During the second lab he simply got stuck. He needed to dilute a 10 mg/ml protein solution 10 times. This was known amongst the teachers to be a notoriously hard aspect of the lab, and most students ended up diluting 1+10 (one part solution and 10 parts water) despite being perfectly competent at diluting squash in their homes (to dilute something 10 times, you dilute 1+9). However, this one student was determined to do it mathematically using the mathematical shortcut $c \times v = c \times v$ (this shortcut is used for dilutions in chemistry involving concentration calculations based on amount of substance and volume). I tried speaking to him about it not being the best way to solve his problem, to no avail, and I also tried to illustrate the dilution graphically to him. There were two other assistants there who were understudies to me that year (in that department there is always one experienced PhD student teaching in each double group, and someone who is in the first year of teaching works together with this PhD student and watches and learns from them). Both of the PhD students spent time trying to reason with this student, who stayed until 8 p.m. trying to solve the calculation, but eventually gave up.

What I found deeply fascinating about this undergraduate student was his absolute dedication to sticking to what he knew, which was maths. He had to describe what was going on in words he could understand, and this calculation was apparently what he knew. But sticking to math in the laboratory only gets you so far. At some point, you have to make sense of the concepts behind the symbols, and that is very hard for many students. To some extent, they can be helped using methods of teaching suggested by research (as I did), but to me, the chemistry education literature was not helpful enough (and, from what have I read, this is also true today; see M. M. Cooper & Stowe, 2018).

I taught the biochemistry laboratory course for three consecutive years. Although I had previously considered becoming a teacher, I really became fascinated with learning chemistry in the laboratory when I started teaching biochemistry to undergraduates. It was as if half of the students did not connect what they were doing to the theory at all. One student became particularly sheepish when he had to remake a solution because he done a calculation for one volume and then dissolved the powder into a different volume without noticing. The connection between theory and practice was not there, and the students behaved accordingly. The question I asked myself was: why can the students not make sense of what they are doing in the chemistry laboratory?

In 2015, I finally took the first step toward becoming a teacher for upper secondary school. Armed with my licentiate degree in biochemical toxicology and some extra biology courses taken during the autumn 2015, I applied to the Supplementary Teacher Training Programme at Lund University to become a teacher of chemistry and biology. I enjoyed my studies, but again found myself asking a similar question during my placements: why do students attempt but fail to learn chemistry and how can they be helped? To me, the question was so urgent that I happily applied for a doctoral position in chemistry teaching and learning when it was announced. This thesis represents an attempt to answer the question of why some students cannot make sense of chemistry, and I hope it also can support new ways of thinking about teaching and learning in this subject.

I will now briefly summarize what the research says about why learning in chemistry causes difficulty for students, after which I will present the thesis and the studies therein.

1.2 The complexity of learning chemistry

According to the Swedish National Agency for Education (Skolverket, 2022), the purpose of the chemistry subject at upper secondary school is for students to develop knowledge about chemical concepts and methods, understand chemical processes, develop an understanding of the importance of chemistry to the environment and the human body, and gain knowledge of how chemistry can be applied to develop pharmaceuticals, materials and new technology. Students also need to be able to relate to societal issues involving chemistry in a competent way and make ethical judgements (ibid.). Students need to be able to work theoretically and experimentally and communicate using the language of science and critically evaluate their experimental results and argue their conclusion based on experimental data (ibid). In short, connecting theory and experiment, relating knowledge to everyday life, evaluating data and being able to master the scientific language, are central to the chemistry subject at upper secondary school. These goals (evaluate, relate, apply, etc.) can be described as being aimed at students achieving a higher level of understanding, and for students to reach these goals they would need to adopt a deep approach to learning (Biggs & Tang, 2007). They would also need to have developed a capacity for abstract thought and complex problem-solving. This conceptual development takes place during adolescence, partially in response to teaching and learning and partially as part of individual development, leading to diversity in terms of thinking capacity in student groups (Newman & Newman, 2020; Vygotsky, 1931/1994). Even when adolescents have developed abstract thinking, they do not always use it to solve problems (ibid.). Hence, it can be assumed that the goals for the chemistry subject will not be attained by a fair proportion of the students.

At the same time as there are high demands on students' chemical thinking at upper secondary school in general, the subject itself puts great demands on students. This is partly due to the subject's abstraction level, partly due to its focus on substances that the students have a hard time relating to, and partly because of its complicated symbolism (Taber, 2017). For instance, in the reaction $2\mathrm{Mg} + \mathrm{O_2} \rightarrow 2\mathrm{MgO}$, the '→' sign represents both 'produces' from a process perspective and 'is interchangeable with' from the mathematical perspective focused on the calculation of, for instance, masses (ibid.). To complicate matters further, 'MgO' represents both the product of the reaction and the ratio of Mg:O of 1:1 in the salt being produced (ibid.). Finally, when used in conversation, the reaction $2\mathrm{Mg} + \mathrm{O_2} \rightarrow 2\mathrm{MgO}$ can allude to both the oxidation of magnesium (usually achieved through heating a strip of magnesium inside a crucible over a Bunsen burner) and the interaction of particles leading to bonds being broken and formed (Taber, 2017). As this example shows, the meaning mediated by the chemical equation is both complex and sensitive to a conversational context.

The learning demands could result in the fragmentary knowledge that has been observed for many chemistry students, which is one of the most general and solid conclusions that can be drawn about learners from chemistry education research (Cooper & Stowe, 2018). This inherent difficulty in learning chemistry led to Johnstone's (2006) proposal that the subject's different aspects (the observational domain, the symbolic domain and the theoretical domain; that is, the chemistry *triplet*) simply overloaded the students' working memory and made it hard for them to reason.

Although all aspects of learning chemistry can be regarded as difficult for students, teachers generally regard chemical equilibrium as the most difficult topic to teach and the most difficult for students to learn (Barke et al., 2010; Kind, 2004). This is unfortunate given that an understanding of chemical equilibrium is necessary in order to understand most of the fundamental concepts of chemistry, including acid-base reactions, redox reactions and solubility (Barke et al., 2010). From a biochemical perspective, understanding chemical equilibrium means understanding reactions and interactions, including all the reactions involved in our body's metabolism. Understanding chemical equilibrium also means understanding why some proteins are stable and others are not; therefore, chemical equilibrium helps us understand why some diseases, such as amyotrophic lateral sclerosis (ALS) and Alzheimer's disease, occur. Hence, proper understanding of chemical equilibrium has implications for the understanding of other sub-topics of chemistry and for the development of applied fields such as medicine.

Although it has been observed that structured, collaborative learning generally improves learning outcomes in chemistry compared to students learning on their own, the reason for this remains unexplored (M. M. Cooper & Stowe, 2018). However, the research supports learning in the presence of a 'knowledgeable other', first suggested by Vygotsky to be the prerequisite for learning as a social process (M. M. Cooper & Stowe, 2018; Vygotsky, 1934/1987). Several studies on student guided collaborative talk have shown that such activities, both in science and other subjects, lead to improvements in individual student reasoning over time (Mercer, 2013).

It is also clear from science education research that learning in the science laboratory, an activity that involves using the chemistry language, and connecting experience to theory, needs careful planning in order to be effective for any science subject. Based on school science research conducted over several decades, the National Research Council (2006) recommended that laboratory activities should have clear learning outcomes, be thoughtfully incorporated into the overall teaching sequence, integrate theory and experience, and include student reflection and discussion. However, based on the inherent properties of the subject of chemistry, especially its symbolic complexity (Liu & Taber, 2016), I would argue based on the literature that there are subject-specific difficulties that make the theoretical-experimental aims for learning in chemistry a particularly difficult task for teachers.

In this thesis, I wish to address the issues with learning chemistry by attempting to explain why issues with connecting theory and practice occur and how teachers might be able to help students reach all the learning outcomes for the subject. I have chosen to study the learning of chemical equilibrium because of its central place in the learning of chemistry. Addressing the issue of connecting theory and practice in chemistry, I use the theoretical concept of sensemaking, which has been used in science education to describe how students make sense of what they observe and build an explanation through connecting everyday experience and scientific theory to resolve a gap in their understanding (Odden & Russ, 2019). However, being sensitive to the importance of the language of chemistry to learning chemistry, and being aware of learning involving both development and social interaction (Illeris, 2007), I have used the theories of Vygotsky on thinking and speech (1934/1987) to define sensemaking as an act of learning rather than a specific way of making meaning within a learning context. Thereby, I pay attention to the importance of viewing collaborative learning events as parts of a long-time developmental process that help students access new ways of thinking (Smagorinsky, 2018), and I view words as tools that mediate thinking (Kozulin, 2003; Vygotsky, 1934/1987) as students make sense of what they see in the chemistry classroom.

1.3 Overview of the thesis

The four studies in this thesis examine how students use words to relate theory and experience on the topic of chemical equilibrium, and also how teachers can help students bridge this gap. These topics are examined first through a pilot study and then through a comparative case study approach. The case study approach involves the analysis of concept maps produced by 88 students in five classes at four different schools, and the analysis of teacher–student dialogues during practical work in these same classes. The work is guided by the assumption that words are tools that mediate the formation of word meaning as part of sociocultural activities, where, for instance, the teacher or parent acts as a mediator of meaning and intention in an interaction that is reciprocal (Kozulin, 2003; Vygotsky, 1934/1987). As part of learning, learners gradually learn to form meanings on their own and can utilise the words as thought to mediate conscious and meaningful action (Arievitch & Haenen, 2005; Lantolf, 2003; Vygotsky, 1934/1987). Following this assumption, the thesis focuses on the role of scientific language use in connecting theory and experience, both from the perspective of the students' own sensemaking, and how teachers mediate reciprocal sensemaking in the classroom. The overarching research question is: *How does student language use relate to sensemaking in chemistry at upper secondary school, and how can teachers help students make sense of chemistry through classroom dialogue?*

To answer this question, I utilised an ethnographic approach to content analysis (Altheide & Schneider, 2013) to analyse student concept maps and teacher–student dialogues as data that has cultural meaning; that is, a meaning that arises from within the teaching and learning situation at upper secondary school. This cultural meaning involves subject-specific ways of communicating, as well as subject-specific ways of reasoning, teaching and learning within the subject of chemistry. The research for the thesis was conducted as a comparative case study at four different schools that were selected for their overall variability in terms of student achievement level, city size and student home languages. Two school systems were also represented (Swedish and International Baccalaureate), but the topic of study was the same in all classrooms: shift in chemical equilibrium. Through the use of concept mapping and filming, students were followed as they made concept maps of their understanding of shift in chemical equilibrium before a practical lesson on this topic and then discussed with the teacher as they encountered the phenomenon in practice. A pilot study was conducted at a fifth school to test the feasibility of the study design. To ensure the credibility of the results, a triangulation approach to establish internal validity was adopted where concept maps were checked against student–teacher dialogues to look for discrepancies between the written and the spoken word, and teachers were also asked to verify both the authenticity of a sample of the concept maps as well as the authenticity of their conversations with the students.

The purpose of the analysis was to elaborate on the role of language in sensemaking in chemistry, and how teachers can promote sensemaking through language. My first focus was to look at how students of different achievement levels and language competencies fare in the chemistry classroom in terms of making sense. My second focus was to find specific teacher–student interactions that are beneficial to sensemaking and that can be used as a model for teachers who wish to help their students make sense of what they see in the chemistry classroom. This thesis will show how students of various achievement levels and language competencies use language to make sense of chemistry on their own, but also how four experienced teachers organise dialogical sensemaking during practical work.

1.4 Outline of the comprehensive summary

This is a compilation thesis consisting of two parts: a kappa (comprehensive summary), and four original papers. The presentation of the chapters below provides an outline of the kappa.

Chapter 1 introduces the thesis and its point of departure, its focus and its objective. This chapter introduces issues with teaching and learning chemistry as problems of using language to make sense of chemistry. My focus is presented as exploring student sensemaking in chemical equilibrium in relation to language use and previous chemistry achievement, as well as how teacher–student sensemaking can be achieved in the classroom.

Chapter 2 positions the thesis as belonging both to science education and chemistry education and discusses the main aspects of the research fields that the thesis touches on. These research fields include the chemistry triplet, laboratory learning in science, the role of language in science learning, sensemaking, and learning of chemical equilibrium.

Chapter 3 provides the aim and research questions of the thesis.

Chapter 4 introduces the different theoretical perspectives that have been merged in the thesis; that is, the Vygotskian perspective on learning, conceptual and sociological perspectives on sensemaking, and the chemistry triplet. These three theoretical perspectives are related to establish a theoretical framework for sensemaking in chemistry from a Vygotskian perspective.

Chapter 5 focuses on methods and methodology and introduces the case study research approach and the overall setup of the data collection. It also discusses sampling, the approach to data analysis, the methods used for the thesis, and ethical considerations. I discuss the choices made for the thesis in terms of methods and methodology and the reasoning behind them. I also elaborate on the methods and methodology to a greater degree than was possible in the articles due to word limitations.

Chapter 6 summarises the results of the articles included in the thesis. It provides an overview of the findings regarding language use and sensemaking in chemical equilibrium, previous assessed achievement level and sensemaking in chemical equilibrium, symbols and sensemaking. The chapter also offers an overview of findings on teachers' strategies in managing sustained sensemaking in chemistry during student–teacher conversations while students study shift in chemical equilibrium.

Chapter 7 discusses the benefits of the Vygotskian perspective on sensemaking, the impact of student language on sensemaking achievement in chemistry, and meaningful learning in chemistry in relation to sensemaking. Teacher–student sensemaking is also discussed in relation to Vygotskian theory, as well as the role of symbols and other tools, and the students' academic self-concept. Finally, I discuss the limitations of the study, my conclusions from the data, and possible implications for theory and practice.

Chapter 8 presents a summary of the thesis in Swedish, which includes an introduction, a brief overview of the theories that have been used, the methodological approach, an overview of the results, a summary of the discussion and the final conclusions of the thesis. This concludes the kappa, or the comprehensive summary, of the compilation thesis.

The original papers included in the compilation thesis are outlined below.

1.5 Overview of the different studies

In Paper I, which was a pilot study, I examined the utility of the concept mapping setup, both for the study and as a classroom tool. I did this through looking at how the students in the study interacted with the concept maps and also how the concept maps could possibly be analysed through an initial round of coding. A focus of this study was how the students defined symbolic meanings and felt they understood the differences among observations, symbols and theory.

In Paper II I utilised a Vygotskian (1934/1987) perspective on sensemaking to look at how the students connected the everyday, experiential concept of 'colour change' with the scientific concept system of chemical equilibrium while making sense of shifts in chemical equilibrium in their concept maps. I also looked at how this aspect of sensemaking (connecting everyday and scientific concepts) related to their language use.

In Paper III, I looked at sensemaking through the chemistry triplet lens (Johnstone, 1991; Taber, 2013) and looked at how both student achievement level and use of language were related to how they made sense of shift in chemical equilibrium in their concept maps through organising and connecting among observations, symbols, and theory. I also looked at the relationship between student language use and their previously assessed achievement levels.

In Paper IV, using the concept of sensemaking both from a science education perspective (Odden & Russ, 2019) and a sociological perspective (Weick, 1995), I studied how four experienced chemistry teachers helped their students make sense of chemical equilibrium through conversation analysis. Specifically, I studied how the teachers managed to sustain sensemaking through probing gaps and helping the students connect concepts, while at the same time presenting the students as competent contributors in the interaction.

Chapter 2 presents an overview of the previous research relevant to this study and positions my research in relation to this literature.

2 BACKGROUND

2.1 Positioning of the thesis

The research field of educational sciences is a transdisciplinary field that encompasses a wide range of research topics: educational history; educational systems, curriculum and governance; ethics and moral issues related to democratic values; learning psychology and group sociology; teaching and learning processes, both general and subject-specific; teacher's professional work; and studies on the effects of reforms and productivity in learning (Askling, 2006, pp. 30–31). The present thesis belongs to the dimension of educational science that researches subject-specific teaching and learning processes and uses concepts from both science education and chemistry education research. The thesis is positioned in relation to these research fields below.

2.1.1 Positioning of the thesis in relation to learning theories in science education

Within science education, learning theories have traditionally been rather learner-centred. Two influential learning theories are conceptual change theory (Strike & Posner, 1985) and generative learning theory (Osborne & Wittrock, 1985), both of which have their roots in cognitivism. Some researchers have also introduced sociocultural theory into science education, for instance through studies of language genres in the science classroom dialogue and studies that focus on how multimodal language can convey meaning (Jakobsson, 2012; Lemke, 1990; Mortimer & Scott, 2003; Nygård Larsson & Jakobsson, 2020; Pozzer & Roth, 2020; Staarman & Mercer, 2012), but the recognition of the importance of context to the learning is a more recent development (Duit & Treagust, 2012; Mercer, 2008). Here I provide a very brief review of early cognitive learning theories that have shaped science education.

The conceptual change theory (Strike & Posner, 1985) forms the basic assumption, influenced by the writings of Piaget (Blunden, 2013, pp. 53–54), that children carry with them naïve ideas, or misconceptions, about the natural sciences and that these ideas need to be replaced through education (learning through cognitive conflict).

According to Strike and Posner (1985), ‘All knowledge originates in experience’ and ‘Knowledge is additive and bottom-up’ (p. 213). Hence, according to the conceptual change theory, individuals learn from interacting with their environment through a continuous revision of models based on changes in their experience. From this perspective, the teacher is seen as a facilitator of experiences and the learner becomes the focus of the research. Learners are assumed to follow similar paths to learning as the science field, and experience paradigm shifts much like in the field of science (Kuhn, 2012). To accommodate a new principle, students must be dissatisfied with a current conception, have some understanding of the new conception, be convinced by its plausibility and find it useful for research (Strike & Posner, 1985, p. 216). Conceptual change theory has been very influential within science education and has given rise to an abundance of competing theories on the process of how students construct conceptions (Potvin et al., 2020).

The generative learning theory (Osborne & Wittrock, 1985; Wittrock, 2010) is also essentially constructivist, but adds to Strike and Posner’s model the importance of previous experience to how the learner interacts with new information input. In the generative learning theory, the previous knowledge of the learner is considered vital in terms of a learner’s sensemaking, what is selected by the learner’s attention, and how knowledge is constructed by the learner in any learning situation (Osborne & Wittrock, 1985, pp. 64–65). In this learning situation, the teacher also becomes a guide in directing attention and facilitating memory storage through providing a multitude of different sensory experiences for the student. Emphasis is also placed on the active processes involved in knowledge construction, the assumption that learners are intrinsically motivated to constantly construct knowledge, and the importance of evaluation of constructs through experimental practice (Osborne & Wittrock, 1985, pp. 75–76). Hence, compared to the conceptual change theory, the generative learning theory emphasises the importance of the teacher as a guide.

Although the research on learning in science has traditionally focused largely on the ideas of the individual, the above-mentioned individual constructivist approaches (Duit & Treagust, 1998) have seen it broaden into more situated perspectives recently (Duit & Treagust, 2012). Current research in science learning can be seen as coming from a spectrum of epistemological positions of learning theories that regard learning differently, ranging from learning as individual and cognitive to learning as social, discursive and culturally based, where knowledge is regarded as externally distributed (Alexander, 2007). Learning situations are a common topic of study, such as in sociocultural research (Jakobsson, 2012). Within physics education research, Piet Lijnse (2010) is noteworthy because he has problematised assumptions within the research field regarding particulate understanding and what meaning making in the classroom entails, and has pointed to partial intersubjectivity of meaning between teacher and student as a source of researcher-proposed alternative conceptions.

Due to these different epistemological perspectives, some researchers are directly opposed in terms of how they believe knowledge is generated (socially or in the mind)

(Alexander, 2007). Neil Mercer (2008) pointed out that, from the perspective of sociocultural theory and research, there is clear evidence of the importance of dialogue in driving conceptual change, but that this aspect of conceptual change needs further investigation. Mercer further argued that there is a need in the research literature for the use of multiple research perspectives and analytical frameworks to shed more light on this issue (p. 361).

For the present thesis, where the focus is on language use in sensemaking and sensemaking in teacher–student-interaction, the research follows the tradition of studies in science education on learning context and dialogue that have an underlying assumption that learning originates in social interaction rather than individual reasoning. These sociocultural perspectives on learning do not prescribe to the Descartian view of mind/body-dualism, but consider cultural tools and artefacts in the material world as important mediators of thought (Jakobsson, 2012). These theoretical perspectives are based on a Vygotskian view of learning, but can have more or less of a focus on physical artefacts and communities as mediators of thought (ibid.). In addition, these perspectives include viewpoints that prescribe to more or less of an inseparability between the individual and the collective (Daniels, 2008), up to a point where knowledge is assumed to only exist in the space between individuals rather than in the mind (Alexander, 2007). These widely differing viewpoints on learning within the sociocultural field can be attributed to some Western researchers taking on the activity theory perspective that merges cognition and behaviour, where 'psyche as activity … is replaced by the psyche within activity' (Zinchenko, 2004, p. 33). However, Vygotsky's original view was capable of including both cognitive and social aspects on learning in his theory of thinking and speech and studying the relation between them (Miller, 2011; Vygotsky, 1934/1987). Due to the focus on both individual sensemaking and social interaction in this thesis, I have chosen to adopt a more Vygotskian approach to how I view learning, as this view is able to incorporate both individual reasoning and learning in interaction. The Vygotskian view on learning will be elaborated on in Chapter 4.1, and how this view be related to sensemaking is considered in Chapter 4.2. However, aspects of the chemistry triplet, originally a cognitivist approach that has become a learning theory in its own right within chemistry education research (Johnstone, 1991, 2006; Taber, 2013), have also been incorporated into the theoretical basis for the thesis. The chemistry triplet, which is used as a framework to outline the knowledge domains chemistry students need to navigate as part of learning chemistry, will be elaborated on in the next chapters, where I delve further into chemistry education as a research field.

2.1.2 Positioning of the thesis in relation to learning theories in chemistry education

Taber (2019) proposed that, based on indicators such as having its own international journals, conferences, chairs, and research groups, chemistry education research (CER) can be regarded as a research field in its own right. Although theoretical perspectives are wide-ranging in the field, challenges with learning specific to chemistry mean that the field also has a well-established focus on the chemistry triplet and the role of models and modelling (ibid.). The reason for this is that that the understanding of models, and how to use models to explain and predict phenomena is essential for making sense of chemistry (Taber, 2010). The particular challenges for chemistry learners are caused by the fact that they are introduced to numerous models during their studies, many of which are changed into more complex models as the education progresses (ibid.). This is due to chemistry educators needing to adopt a pragmatic approach to teaching and use understandable models that are useful and work within the teaching context (ibid.). However, this simplification can lead to aspects of the new models coming into conflict with previously taught models, which impedes learning (ibid.). Therefore, according to Taber (2019), it is important to distinguish the chemistry education research field from the science education research field, as CER largely aims to explore issues with learning that are particular for chemistry rather than examining general principles for learning within the context of the chemistry classroom. The field is outlined below.

Lecturers in chemistry were initially sceptical about pedagogical theories. When the research field of CER was formed, most research articles focused on lecturer's personal teaching practices and laboratory exercises, where learning was assumed to emerge from practice (M. M. Cooper & Stowe, 2018). However, there was a paradigm shift in the research field in the mid-20th century towards constructivist theory (mostly inspired by Piaget's research on children), and a lot of the recent research in the field has focused on student-centred learning and the relationship between students and learning materials (ibid.). Twenty-first century research has had an increased focus again on what Cooper and Stowe (2018) called expert practice, although the focus is now on how experts in the field think and how students can be helped to think in the same way. According to Anderson and Schönborn (2008), expert conceptual understanding has the following central aspects: mindful learning (as opposed to rote learning), integrating knowledge to create sound explanations, transferring knowledge for novel applications, using analogies in reasoning, and being able to evaluate both local and holistic effects with regard to chemical reactions. Central to this aspect of the chemistry education research field is the chemistry triplet that Johnstone (1982, 1991) proposed to describe thinking in chemistry. This model focuses on the 'triangle of levels of thought' (Johnstone, 1991, p. 78; see Figure 1) covered by teachers of chemistry: the macroscopic or experiential, the symbolic or representational, and the submicroscopic or theoretical. For experienced chemists, these knowledge domains are often integrated in conversation, which can be hard to follow for learners (Johnstone, 1991, 2006; Stieff et al., 2013). The focus on knowledge integration as expert practice in terms of thinking has led to prolific research, where the research on the use of representations in chemistry education as well as the use of models and modelling is prominent (M. M. Cooper & Stowe, 2018). Other research in the CER field has focused on learning sequences, online learning, curriculum design and issues with societal relevance of the subject and context-based learning. However, a common focus for a large majority of CER is small quasi-experimental studies, which makes it hard to draw solid conclusions about learning in chemistry from the research being produced (ibid).

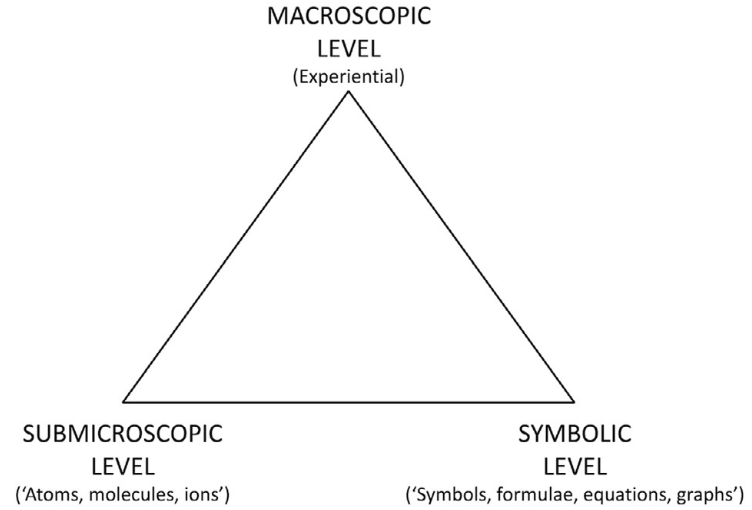


Figure 1. The chemistry triplet, showing the thought levels of experience (macroscopic), representation (symbolic) and explanation (submicroscopic) involved in 'multilevel thought' (Johnstone, 1991, p. 78). Image based on models proposed by Johnstone, 2006 (p. 59) and Johnstone, 1991 (p. 78).

However, there are some general trends in the chemistry education research in terms of recommendations for best teaching practices. In a report to the National Research Council, summarising research produced between 2000 and 2010, Towns and Kraft (2011) argued that three conclusions can be drawn. Firstly, in general, students do not develop strong modelling skills (such as the ability to mediate particulate thinking) during their time in education, but this can be helped by the use of animations in class. Secondly, there is widespread support in the research literature for active small-group learning. Thirdly, low-achieving students' motivation and belief in their own abilities in chemistry decrease over time, whereas high-achieving students' motivation and belief in their own abilities increase over time. In a more recent review, M. M. Cooper and Stowe (2018) added that, first, visualisations and animations may improve student capabilities for modelling but do not necessarily improve test performance; second, that social, active learning is especially effective for low-achievers and women, but mixed-achievement groups is a necessary prerequisite (the author's link this connection to Vygotsky's theories of social learning); and, third, that despite all the online learning tools and technologies available to chemistry teachers, there is little support in the research for their effectiveness – rather, attempted online courses have shown very low pass rates. Towns and Kraft (2011) also pointed out the widespread lack of meaningful reasoning of students, even at university level, and M. M. Cooper and Stowe (2018) pointed out that students often fall back on surface-based mechanistic approaches rather than in-depth reasoning when solving problems. This is in line with Anderson and Schönborn's (2008) definition of novice approaches to learning as fragmented knowledge leading to formula-based solutions.

Bretz (2008) noted that one problem with the chemistry education research field being dominant in constructivist thinking and quasi-experimental methodology is the poor understanding for qualitative research. This leads to a need for in-depth explanations of its utility and purpose to convince chemistry education researchers of its usefulness, where failure to provide best recommendations for evidence-based practice can be regarded as failure of the research project (ibid.).

In essence, the CER field can be viewed as having emerged from a heavily Anglo-American tradition with a strong focus on learning psychology (Kansanen et al., 2011). The Swedish research field that is educational science with its broader focus on learning and learning context can be seen as a little different, from a CER perspective. In addition, the Swedish educational science research is, due to its dominant focus on learning processes rather than learning outcomes (Askling, 2006), more likely to be qualitative compared to CER. In terms of its broader perspectives, the field of science education research can be viewed as a more similar field to the Swedish educational research field in terms of breadth and outlook.

In my research project, I have chosen a qualitative perspective on learning, where I use a comparative case study to look at learning in chemistry in different classrooms on the topic of chemical equilibrium. I have chosen to focus on sensemaking and the scientific language use of learners, and I am interested in questions such as how students make sense of chemistry and how participation in learning and learning interactions between teachers and students is related to classroom learning. Coming from a Swedish educational research perspective, I have chosen to look at the contextual facets such as achievement level and language use, as well as the social interaction embedded in the learning process in the classroom. At the same time, I use the model of the chemistry triplet (Johnstone, 2006), in combination with theories on sensemaking in science (Odden & Russ, 2019a) and concept development from a sociocultural perspective (Vygotsky, 1934/1987), to understand sensemaking in the classroom. My focus on how students learning chemistry at upper secondary school make sense of chemistry through connecting phenomena and theoretical models can be said to be well grounded in CER research. Specifically, I focus strongly on how students describe chemical equilibrium, by themselves and in teacher–student dialogue, and I also look at how teachers and students use language, symbols and theoretical models to mediate concept formation as part of sensemaking. This practice involves multimodal meaning making, which is a well-established field in science education (Lemke, 2005), but CER also has a strong focus on the use of representations and models in learning due to the nature of the subject, as I mentioned previously. However, despite their focus on symbols and models, theories in CER are constructivist and focused on individuals as learners separated from the environment (M.M. Cooper & Stowe, 2018). I differ from the constructivist perspective in that use sociocultural perspectives on learning with a focus on language as a socially and culturally developed tool for thinking (Vygotsky, 1934/1987), which can be seen as oppositional to the Piagetian theories used in the CER field that prescribe to mind/body dualism (that is, separating the mind and the material world) and sees thinking as isolated in the mind (Jakobsson, 2012).

Traditionally, Swedish researchers in chemistry education have tended to utilise both the science education research field and the chemistry education research field in their work (e.g. Broman et al., 2018; Broman & Parchmann, 2014; Dudas et al., 2022; Hamza & Wickman, 2008; Patron et al., 2017). The work presented in this thesis follows this research tradition, where different aspects of the results are explained either within the context of the chemistry education research field, or within other contexts such as the science education field. However, the focus of the thesis as a whole is on chemistry education as a subfield of teaching and learning with its own unique challenges, using the teaching and learning of chemical equilibrium as an example. Chemical equilibrium is an ideal example of a learning topic that causes difficulties for learners due to issues with learning models, as learners are introduced at secondary school to reactions as proceeding from reactants to products, at upper secondary school to reactions as reversible, and at university level to reactions from a thermodynamic perspective (more on this in Section 2.6).

2.1.3 The chemistry triplet model for learning

The concept of sense and sensemaking has clear importance for learning in chemistry, as students often struggle with learning chemistry concepts (De Jong & Taber, 2007; V. Kind, 2004; Talanquer, 2015). It has been well established that students of chemistry often have difficulty differentiating between the macroscopic (observable) and the particulate worlds, and in effectively using the symbolic language of chemistry (Andersson, 1990a; Ben-Zvi et al., 1988; Gabel et al., 1987; Johnstone, 2006; Talanquer, 2008; Treagust et al., 2003). For instance, Stieff, Ryu and Yip (2013) studied classroom discourse from the perspective of teachers and students reaching intersubjective agreement (mutual agreement of meanings) and they confirmed that teachers and students can face difficulties in establishing a common understanding regarding words such as 'water', with learners tending to remain on the macro level due to the failure of the teacher to produce 'explicit re-orienting moves to resolve levels confusion' (p. 387). Talanquer (2015) proposed that focusing on threshold concepts in chemistry teaching, such as chemical equilibrium and chemical bonding, can help students navigate the macroscopic and particulate realms as they implicitly foster thinking about chemical events as complex, dynamic systems rather than for instance causal or homogenous processes.

Within chemistry education, the idea of the chemistry triplet, originally presented by Johnstone (1982, 1991), has become a paradigm for defining what sensemaking in chemistry entails (Talanquer, 2011), and has been used as a theoretical framework for the study of meaningful understanding of classroom discourse (see, for instance, Stieff, Ryu, & Yip, 2013). As a model, the idea of the chemistry triplet has been useful for identifying issues in chemistry teaching and learning that deal with difficulties students face trying to differentiate between the macroscopic and the particulate (Ben-Zvi et al., 1988; Gabel et al., 1987; Johnstone, 2006; Stieff et al., 2013; Talanquer, 2008). Originally postulated as a model for 'multilevel' thinking within the chemistry domain, but also applicable with some adaptations to the domains of physics and biology (Johnstone, 1991), the triplet model divides the thinking about chemistry into three levels: the 'macroscopic', experiential level, the 'symbolic', representational level, and the 'submicroscopic', theoretical/particulate level (see Figure 1). Effective use of all three levels is necessary for comprehension and communication of knowledge about a chemical process (Taber, 2013). Hence, the model can be used as a framework to map how students use or do not use the different knowledge domains of chemistry as they make sense of chemistry phenomena.

Johnstone proposed that students have difficulty learning chemistry because they have problems traversing the three thought levels of 'macro' (what is being experienced or described), 'symbolic' (where signs are used to represent ideas) and 'submicro' (where phenomena are being explained through particulate models, 'the molecular, atomic and kinetic'; Johnstone, 1993, p. 702) for any given concept (Johnstone, 1991; Talanquer, 2011). Johnstone (1991) visualised the learning situation using the same triangle (see Figure 1), proposing that the student can have difficulty navigating the triangle without help, whereas the teacher stands on the inside and utilises all levels simultaneously. Based on this model for how to think about why students find chemistry difficult, Johnstone (2006) connected his theory of the triplet to cognitive theories on working memory.

Working memory and fluid intelligence (reasoning capacity, or non-verbal reasoning skills) are highly related when it comes to problem-solving, and is also predictive of learning in various disciplines (Engel de Abreu et al., 2010; Shipstead et al., 2016; Yuan et al., 2006). There is general agreement amongst cognitive scientists that working memory (previously known as short-term memory) has separate storage for phonological (acoustic or verbal) information and visuospatial (visual and spatial) information (Yuan et al., 2006). The ability to reason using mental representations held into focus by working memory is a general capacity (Shipstead et al., 2016). However, this ability is particularly important to chemistry learning because of the many representations and models that need to be coordinated. Research has shown that it is primarily visuospatial working memory that is correlated to and predictive of chemistry performance (Harle & Towns, 2011; Rhodes et al., 2016). Johnstone observed (2006, p. 78) that much teaching in chemistry takes place simultaneously at all three conceptual levels of chemistry (see Figure 1), which he proposed meant overloading a student's working memory as each conceptual level took up working memory space. Johnstone also showed, in several studies, that student performance in chemistry was heavily dependent on working memory space, which is indicative of rote learning rather than deep learning (reviewed in Johnstone, 2006).

Researchers have interpreted the triplet model in various ways, with the three aspects of the triplet interpreted both as levels of representation and as a mixture of concepts and representations (Talanquer, 2011). Using a constructivist perspective, Taber (2013) proposed a solution to this ontological difficulty, dividing the triplet into three domains of knowledge: experiential, macroscopic (theoretical and descriptive), and submicroscopic (theoretical and explanatory). He proposed that Johnstone's symbolic domain of thought can be utilised as a linguistic resource to communicate about and transfer between these different knowledge domains (see Figure 2).

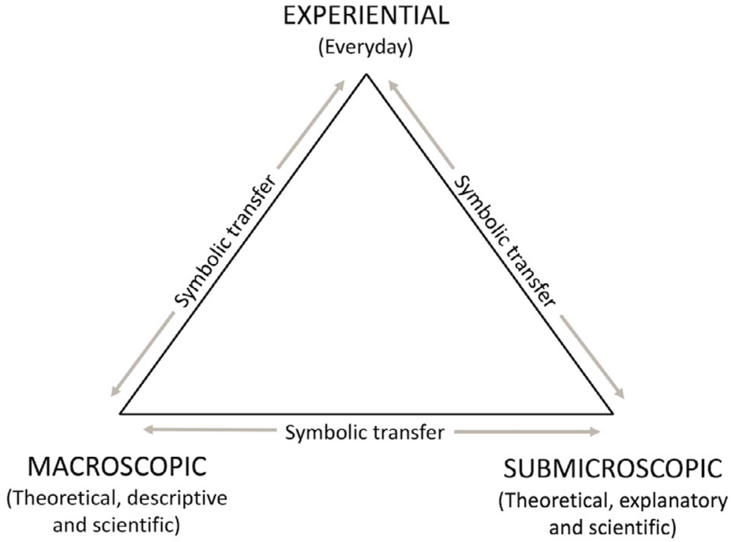


Figure 2. An overview of Taber's (2013) proposed development of the triplet model, where a division is made between the domains of the everyday/experiential, and the macroscopic/scientific/descriptive, in terms of the larger-scale, tangible world of the chemist. In Taber's (ibid.) suggestion, the submicroscopic domain is kept as the explanatory domain, and the symbolic domain is utilised to transfer between three domains depicted in the triangle. For instance, the descriptive macroscopic theoretical level and the explanatory submicroscopic theoretical level can be bridged by using chemical equations during discussions. These two levels can then be related to the everyday, descriptive, experiential conceptual level through a shift from scientific to everyday language (Taber, 2013). This image is a simplification; for the full model, see Taber (2013, p. 165).

According to Taber (ibid.), learning, speaking and doing chemistry means that the language of chemistry is utilised to relate the different conceptualisations to what is being experienced. Therefore, learning chemistry is heavily dependent on learning this language (ibid.). Following this reasoning, using the language of chemistry as well as everyday language to relate between theory and experience is not only representative of what chemistry is all about, but also becomes the learning objective for every subtopic of chemistry being taught. However, a sociocultural perspective on how the chemistry triplet relates to concept development through language use has not yet been proposed.

Although Johnstone himself proposed the use of information-processing learning models to solve the issues in chemistry learning (Johnstone, 1993, 2006), supporting students to traverse knowledge domains can also be viewed as a support for abstraction and conscious awareness, which according to Vygotsky is support and learning within the zone of proximal development (ZPD) (Gredler, 2012). In addition, triplet classroom exercises can also be viewed as introducing students to an expert practice steeped in the cultural tradition of chemistry (Kozma & Russell, 2005), and triplet talk between teachers and students can be viewed as learning how to think in chemistry through talk with others (Mercer, 2013).

Studies on dialogic discourse have shown that explicit language scaffolding in classrooms that involve triplet transitions are successful in promoting learning (Becker et al., 2015; Chiu et al., 2002; Jaber & BouJaoude, 2012; Warfa et al., 2014). It has also been shown that using an adapted version of the triplet to stimulate student metacognitive reflection can lead to changes in how students think about chemistry and approach connecting between the different triplet knowledge domains (Thomas, 2017). Hence, it is necessary to take the triplet as a model into account when dealing with sensemaking in chemistry, both in terms of relating to the research in chemistry education and in terms of following a 'best practice' when it comes to classroom interventions. In this thesis, the triplet has been reinterpreted from a sociocultural perspective to study the relations among context, language use and the integration of knowledge as part of learning (see Chapter 3.2–3.3). Because the focus was to use this perspective to study the learning of chemical equilibrium in the laboratory, the next section will elaborate on the laboratory as a learning environment.

2.1.4 The chemistry laboratory as a learning environment

The laboratory has great potential in terms of learning about chemical concepts, as it offers an opportunity for reasoning within and between all conceptual levels in chemistry. According to Strike and Posner (1985), the laboratory milieu can also provide an environment for supporting new conceptions, since ideas can be tested and deemed plausible and fruitful if the experiment is successful. The laboratory, with its possibility of giving students an opportunity to connect the observable properties of a substance with explanatory models of particles through collaborative practice, should be an ideal place for students to be helped to make sense of threshold concepts such as chemical equilibrium. However, there are some issues with teaching through laboratory work. Teachers are often disappointed with the outcome of conceptual learning from lab work (Séré, 2002). In many ways, the practical setting, where learning aims are a mixture of conceptual learning and the learning of practical skills, becomes a mystifying practice for students where the objects that are used are complex, and understanding how to use them and why requires a separate set of theoretical concepts (ibid.). Therefore, objects within the laboratory can be carriers of implicit theory and students are expected to analyse the data they collect based on theory that may not be explicitly stated. For instance, during a biochemistry practical lesson, matters such as how absorbance measured in a spectrometer is related to the concentration of proteins, and why the concentration is measured at a certain wavelength, may not be explained to a student who needs to measure protein concentration before an experiment. In addition, in many laboratory classrooms, theoretical concerns tend to be less attended to when students are faced with practical matters and are set on finishing their protocol (reviewed in Hofstein & Lunetta, 2004). Hence, it has been suggested that it is crucial to understand how context influences learning through practical work to help science teachers in their daily practice (Hofstein, 2017).

These concerns about laboratory learning are not new; the effectiveness of laboratory lessons has been questioned for decades, as qualitative and quantitative studies of learning show that students recollect very little from these lessons (Abrahams & Millar, 2008; Lunetta et al., 2007). When students interact with artefacts as part of scientific experiments, they appear to lack the conceptual knowledge required to interpret the experiment correctly on their own (Gunnarsson, 2008; Gunstone, 1990; Gunstone & Champagne, 1990; Lidar, 2010; Roth, McRobbie, Lucas, & Boutonné, 1997). It may be that teachers' views of learning and their execution of the classes based on these views also affect student learning, as can be shown in a case study of 25 laboratory lessons in England (Abrahams & Millar, 2008, p. 1965), where teachers expected students to deduce the correct theoretical knowledge from experiments as long as they were executed correctly. Unfortunately, students did not recollect learning any theory at all during these lessons.

Since the effectiveness of laboratory lessons have been questioned by researchers, the mainstream execution of laboratory lessons has also been questioned due to the cost involved, and greater emphasis has been placed on the value of laboratory lessons to teach the nature of science as what a scientist does, as well as improving students' conceptual learning through more socially oriented practices such as posing questions, arguing, explaining and reflecting (Lunetta et al., 2007; National Research Council, 2006). According to a recent review by Gericke et al. (2022), the success of learning in the secondary-school laboratory depends largely on how the teacher plans the practical work and supports the students in reflecting about the theory and the learning goals. Specifically, the complexity of the student task, both in terms of inquiry level and variables being measured, needs to be adapted for the student group and context (ibid.). In addition, the teachers need to support student reflection through a counter-questioning practice, integrate student writing, and encourage collaborative work (ibid.). Finally, Gericke et al. (2022) pointed out that the research shows that students have difficulties connecting theory with practice, and that they need to be both theoretically and practically prepared in order to successfully execute an experimental procedure.

However, just because research shows that learning in the laboratory is challenging, this does not mean that practical work is not important for learning. Based on the triplet understanding of chemistry (Johnstone, 1991; Taber, 2013), the laboratory environment where observations are made and discussed could be a crucial environment for developing the basic reasoning skills of chemistry, or, as described by Kozma and Russel (2005), the essential 'multi-representational competencies' of the chemist. Hence, it is necessary to study how practical lessons can influence the development of students' reasoning abilities in chemistry, as this is key to meaningful learning in the subject. By promoting paths to meaningful learning, schools and universities can provide students with tools for long-term success in science subjects.

In this research study, I chose the school chemistry laboratory as a learning context because of its potential in terms of sensemaking related to learning about chemical equilibrium as a concept. Because of the historical problems with school laboratories as learning environments, I also believed that studies of successful practical learning, as well as studies of the role of language use in sensemaking in the laboratory, could contribute to science education research from a more general perspective.

2.2 Perspectives on language use and learning from the science education and chemistry education research fields

2.2.1 The role of language in science learning

2.2.1.1 How the characteristics of the language of science influence teaching and learning

The role of language in science learning has been studied from many different perspectives. Carlsen (2007) divided these perspectives into four contemporary research approaches, but also noted that they overlap and that one should look at these perspectives as having different emphasis on what is being studied (p. 58):

- *Vygotskian* (the study of language, conceptualisation and word meaning)
- *Conceptual change theory* (the study of the differences between individual and public knowledge of science concepts)
- *Sociolinguistics* (the study of language discourse as derived from its cultural context; that is, local norms and practices; this perspective includes the sociocultural tradition)
- *Situated learning* (the study of learning as a social activity, including learning within communities of practice).

The theoretical underpinnings of these research approaches vary, from the constructivist approaches that are more associated with conceptual change theory to the Vygotsky-based perspectives on learning, such as the sociocultural tradition and situated learning (Carlsen, 2007; Daniels, 2008). Here, a fundamental difference can be seen in views on thinking within research on the role of language in science education. Some perspectives view thinking as mediated and learning that is based in social interaction (Vygotskian and sociocultural perspectives; Vygotskian theory will be elaborated on in Chapter 3), whereas the conceptual change approach argues that knowledge resides in the mind and grows as a result of learners interacting with their environment (see theories in science education; Section 2.1.2). Following Carlsen's (2007) perspective, sociolinguistics and situated learning perspectives appear to be more focused on human activity from a societal or systems perspective, whereas Vygotskian studies focus more on language use and meaning. From a methodological perspective, this can be seen clearly in the difference between the Vygotskian perspective and the situated learning perspectives. For Vygotsky, the language is a tool for internal action; that is, a tool for mastering one's thought and developing the mind (Vygotsky & Luria, 1930/1994), whereas the situated learning perspectives look at language as one of many tools that mediate outward action (Miller, 2011; Zinchenko, 2004). This latter perspective has emerged from Leont'ev's activity theory, and although some researchers claim this perspective is Vygotskian (which Leont'ev initially proposed; van der Veer & Valsiner, 1993), the perspectives are clearly different with regard to the importance put on various forms of tools. The choice of which one to use has implications for what is being studied and for what conclusions can be drawn.

One problem with dividing research into perspectives such as the one above is that it can obscure what Vygotsky's purpose was with his research on thinking and speech. Vygotsky was primarily concerned with the tendency in psychology to study aspects of the human mind in isolation (Vygotsky, 1934/1987). He wished to adopt a holist approach that would allow for the study of the interaction of different functions of the individual, while he was also aware of the importance of the social environment for the development of human thought (ibid.). Instead of viewing thinking and speech as separate aspects of psychology, Vygotsky viewed the word as a unit that still contained aspects of the whole (ibid.). According to Vygotsky (1934/1987) 'it may be appropriate to view word meaning not only as a *unity of thinking and speech* but as *a unity of generalization and social interaction, a unity of thinking and communication* (original emphasis)' (p. 49). Based on his reading of Vygotsky's writings and notebooks, Rowlands (2000) made a convincing argument that Vygotsky viewed the study of the word to be in line with Karl Marx's study of value in Capital; that is, the study of a unit that can illuminate the structure of a whole system. In Vygotsky's (1934/1987) own words, 'Consciousness is reflected in the word like the sun is reflected in a droplet of water … The meaningful word is a microcosm of human consciousness' (p. 285).

Another important aspect in relation to the various research perspectives above is the varying emphasis these perspectives put on the individual and the social in terms of learning. Whereas conceptual change theory takes on a purely individualistic approach, seeing knowledge as 'in the mind' (Alexander, 2007, p. 69), sociolinguistic perspectives – and, to an even larger extent, situated learning perspectives – can question whether there is such a thing as individual knowledge (Alexander, 2007; Daniels, 2008). Vygotsky's focus was very much on the individual (van der Veer & Valsiner, 1994), even though he studied the individual from the perspective of the dialectical social-individual unit, which involves change and mutual interaction (Daniels, 2008). Vygotsky's dialectical stance is further elaborated on in Chapter 3.1.5.2.

This thesis can be said to follow the Vygotskian holist approach described above through incorporating aspects of language use and reasoning, as well as aspects of sociolinguistics, as Papers 1–3 focus on individual language use and sensemaking, whereas Paper 4 describes the role of teacher–student discourse in conveying meaning; that is, making sense (Carlsen, 2007). Hence, the thesis follows the Vygotskian holist approach rather than the sociolinguistic (or sociocultural) approach as it retains the focus on language as a mediator of thought (directly) and development (which is implied through the theory rather than studied directly in this thesis). I chose the Vygotskian perspective, partly because my data collection (which started before I decided on the theoretical framework) was largely focused on language, and partly because the development of thought through the use of language can be connected through this perspective with the use of models and with learning in chemistry. Chemistry as a subject is heavily dependent on students learning the language of chemistry for learning and understanding the subject matter (Liu & Taber, 2016), which explains my focus for the data collection. Because of the prominent role of language in the thesis, I will now attempt to describe the role of scientific language in student learning.

In many ways, teachers of science are also teachers of language, as they need to teach both the way sentences are structured in science and the technical terms that are being used as part of classroom communication (Fang, 2005; Lemke, 1990; Seah & Silver, 2020). In general, the language of science is more complex than everyday language. In addition to the words being used in the classroom, multimodal representations form a critical part of the language used in science learning (Hand & Choi, 2010). Finally, gestures also have an important function in communicating science, as they can make clear the meaning of multimodal representations (Ngo et al., 2022). As students are learning, they can be observed to move from more muddled or changing verbal descriptions to a more specific scientific discourse, and gestures can also help students transfer from experiential to abstract communication (Roth & Lawless, 2002). Similarly, studies on language support for English language learners have shown that scientific language can be described as becoming more *explicit* and *precise* when these learners engage in collaborative classroom practices that include the description of phenomena (O. Lee et al., 2013, 2018, 2019; Quinn et al., 2011). According to O. Lee et al. (2019), when students learn the scientific language, they use less deictic words like 'this' or 'here' and replace them with scientific words (increased *explicitness*). They also learn to use scientific concepts in an appropriate way and in a nuanced manner when they describe a phenomenon (increased *precision*) (ibid.).

Making sense from a science perspective requires a specialised literacy that involves rapid movement across different linguistic modalities, such as verbal, symbolic and mathematical (Lemke, 1998). The explicit, clear and precise nature of the scientific language can also be said to reflect the values of the scientific community (Fang, 2006), although the style of the language can cause learning difficulties for students, especially in heterogenous classes (O'Toole, 1996). Specifically, the use of complex classroom language can reduce cognitive capacity for students (Rincke, 2011).

Three important factors for comprehension of a language are fluency, breadth of vocabulary and knowledge of the language domain (that is, contextual knowledge) (Hirsch, 2003). Hence, learning the language of science also requires learning from experience when to use it and how, as it is situated within contextualised practices (Gee, 2004). Knowing how to use contextually appropriate words is associated with academic performance in science (Rector et al., 2013), and integrating science language learning as part of teaching practices can bring significant improvement in student achievement (Fazio & Gallagher, 2019). However, teachers need specific and explicit support in order to develop their classroom practices (Seah, 2016).

In conclusion, there are many challenges facing learners of the language of science, which can bring differences in language comprehension between students (O'Toole, 1996), and inhibit cognitive capacity for students (Brown et al., 2019). Such challenges include negotiating everyday and scientific meanings (Rector et al., 2013; Rincke, 2011), unpacking complex scientific grammar (Fang, 2006), learning the meaning of scientific terms (Vladušić et al., 2016) and symbols (Liu & Taber, 2016), mastering the rapid movement between different modalities (Lemke, 2005), and learning in which context certain scientific words are appropriate to use (Rector et al., 2013; Seah & Silver, 2020). Hence, language itself can be a barrier when students make sense of scientific phenomena. However, students who are able to participate extensively in classroom reasoning through teacher–student interaction show significant learning gains (Howe et al., 2019).

2.2.1.2 Traversing everyday language and scientific language as part of science learning

To take part in learning, students need to shift between their everyday language and the scientific language that is both a part of the science classroom dialogue and scientific practices (Gee, 2004). The definition of 'everyday language' is not always clear, however; Vygotsky defined everyday language as language learnt through everyday experience (Vygotsky, 1934/1987), whereas Brown and Spang (2008) used the definition of vernacular language, meaning a social language that is spoken and understood within a common culture. In most studies in the field, 'everyday' language is defined as language used by the speaker as part of their everyday life.

Throughout schooling, students progressively learn how to 'speak science' (Lemke, 1990). In a study of children's language with the cultural influence of the interviewer minimised, everyday and scientific language was used interchangeably in primary school, whereas in secondary school, pupils tended to use scientific language for scientific explanations, possibly as they learned which discourse was culturally appropriate (Blown & Bryce, 2017). The teacher plays a large part in controlling the discourse of the classroom and can model the language use to be more or less accessible for the students (Brown & Spang, 2008). However, the everyday language also plays a part in the students' learning, as movement between everyday and scientific discourse as part of classroom learning can be used in teacher–student discourse as an exploratory reasoning practice (Nygård Larsson & Jakobsson, 2020). Everyday language has also been shown to be used by students as a resource for refining scientific definitions through the use of hybrid language (Olander & Ingerman, 2011).

According to Rees et al. (2021), as students develop their scientific understanding. their words become more scientific and they also describe scientific theory more explicitly and precisely. In this way, they move from using a mixture of everyday and scientific words to using scientific words correctly to describe events (ibid.). Although Rees et al. (2021) claimed that a lack of scientific language impedes student learning, it is also possible to follow Vygotsky's (1934/1987) reasoning; namely, that word use is indicative of the word meaning being mediated. From this perspective, the use of a mixture of everyday and scientific language could be interpreted as scientific and everyday concepts moving towards one another as students attempt to express themselves in a language that they understand.

Teaching in vernacular language – that is, replacing new scientific terms with vernacular ones (for instance 'glucose' for 'sugar') and thereby modelling an interlanguage space for the students – appears to especially benefit second-language learners (Ryoo, 2015). In addition, competence in negotiating different scientific and everyday meanings also means paying attention to contextual cues: different meanings reside within different discourses, which can lead to students having difficulties solving problems if they cannot identify the current discourse (Serder & Jakobsson, 2016).

The developing segregation in the Swedish school system has led to increased inequality in schooling (Yang Hansen & Gustafsson, 2016). Previous research shows that speaking a different language at home from what is spoken at school is negatively correlated with science achievement, whereas reading comprehension proficiency is correlated with higher science achievement (O'Reilly & McNamara, 2007; Van Laere et al., 2014), and students with less knowledge of science have been shown to have an advantage when taking science tests if they are proficient readers compared to less proficient readers (O'Reilly & McNamara, 2007). It has also been shown that general literacy significantly increases the students' likelihood of continuing in secondary school science (Cooper et al., 2022). Finally, it has been shown that a student's chemistry self-concept (the student's feeling about their ability in chemistry) is highly dependent on self-perceived chemistry language competency (Rüschenpöhler & Markic, 2020), and in turn, long-term achievement (Wu et al., 2021). Therefore, it is reasonable to assume that language proficiency in general, as well as whether the students speak the school language at home, will have a significant influence on both students' school language use and on their achievement in science.

2.2.2 The role of language in chemistry learning

Chemistry itself also has a complex language, which includes the use of Greek/Latin words, or everyday words, as well as technical language, symbolic language (including chemical symbols, mathematics and diagrams) and subject-specific ways of communicating with other chemists (Markic & Childs, 2016). Therefore, the complexity of chemical symbols can make them hard for novice students to interpret (Liu & Taber, 2016), which could explain the connection between perceived chemistry language proficiency and chemistry self-concept (Rüschenpöhler & Markic, 2020). Gieske et al. (2022) has shown that teaching a chemical concept in vernacular language before introducing terminology is especially effective for learners with lower language competencies, possibly because this reduces cognitive load (Brown et al., 2019).

Following the trend of the research in science education with regard to learning in a second language and its negative impact on achievement, it has been shown that university students studying chemistry in their second language produce less causal reasoning when writing arguments compared to students studying in their first language (Deng et al., 2022). Second-language students have also been observed to utilise code-switching (switching between their native language and the language of instruction) during cognitively challenging tasks (Adams et al., 2015), possibly since learning chemistry in a second language limits working memory capacity (Johnstone, 2006).

In terms of what could help second-language learners in the chemistry classroom, E. N. Lee and Orgill (2022) have shown that these learners prefer to have their question items designed with a highly organised visual appearance, illustrations, and scaffolded sub-sections. This is different from native-language learners, who rely on language clarity and readability, indicating that second-language learners could be more dependent on peripheral cues for understanding chemistry (ibid.). The fact that second-language learners appreciate scaffolded, illustrated questions (ibid.) is in line with the research showing that second-language learners experience higher cognitive loads in the chemistry classroom and have a harder time identifying which information is important (Johnstone, 2006).

Changing from lower secondary to upper secondary school in Sweden, the language of chemistry in particular shows an increase in complexity with regard to becoming more information-dense and containing longer words (Ribeck, 2015). It has also been shown in Swedish classrooms that some teachers do not help their students traverse between everyday and scientific languages (Hipkiss, 2014), which could add to the difficulty that some Swedish students have accessing classroom sensemaking.

2.3 Sensemaking

2.3.1 Sensemaking in science education

As the concepts of meaning making and sensemaking are similar, I will first comment on the similarities and differences between meaning making and sensemaking, and then describe sensemaking in more detail.

Meaning making can be broadly defined as the process of meanings being construed in a situation by people depending on context, experience, emotion and identity, although the definition of meaning making in the research literature varies depending on the researcher (Zittoun & Brinkmann, 2012). Meaning making has been defined in various ways in the science education literature, such as: meaning emerging from the situated use of words formed through an activity (Nygård Larsson & Jakobsson, 2020); the interpretation of events involving reconstruction of memory through cultural influence involving a dialectic between new and prior knowledge (da Silva, 2021); meaning made through the use of a sequence of multiple representations (Widing et al., 2023); an individual bringing together existing ideas with new ideas being encountered, either through musings or through discussion, in an essentially dialogic process (Mortimer & Scott, 2003); or meaning formed as patterns of connections between meanings of words (Lemke, 1990). In some cases, meaning making has also been used interchangeably with sensemaking (Matusov, 2020). Hence, meaning making as a concept in science education is a loosely defined concept that involves situated meaning production, which in some cases could include a dialectical thought process of some kind. Depending on the context, therefore, meaning making could have a transient and purely communicative function; therefore, studies based on this aspect of meaning making in science education often involve transient dialogic episodes where some sort of scientific meaning is being established. Sensemaking, on the other hand, has recently been more clearly defined in relation to various domains within research in science education (Odden & Russ, 2019a). Here, it is defined as a construct separate from arguing, reasoning or explaining (ibid.), concepts that could all contain aspects of meaning making.

Sensemaking in science learning has been defined as 'a dynamic process of building an explanation in order to resolve a gap or inconsistency in knowledge … built in one's own words, through an iterative process of construction and critique' (Odden & Russ, 2019, p. 199), while at the same time connecting to prior knowledge and lived experience. According to Odden and Russ (2019a), sensemaking can be seen as a stance to science learning (figuring something out), a cognitive practice (integrating knowledge and connecting representations) and a discursive practice (constructing and critiquing an explanation). Hence, sensemaking is essentially a language practice that involves the students' own words, both scientific and everyday ones (Kapon, 2017; Odden & Russ, 2019a). Studies have shown that students who are regularly engaged in scientific sensemaking learn the scientific content better than students who do not (Cannady et al., 2019).

As students learn, they can be observed to move from a more muddled scientific language use to a more specific one with higher explicitness and precision (O. Lee et al., 2013, 2019; Quinn et al., 2011; Roth & Lawless, 2002). It has been suggested that everyday language can be used in combination with scientific vocabulary to drive the process of sensemaking forward through the creation of 'hybrid' discursive spaces (Kamberelis & Wehunt, 2012; Nygård Larsson & Jakobsson, 2020; Olander & Ingerman, 2011; Sherin, 2006). These spaces can support sensemaking in a continuous dialectic between theory and phenomenon (Russ & Odden, 2017).

Drawing from research in chemistry education, sensemaking can be described as involving an interaction of the three knowledge domains of the triplet through the use of language: describing phenomena, utilising symbolic representations and relating to relevant scientific models (Taber, 2013). For meaningful learning, knowledge of different subtopics must also be integrated into the sensemaking process (Odden, 2021a; Taber, 2015). The use of language in this way requires knowledge of specific terminology, its link to scientific concepts, and how to use both language and concepts in an appropriate way (Seah & Silver, 2020). The use of scientific representations as linguistic resources also plays an important role: a varied use of representations can give different insights as part of the sensemaking process (Prain & Tytler, 2022; Yeo & Gilbert, 2022), and has been seen to increase with learning (Blown & Bryce, 2017; Yaman, 2020). However, symbolic meanings need to be clearly explained as part of the learning process (Liu & Taber, 2016; Redish & Kuo, 2015). Practical work can be a particular support for sensemaking practices in that it stimulates students to go back and forth between reasoning about experimental data and reasoning about models (Russ & Odden, 2017).

In addition to the general language difficulties students face when learning science, challenges with relating between knowledge domains have also been observed, especially connecting theory to observable phenomena (Gunstone & White, 1981; Hofstein & P. M. Kind, 2012; P. M. Kind et al., 2011). It has been suggested that teachers need to spend more time helping students connect these two domains (Abrahams & Millar, 2008). Connecting symbolic and theoretical domains can also be supportive of sensemaking, in that mathematical symbols carry many implicit meanings that can be utilised in sensemaking practices (Zhao & Schuchardt, 2021). This type of connection allows for deep learning for students (Bain et al., 2018, 2019), and improves student problem-solving (Schuchardt & Schunn, 2016). However, students can find it difficult to apply mathematical concepts within the context of the scientific classroom (Becker & Towns, 2012; Redish & Kuo, 2015), and may need teacher support to do this. Peer talk has been also shown to be effective, especially for low-achievers, in supporting sensemaking as part of a classroom practice (Rivard, 2004).

2.3.2 The issue of tension during sensemaking

It is well established that emotions can affect learning; whereas some negative emotions such as confusion can lead to deeper learning for students, other negative emotions such as stress and frustration can increase the cognitive load for a student, thereby reducing the student's access to cognitive resources, which leads to slower learning and lower student performance (Plass & Kalyuga, 2019). On the other hand, positive emotions facilitate creative thinking, which improves both intrinsic motivation and broadens the availability of cognitive resources for students, leading to positive impacts on learning (ibid.). Confusion can be beneficial to learning because it leads to increased deliberation and focus (D'Mello et al., 2014). Confusion during sensemaking has been observed at the same time as both curiosity and surprise, and can enhance learning for students studying at upper secondary school (Vilhunen et al., 2022). However, if unresolved, confusion can lead to frustration and disengagement from the task at hand (D'Mello & Graesser, 2012).

Emotions can also be connected to perceived self-efficacy (belief in one's ability to execute a task (Zittoun & Brinkmann, 2012). High perceived self-efficacy leads to better problem-solving capacity, higher active engagement and greater perseverance in the face of difficulty (Bandura, 1989). However, low perceived self-efficacy leads to distress and poor functioning (ibid.). Because of the need for students to express their own reasoning and connect to their own experience in order to make sense of scientific phenomena, it has been suggested that there may be a tension between the type of sensemaking produced by the students' own curiosity and the need for the teacher to guide the sensemaking according to the pre-existing norms of scientific reasoning, thereby representing the scientific community (Russ & Berland, 2019).

Perceived teacher support has been shown to be an important factor influencing student engagement in intellectual risk-taking while studying science at school (Beghetto, 2009). Guarded student responses in teacher–student interaction can arise from students' fear of failing or students feeling like they are asked for the purpose of being assessed. If students in the chemistry classroom are encouraged to present alternative ideas of phenomena for the purpose of inducing cognitive conflict and labelling them publicly as incorrect, this can lead to the students reducing their participation due to an unwillingness to be exposed (Criswell, 2012). However, questions that aim to have students articulate their ideas and reasoning can place students in the role of 'complementary experts' (p. 445) in the interaction. This type of teacher moves lead to students not only taking up more conversation space, but also providing more sophisticated explanations (Oliveira, 2010).

2.3.3 Promoting sensemaking in teacher–student dialogue

General practices for promoting sensemaking in dialogue includes differentiating instruction, asking questions that lead to productive discussions, challenging students for higher-level answers, keeping to discipline-specific norms and making connections between both different types of concepts and levels of knowledge (Fitzgerald & Palincsar, 2019). Teacher questioning strategies that build on student responses and promote student elaboration on their statements can lead to students producing more cognitively complex answers, which include relating observations to theory (Chin, 2006). Research also shows that, to promote learning through student-centred activities, teachers can work toward anticipating responses, monitoring student ideas, selecting which ideas to display and in which order, and connecting concepts and experience (Stein et al., 2008). Teacher-questions that are either open-ended or ask students to apply their knowledge leads to more student reflection about concepts (Smart & Marshall, 2013).

Teacher moves that promote dialogic sensemaking can be Socrative questioning to elicit student reasoning, supporting the use of several modes of representation, connecting the macroscopic and visible with the submicroscopic level of thinking, as well as supporting students' use of scientific terminology (Chin, 2006). Lidar et al. (2006) also pointed out that teachers can guide student sensemaking through specifically pointing out to students what path is useful for further reasoning; and through teaching students what to pay attention to and what counts as relevant knowledge when observing a scientific phenomenon. Finally, helping students to use terminology to describe phenomena can also support productive sensemaking (Benedict-Chambers et al., 2017). Teacher questioning focused on student reasoning can scaffold student connections between theory and practice and influence classroom dialogical norms towards sensemaking (ibid.).

In addition to this conceptual guidance, teachers have also been observed to utilise dialogical 'politeness' strategies, including the use of student (vernacular) language, giving excuses for student difficulties and using inclusive dialogue that includes both people in the statements (using pronouns such as 'we' or 'us') (Bills, 2000). It has been suggested that this teaching strategy downplays the intrinsic power dynamic of the teacher–student relationship (ibid.). Teachers can also increase cognitive engagement for students through promoting an atmosphere of mutual respect for all speakers in the classroom (for instance, encouraging face-to-face interaction in dialogue) and through engaging students in expressing their thoughts in their vernacular language before introducing scientific terminology (Soysal & Yilmaz-Tuzun, 2021).

2.3.4 Sensemaking in chemistry

The conceptual integration that is part of the sensemaking process (internally relating different concepts to one another) is important for meaningful learning in chemistry (Taber, 2015). Sensemaking practices between experts and novices are clearly different in the subject of chemistry. Whereas trained chemists have been shown communicate freely and purposefully using representations and symbols from all three knowledge domains (Kozma et al., 2000), learners have been shown to have difficulties both comprehending representations and using representations to connect across domains (Daubenmire, 2014; Kozma & Russell, 2005). These student difficulties include differentiating between observational and the particulate knowledge domains, and making effective use of the symbolic language of chemistry (Andersson, 1990; Becker et al., 2015; Ben-Zvi et al., 1988; Gabel et al., 1987; Haigh et al., 2012; Hernández et al., 2014; Johnstone, 2006; Stieff et al., 2013; Talanquer, 2008; Treagust et al., 2003). In chemistry sensemaking, representations can be especially effective in mediating the connection between knowledge domains (Pham & Tytler, 2022; Yaman, 2020). Pham and Tytler (2022) have suggested that blended representations that represent both the observational domain and the theoretical domain can be helpful in achieving such a connection.

Seah et al. (2011) showed that students may have a poor understanding of how to connect theory to phenomena in an appropriate way linguistically as part of a sensemaking act in chemistry, and that this produces variation in sensemaking. Students can be supported in their sensemaking practice through the establishment of normative classroom criteria for what counts as, for instance, a good explanation or an appropriate interpretation of a chemical representation (Becker et al., 2013). The support of the teacher is also important. A case study of classroom talk in chemistry showed that teacher–student dialogue was very effective in supporting sensemaking in chemistry, whereas teacher monologues had limited influence (Warfa et al., 2014). Instructors in chemistry can promote student sensemaking through the direct practice of asking for justifications and elaborating on student answers relating to the submicroscopic domain (Towns et al., 2019). Another case study showed that instructor questioning and revoicing or elaborating on student answers can be essential for guiding student reasoning across knowledge domains (Becker et al., 2015). If teachers introduce alternative concepts to students when they are struggling to understand a concept, this can lead to sensemaking through the students bringing their reasoning forward via blended conceptual spaces (*conceptual blending*) (Odden, 2021b). It has also been shown that when students articulate their own questions in response to a teacher-set problem, this can support them in engaging in a sustained sensemaking conversation (Odden & Russ, 2019b).

A challenge for chemistry teachers who wish to promote sensemaking in their classrooms is to include all students in the sensemaking practice. There can be variability in conceptual knowledge for students in chemistry, even at the same achievement level in the same classroom (Hinton & Nakhleh, 1999). School chemistry teachers can also face challenges when teaching differentiated classes, especially in terms of not knowing how to best include students in classes with varied language abilities (Kousa & Aksela, 2019).

2.4 Chemical equilibrium as a research topic

Many teachers will recognise that science subjects all have concepts that may be more challenging than others to teach and learn. Within the field of chemistry, chemical equilibrium is one of the more difficult concepts to grasp in chemistry (Barke, 2015; Childs & Sheehan, 2009; Huddle & Pillay, 1996; Johnstone, 2006), and the understanding of this concept requires use of complex reasoning processes involving macro, symbolic, and submicroscopic knowledge domains (Ghirardi et al., 2015).

For chemists, the basic definition of chemical equilibrium is rather simple: it is a reaction where the rate of formation of the products is equal to the rate of formation of the reactants (Burrows et al., 2013). If it is not interfered with, an equilibrium reaction will proceed toward an equilibrium state where a certain concentration of product is always present in the solution, and the concentration of products/reactants is decided by the equilibrium constant, K (sometimes denoted K_c). K is a quotient that does not change as long as the temperature is constant. How fast the reaction proceeds towards equilibrium is not dependent on the equilibrium constant, which means that equilibrium can be reached quickly or slowly depending on the reaction. A rule of thumb that is often used in teaching is *Le Chatelier's Principle*, which is used as a guide to predict what will happen when equilibrium is disrupted. Le Chatelier's principle means that if the concentrations change on one side of the equilibrium arrow, the system will adjust to counteract the change: if more reactants are added, the system will convert more reactants into products until K (a quotient of concentrations between products/reactants) is again reached.

Students can find the concept of equilibrium counterintuitive, as they see 'finished' reactions as static since they cannot observe the reactants being formed from products and vice versa (V. Kind, 2004). In other words, they have a hard time seeing equilibrium arrows ($\rightleftharpoons$) as the representation of a system and not as two separate reactions (ibid.). This leads to alternative ideas; for example, that concentrations should be equal on both sides of the reaction arrows (Barke et al., 2010), that reactants and products remain separate in solution (ibid.), and that the rate of one reaction in the system could change independently of the rate of the other reaction (V. Kind, 2004). Barke (2010) has also shown that some students have difficulties separating stoichiometric calculations (used to calculate a theoretical amount of product achieved only if all reactants are converted into products; that is, the chemical equation is interpreted as proceeding from left to right) with practical calculations (where actual amounts are calculated; that is, the entire chemical equation represents the finished reaction). Because of the many hurdles students encounter when learning chemical equilibrium, it is not surprising that the subject poses difficulties for students (Driel & Gräber, 2002).

An interview study of a range of chemistry students at a large US university showed that even PhD candidates can struggle with the ideas of dynamic equilibrium and stochastic events in reaction processes (Yan & Talanquer, 2015). It may be because of these dynamic aspects included in learning about chemical equilibrium that students take years to fully learn it as a concept (Driel & Gräber, 2002; Yan & Talanquer, 2015), textbooks may misrepresent the equilibrium concept (Quílez, 2012) and teachers may have difficulty applying the concept themselves (Cheung, 2007). According to Talanquer (2015), chemical equilibrium can be regarded as a threshold concept, meaning that the learning of this concept opens up for new ways of thinking about chemistry. Specifically, the understanding of threshold concepts in chemistry enable students to connect the behaviour of a substance with its particulate behaviour in a more nuanced way, which involves a more thorough grasp of the transformation of matter and the understanding of chemical systems (p. 6). Hence, although chemical equilibrium is a complex concept to learn, it opens the door to a deeper understanding of chemistry as a subject.

Difficulties in learning about chemical equilibrium can be caused by how it is presented in school at different levels of learning. During their education, students are expected to progressively refine their understanding of scientific concepts and their interconnectedness. Scientific concept systems can be seen as constantly changing as learning progresses through different school levels, as learnt and new scientific concepts need to be related at different levels of generalisation (Vygotsky, 1934/1987). The concept system related to chemical equilibrium undergoes several changes in terms of how it is presented to students, and its definition is gradually changed and refined (Driel & Gräber, 2002; see Figure 3). At upper secondary school, a qualitative introduction to chemical equilibrium is given with a basis in kinetics, followed by the learning of the Equilibrium Law (Law of Mass Action) (ibid.).

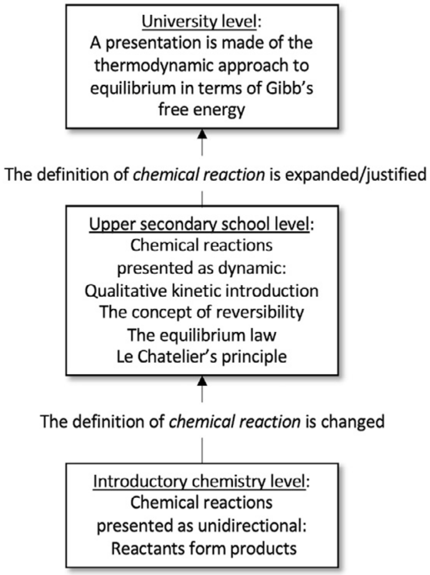


Figure 3. Overview of how the concept of chemical equilibrium is presented in stages throughout education from introductory to university level in many Western countries (summarised from Driel & Gräber, 2002), including Sweden (see, for instance, Borén et al., 2012; Burrows et al., 2013). Initially, reactions are presented as proceeding to completion. This definition is then modified at upper secondary school as the chemical equilibrium concept is introduced. The thermodynamic derivation of chemical equilibrium is presented at university level. From Paper IV (Hamnell-Pamment, manuscript).

As mentioned previously, choices regarding which models to use in chemistry education at what level are usually pragmatic and related to the ease of use (Taber, 2010). However, when models are confused with reality and are learnt as truths rather than more or less sophisticated models, this leads to student confusion and frustration (ibid.), and I think chemical equilibrium is a clear example of this problem. A particular issue with learning chemical equilibrium is that chemical reactions are presented as unidirectional at introductory chemistry level, and then as dynamic at upper secondary school level (Driel & Gräber, 2002). This is contradictory if a facts-based approach rather than a model-based approach is used to reason about chemical phenomena. If not dealt with properly (Taber, 2010) this can lead to problems with understanding chemical equilibrium that remain unresolved. Issues with generating static instead of dynamic meanings do appear to persist at university level (Yan & Talanquer, 2015). Hence, the shift between thinking of reactions as unidirectional at introductory level and dynamic at upper secondary level has consequences for students throughout continuing education.

Because of its centrality to understanding chemistry, and the difficulties upper secondary students encounter when learning it, chemical equilibrium was chosen as a topic of study. This choice was based both on the potential transferability of the results to chemistry learning in general (where reactions and transformations of matter play a central role), and on the possibilities of generating a large variety in the collection of data in terms of student sensemaking. Lastly, the choice was based on the notion that an aspect of research quality is its applicability; that is, its potential to offer worthwhile knowledge and help solve local problems (Miles et al., 2014).

3 AIM AND RESEARCH QUESTIONS

The purpose of this thesis was to gain insight into sensemaking in chemistry at upper secondary school through defining sensemaking in chemistry from a Vygotskian perspective and opening up for an alternative way of viewing sensemaking in chemistry. This purpose included gaining insight into how students make sense of chemical phenomena and how teachers work to promote sensemaking during practical work. In terms of student sensemaking, a specific focus of the thesis was to investigate the influence that previous achievement in chemistry and language use have on sensemaking, as well as how student sensemaking compares to expert sensemaking as represented by use of the knowledge domains of the chemistry triplet.

Before the major data collection for the thesis commenced, triplet concept mapping was piloted in terms of its utility to analyse and promote student sensemaking in chemistry at upper secondary level.

The initial, overarching research question for the thesis was *How does student language use relate to sensemaking in chemistry at upper secondary school, and how can teachers help students make sense of chemistry through classroom dialogue?*

This overarching question was divided into the following sub-questions:

1. How can sensemaking in chemistry at upper secondary school be viewed from a Vygotskian perspective in order to connect sensemaking to social language use, concept formation and development?
2. How do students at upper secondary school structure their sensemaking in relation to the chemistry triplet, and in terms of everyday and scientific concepts?
3. How is upper secondary school student language use and previous achievement level related to their sensemaking about chemical equilibrium?
4. What strategies do teachers use to promote sustained sensemaking about chemical equilibrium in conversations at upper secondary school?

The first research question is addressed in the Kappa; the second research question is addressed in the pilot study, Studies 1 and 2 (Papers I, II, and III); the third research question is addressed in Studies 1 and 2 (Papers II and III), and the fourth research question is addressed in Study 3 (Paper IV).

By asking these questions, I aim to further explore why sensemaking in chemistry is difficult for many students, and what can be done to help teachers create situations in their classroom where chemical phenomena can be made sense of. The contribution to the research field is as follows:

- Sensemaking in chemistry is defined in relation to the triplet, paradigmatic within chemistry education research (Taber, 2013; Talanquer, 2011), and in relation to the sociocultural research field, allowing for the study of mediation of thought through language within the chemistry education research context.
- A study of how students structure their sensemaking about chemical equilibrium allows for a greater understanding of how students utilise their psychological tools to mediate sensemaking in the chemistry classroom.
- By focusing on the impact of language use and previous achievement levels regarding various aspects of student sensemaking, the results of the thesis can further differentiate between learners of different achievement levels and language backgrounds in terms of difficulties with chemistry sensemaking, allowing for a more comprehensive understanding of why it is difficult for some students to interpret chemical phenomena.
- Through studying how experienced teachers help students make sense of chemical phenomena, the results of the thesis can be used to further understand the impact of teacher–student interaction on student sensemaking.

4 THEORETICAL PERSPECTIVES USED IN THE THESIS

As I have described previously, the chemistry subject poses a special challenge in terms of teaching and learning due to the subject's language demands and the problems students face in making sense of chemical phenomena. As the theory of learning proposed by Vygotsky has the advantage of combining the role of language in learning with the development of thinking within a social context, this learning theory is useful as an overarching frame to define the role of language, learning and sensemaking in chemistry. In this theoretical chapter I will utilise Vygotskian theory to frame the analysis of how student language use and sensemaking play a part in their learning about chemical equilibrium in the school laboratory. First, I will introduce Vygotsky's theories on learning and how they relate to language use, learning and development of thinking in the chemistry classroom. Second, I will introduce sensemaking in science as a concept and relate sensemaking to acts of knowledge domain integration in the chemistry classroom, relating to concepts in chemistry education research. I will end the chapter by examining sensemaking in chemistry from a Vygotskian perspective, summarising the standpoint of learning that I take, and explaining what aspects of learning the different sub-studies investigate.

4.1 The Vygotskian perspective on learning

In this section, I will relate the research in the thesis to the sociocultural research field and then describe different aspects of Vygotsky's theories on learning.

4.1.1 The thesis' position in relation to the sociocultural research field

The theories of Vygotsky related to learning (most succinctly summarised in the volume *Thinking and Speech* (1934/1986, 1934/1987) have inspired a wide range of sociocultural research utilising slightly different perspectives on human development and learning (Jakobsson, 2012), such as studies on mediated action, socio-historical studies, studies in distributed cognition and action within communities of practice as well as activity theory (Daniels, 2008; Jakobsson, 2012). All of these research perspectives focus on slightly different interpretations on Vygotsky's learning theory, which Smagorinsky (2018) summarised as 'understanding human development as a historically grounded, culturally oriented, socially-mediated, long-term process' (p. 74). Whereas many researchers (e.g., Leont'ev, 1974/1981, and Greeno and Engeström, 2014), focused on learning from the perspective of the collective, other researchers within the sociocultural tradition have had more of a dialogical focus. A notable contribution in this area is Wertsch's expansions on discourse in education based on the writings of Bakhtin (1991, 2008), which importantly introduced the idea of the different speech genres of everyday language and scientific language as perspectives on the world being negotiated as part of classroom talk (Mortimer & Wertsch, 2003). Examples of other discursive studies utilising a sociocultural framework can be found in the studies on science classroom dialogue focusing on the nature of productive teacher–student interaction by Mercer et al. (Mercer et al., 2004; Mercer & Littleton, 2007) and Mortimer and Scott (2003). Other research related to Vygotsky's works can be understood to have more of a social semiotic focus (Jakobsson, 2012), such as the studies of science classroom discourse by Lemke (1990), where student learning of the scientific language through teacher–student dialogues was examined, and the scientific language analysis produced by Halliday (1993).

Kozulin (1998) proposed that Vygotsky's main achievement was using a theory that explained the development of consciousness using sociocultural activity as an explanatory principle, thereby avoiding the tautological pitfalls in psychology, where, for instance, behaviour is explained through behaviour. Kozulin further argued that activity theory (which was first developed in the 1930s by Vygotsky's followers) falls into this category of research, explaining activity using activity principles, but that the Russian theorists did so due to the political climate of the time (ibid). Vygotsky struggled to publish his works (his research of *pedology* eventually became blacklisted) and the focus on collective labour activity carried on by Leont'ev was later encouraged through the political climate under Stalin (van der Veer & Valsiner, 1993). Hence, the focus of the research of Vygotsky's followers became human activities mediated by division of labour and collective experience (Kozulin, 1998; van der Veer & Valsiner, 1993; Zinchenko, 2004), without involving the consciousness of man (Miller, 2011; Zinchenko, 2004). Many recent studies focusing on mediation have been criticised for focusing on action outcomes rather than the development of cognitive functions or concept development using signs (Gredler, 2012; Miller, 2011).

As I am interested in language use and sensemaking, the work presented in this thesis can be said to be situated in the tradition that focuses on language and language use in learning and thinking most closely represented by the works of Mercer and colleagues (Mercer, 2013; Mercer et al., 2004; Mercer & Littleton, 2007), which have shown the positive influence of classroom dialogical reasoning on individual reasoning and learning. However, the work of this thesis examines social dialogue and thinking separately when examining language use and sensemaking, focusing on the role of language use in each. This perspective is similar to the approach taken in Vygotsky's original work, and this type of approach can be labelled as more Vygotskian than sociocultural, although the approaches overlap (Carlsen, 2007). Because of this, it is mostly Vygotsky's theories that will be elaborated in relation to chemistry learning in this theoretical section. I will attempt to elaborate on some basic concepts in Vygotsky's theories on mind and development, as presented in the volume *Thinking and Speech* (Vygotsky, 1934/1987), a book that summarised 10 years of research work published between 1929 and 1934 by Vygotsky and Shif (his coworker, who published the final chapters after Vygotsky's death). This edition is the most extensive translation published for the English-speaking audience (van der Veer & Yasnitsky, 2011). To provide sufficient background for understanding the concepts developed in this thesis, the experiments conducted by the Vygotsky group will also be outlined.

In accounting for Vygotsky's theories, I will discuss how the development of word meaning (that is, conceptual development; for Vygotsky, 'concept' and 'word meaning' means the same thing) relates to thinking, the role of everyday and scientific concepts in development of reasoning, the ZPD, and, the social influence on language development.

It should be noted that the different editions of *Thinking and speech* differ in that the earlier two are greatly abbreviated (Vygotsky, 1934/1962, 1934/1986), but the latest edition (Vygotsky, 1934/1987) retains changes to the original texts introduced to the later Soviet editions (van der Veer & Yasnitsky, 2011). Therefore, in this theory section, when quotes are given from the 1987 edition, a comparison will be made with the text in the 1986 version when it differs significantly. This comparison will be shown as a footnote.

4.1.2 Vygotsky's research focus in Thinking and Speech

In his experimental works for *Thinking and Speech*, Vygotsky was mainly concerned with the psychological development of the child and its relationship with concept development (the development of word meaning) during childhood and schooling. He also questioned the conclusions by Piaget on children's egocentric speech (now known as private speech; Alderson-Day & Fernyhough, 2015) as an activity directed to self that gradually fades away in childhood as the child is socialised (Vygotsky, 1934/1987). Instead, Vygotsky proposed that egocentric speech is a social activity that is internalised and becomes thought (ibid.). Finally, he questioned Piaget's ideas of solely spontaneous development in children, and instead proposed a model that included the influence of culture and social interaction on human development (ibid.). Specifically, he contrasted Piaget's ideas on children's development ('inner autistic thinking – egocentric speech and egocentric thinking – socialised speech and logical thinking'; p. 75) with his own ideas ('social speech – egocentric speech – inner speech'; Vygotsky, 1934/1987, p. 75), suggesting a need to overturn current ideas on the role of the social environment in child development. In his own words (Vygotsky, 1934/1987):

> The actual movement in the development in the child's thinking occurs not from the individual to some state of socialization but from the social to the individual. This was the basic conclusion of our theoretical discussion. It is also the basic conclusion of our empirical work. (p.76)

To summarise, Vygotsky was interested in the role of the word in learning and development of thought and studied this both from the perspective of the word's use as a psychological tool and from the perspective of its social origin.

4.1.3 The definition of psychological tools in relation to the thesis

Vygotsky (1934/1987) regarded the word as the most important cultural sign, and showed in his studies that cultural development of the meaning of words (referred to in his writings as *concepts*) is promoted through the collaborative, social use of signs (words, symbols etc.), whereby the activity of sign use becomes used internally by the child to direct actions (*interiorised*), which leads to the development of psychological functions such as attention and memory (Vygotsky & Luria, 1930/1994):

> …the *word* [emphasis in original] plays a decisive role in the formation of the true concept. It is through the word that the child directs his attention on a single feature, synthesizes these isolated features, symbolizes the abstract concept, and operates with it as the most advanced form of the sign created by human thinking. (Vygotsky, 1934/1987, p. 159)

Vygotsky's definition of signs also included other tools for thinking, such as equations, maps and mnemonic devices (1930/1981, p. 37). Signs are commonly referred to in the sociocultural literature as *psychological tools* (tools of the mind that are used to directed action inward towards the self), to differentiate them from physical tools (material tools that are used to direct the action outward towards others), which was the original definition by Vygotsky (Kozulin, 1998). However, some researchers (e.g., Wertsch [1991]) preferred not to separate the two types of tools and to focus on the role of tool use in mediating human action. In this thesis, I have taken the original stance of Vygotsky, which focuses on psychological tools and does not regard physical tools as mediators of thought. This stance has been heavily defended elsewhere, where the study of tools and action is attributed to Leont'ev's activity theory (Miller, 2011).

Davydov (1995) described learning and development according to Vygotsky as collective activity being 'interiorised' through the use of cultural, psychological tools and leading to development of reasoning. Wertsch (1991) preferred the term 'appropriation', a term borrowed from Bakhtin, meaning 'making one's own' (1975/1981, p. 294), to describe how psychological tools are gradually taken up by the individual for reasoning as a result of social, collaborative, problem-solving activity. Eun (2019) described the role of words in Vygotsky's theory as multidimensional. On one hand, they are used to communicate the meaning of words in dialogue, and on the other hand they are 'internalised' by people involved in a dialogue involving negotiation of meaning with a more competent other and then used to regulate their own thinking (p. 23). As a result, all thinking used for planning and self-regulating originates in social dialogue (ibid.). Eun also pointed out that the people taking part in the collaborative activity do this within a specific cultural setting with specific cultural resources (ibid.). In short, psychological tools are inherently cultural and our understanding of their meaning has a social origin, which shapes our thinking (Vygotsky, 1934/1987).

Although various interpretations of the relationship between tools and learning exist in the different sociocultural research perspectives, Kozulin (1998) proposed that learning based on Vygotsky's theories can be understood as two parallel processes – microgenetic and macrogenetic:

> Vygotsky perceived psychological development as a process full of upheavals, crises and structural changes. The developmental process can be observed in both micro- and macrogenetic perspectives. Microgenetically it reveals itself in the restructuring of the child's thinking and behavior under the influence of a new psychological tool. Macrogenetically development manifests itself as the life-long process of the formation of a system of psychological functions corresponding to the entire system of symbolic means available to a given culture. (p. 16)

Therefore, the aim of the present thesis, through the use of this Vygotskian perspective on sensemaking, is to study learning from the microgenetic perspective, with a focus on how students use language as psychological tools to make sense of chemical phenomena in concept maps, as well as how teachers guide student language use to promote sensemaking about chemical equilibrium in dialogue. In this context, the psychological tools or signs studied are the words of the language of chemistry as well as everyday language (elaborated on in Chapter 2.2), and the thinking/behaviour studied is the process of sensemaking (elaborated on in Chapter 2.3). The concept developed is the meaning of chemical equilibrium (the learning of which is elaborated on in Chapter 2.4).

4.1.4 Concept development in children

4.1.4.1 The stages of concept development

Vygotsky's first study, reported in Chapter 5 of *Thinking and Speech* (Vygotsky, 1934/1987), involved over 300 children, both adolescents and adults, as well as subjects with various disabilities related to thinking and speech (p. 130). The experiments were made using shapes of various colour that were labelled with words of a fabricated language underneath. The subjects were asked to group the objects and then they received feedback from the experimenter (p. 128). From these experiments, Vygotsky identified three stages in the development of conceptual thinking, from young child to adult. Whereas very young children identified as belonging to the first stage of development grouped objects according to subjective, unstable meanings, the school-age children who were identified as belonging to the second level of development exhibited associative thinking in various degrees (Vygotsky named this process 'thinking in complexes'; p. 136) where no single generalised property was used by the child to link the objects to each other in a group. However, the experiments also showed that the children could, based on the model given by the experimenter, select one type of shape based on its visual appearance. Vygotsky concluded that the meaning of, for instance, the word 'triangle' was visual and associative for the school-child, but abstract for the adult. He called this type of concept (a meaning that is concrete and visual) a 'pseudoconcept' (p. 142). The adolescents in the same experiments used this same type of thinking, but in some cases were also able to use overarching generalisations; that is, abstract (or 'true'; see, for instance, p. 155) concepts when they grouped objects. For example, an abstract concept could be the meaning of 'triangle' as a mathematical definition (ibid.). Through using abstract concepts, the adolescents exhibited the third stage in concept development. Vygotsky concluded from this research that word meaning is socially acquired:

> …the child's complexes[1] (which correspond to word meanings) do not develop freely or spontaneously along lines demarcated by the child himself. Rather, they develop along lines that are preordained by the word meanings that have been established in adult speech. (1934/1987, p. 142)

Hence, although a concept may have a cultural definition, word meanings used by children usually do not correspond to word meanings used by adults, although a common understanding is usually reached when the words are used in everyday con-

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[1] In the 1986 version, 'in real life' is added as a context here, and large parts of the section are emphasized in italics (p. 140).

versation. According to Vygotsky, students at upper secondary school level are often expected to reason visually and associatively rather than abstractly, and may therefore use associative thinking rather than generalised thinking when making sense of a chemical phenomenon such as chemical equilibrium when encountering a colour change. Such thinking might involve associating to previous reactions involving colour change rather than utilising the theory available for reasoning.

According to Vygotsky, concept development was not regarded as a linear or a developmentally fixed process. On the contrary, he insisted, based on these experiments, that various types of concepts are used in thinking and that the use depends on the context:

> *The various genetic forms co-exist* [emphasis in original], just as strata representing different geological epochs[2] coexist in the earth's crust … When applied in the domain of life experience[3], even the concepts of the adult and the adolescent frequently fail to rise higher than the level of the pseudoconcept. (1934/1987, p. 160)

Hence, associative thinking is not seen as a step on the way toward abstract thinking; rather, abstract thinking, or thinking using models such as models in chemistry, becomes an additional way of thinking that gradually becomes available to children during their adolescent development.

4.1.4.2 The role of mediation: The relationship between sign use and psychological development in children

In his theories about how sign use is related to development of thinking, Vygotsky drew parallels to the relationship between tool use and labour activity in Marxist theory (Marxist theory was encouraged through various means in Soviet Russia; van der Veer & Valsiner, 1993). Vygotsky claimed that, just like a physical tool changes labour production and gives external control of objects in nature, psychological tools are social products that are used to control behaviour, both of the self and others. At the same time, Vygotsky proposed that 'the use of psychological tools increases and immeasurably extends the possibilities of behaviour' (Vygotsky, 1930/1981, p. 141).

Through their studies, Vygotsky and colleagues showed that signs were intimately related to the development of psychological functions such as attention. Apart from

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[2] The 1986 edition reads: '…different rock formations', instead of 'strata' from 'different geological epochs' (1934/1986, p. 140).

[3] The 1986 edition says: 'conceptual thinking … insofar as it is involved in solving daily problems…' (1934/1986, p. 140).

pointing at the critical role that signs have in directing attention, Vygotsky also surmised that the development in concepts observed from child to adult meant a radical change in the child's reasoning processes toward thinking mediated by signs:

> … the process of concept formation is not simply the product of a quantitative transformation of lower forms … This process represents something fundamentally new, something qualitatively irreducible to any type of activity based on associative connections. The basic difference between these qualitatively different kinds of intellectual activity consists in the *transition from unmediated intellectual processes to operations that are mediated by signs* [emphasis in original] [4]. (1934/1987, p. 133)

As noted earlier, Vygotsky claimed that the role of the sign, or the psychological tool, is to direct one's own thought processes. In the quote above, Vygotsky emphasised that mediation using signs leads to access to new forms of reasoning that leads away from the more spontaneous, associative thinking characterised by unmediated thought. Hence, the mediated intellectual process is conscious thinking and direction of one's own actions using words, or reasoning utilising culturally appropriated tools. According to Vygotsky's studies, the transition from unmediated to mediated processes occurs before students enter school (Gredler, 2012).

Wertsch (1991), who developed on Vygotsky's theories through the study of learning discourses, focused much of his writing on mediation, or mediated thought, which he expressed as humans acting with 'mediational means' (p. 12). Wertsch suggested that Vygotsky's view of the sign is in terms of its function, or how it is used to mediate action, and that it cannot, according to this theory, be abstracted from its context. However, Gredler (2012) contested this view by pointing out that mediation using signs is context-bound for the young child, whereas the adolescent acquires new ways of organising sign-mediated thought through developing new mental functions that include synthesis and abstraction. The child is context-bound because of his or her lack of self-awareness, whereas the development of intellectual functions means the adolescent can become self-aware and reflect about reality and others (ibid.). Hence, abstract thinking, according to the theory of Vygotsky, not only involves using models to explain chemical events in new contexts, but also being able to consciously reflect around the fact that this is being done.

In Daniels' (2008) analysis of Vygotsky's work and its influence on current research, he pays special attention to the importance of Vygotsky's dialectical approach

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[4] The 1986 edition reads as follows: 'The process of concept formation, like any other higher form of intellectual activity, is not a quantitative overgrowth of the lower associative activity, but a qualitatively new type. Unlike the lower forms, which are characterized by the immediacy of intellectual processes, this new activity is mediated by signs [author's own emphasis]' (1934/1986, p. 109.

as involving the struggle of opposites, leading to a 'reciprocal transformation of the individual and the socio-cultural setting' (p. 32). Therefore, Vygotsky's view on development involved seeking holism rather than identifying with a particular branch of psychology (ibid.). Gredler (2012) noted that Vygotsky utilised his dialectical view of opposition within unity both in his research on developmental change and in his research on the relationship between concept development and thinking. Specifically, Vygotsky noted that developmental changes (such as between the school-age stage and the adolescent stage of development) involved negation of the previous patterns of behaviour and were characterised by large changes in terms of the structuring of thought as a result (ibid.). The different ways of thinking develop on the basis of their opposition. Hence, Vygotsky argued that contrasting in class between the child's everyday reasoning and the scientific reasoning representing scientific culture is necessary for developing new ways of thinking.

Based on further studies on mediation by psychological tools in school and home environments, and the relationship with development of cognition, Kozulin (1998, 2003) pointed out that the use of psychological tools, including their purpose, is embedded in cultural practices. Therefore, according to Kozulin (ibid.), teachers in contemporary classrooms need to pay a lot more attention to decoding signs and elaborating on the underlying principles of elements such as tables, diagrams, maps and graphs, to accommodate students of different cultural backgrounds. Following this reasoning, sign use in the chemistry classroom can also be regarded as contextualised practice. For instance, equations and symbols used to make sense of chemical processes contain layers of meanings (Ribeck, 2015) are useful for chemists communicating in their daily practice, but may be opaque to many students, which complicates sensemaking (Liu & Taber, 2016).

Kozulin (1998) also emphasised the importance of communicating the intentionality and meaning of tools, as well as emphasising their general properties within education. According to Kozulin, 'Emphasis on process rather than product leads to the development of metacognitive awareness and control' (ibid., p. 89). Hence, Kozulin underlined the importance of Vygotsky's observations on the connection between learning and conscious action (with a focus on *conscious* rather than *action*). As Mercer et al. (2004) showed, scientific reasoning is a skill that needs to be taught through dialogical practice. Therefore, students need help in navigating *which* signs to use and *when* to use them with regard to interpreting a chemical process.

Hence, in the chemistry laboratory classroom, it can be expected that the sensemaking the students are able to do while learning about chemical equilibrium will be mediated by the psychological tools they have at their disposal, as well as the intersubjectivity of how these tools are to be used as part of the collaborative meaning-making practice (see also Mortimer & Wertsch, 2003). The use of psychological tools in learning has been shown to change depending on how the students frame their activity within its institutionalised context. For instance, students can focus on making sense, winning an argument or finishing an assignment, which changes how they approach sensemaking (Furberg & Arnseth, 2009).

As Wertsch (1998) argued, tools have both limits and affordances, and can therefore shape human action. Following this line of reasoning, psychological tools in chemistry can be seen as having different affordances with regard to understanding processes, which can be exemplified by the different signs used to mediate understanding of chemical equilibrium at secondary school level (see Table 1). Each representation has certain limits and affordances for sensemaking around a phenomenon being observed in the chemistry laboratory. For example, a chemical equation can, on its own, be seen as a more qualitative psychological tool that mediates some basic information about the chemical species involved in a reaction and the direction of the reaction as it undergoes change. When reworked as a mathematical formula involving concentration, the algebraic expression enables quantitative reasoning around the concentrations of the different chemical species, which allows for more elaborate mediations of the meaning of chemical equilibrium in terms of relative proportions of reactants and products. Finally, if the psychological tool is expressed as a graph, meanings regarding how the chemical process develops over time can be mediated.

Table 1. Examples of some psychological tools (in this case, representations used as part of the language of chemistry) utilised for the mediation of meaning of chemical equilibrium at upper secondary school level, and my suggestion of their affordances in terms of mediation of meaning. Affordance of a certain mediation of meaning using one psychological tool means limitations regarding the sensemaking provided by the use of other psychological tools. The psychological tool used for mediating the sensemaking as part of the social interaction decides the affordance and the limits of the socially produced dialogue in the chemistry classroom. In this interpretation of mediation in the chemistry classroom, I build on the argument of Wertsch (1998).

	Type of psychological tool ordered after increasing complexity		
General types of sensemaking tools used in chemistry	Chemical equation	Algebraic expression	Graphical expression
Examples of tools used for chemical equilibrium	Equilibrium expression using double arrows	Reaction quotient	Concentration vs. process over time
Affordance of psychological tool	Mediation of qualitative reasoning regarding formation of reactants/products	Mediation of quantitative reasoning in terms of ratio of reactants/products	Mediation of reasoning concerning ratio of reactants/products over time

When recruited in the chemistry classroom to mediate sensemaking around a chemical process, the limits and affordance of the psychological tool will frame the social dialogue. For instance, the everyday meaning regarding what happens to salt when it is dissolved in water can be developed through the recruitment of a scientific model through a collaborative classroom activity. This gives students an opportunity to reorganise possible everyday meanings of items that appear to disappear when they are not seen (a common reasoning process emerging from everyday experience [Åkerblom et al., 2019; Andersson, 1990]). The productivity of discursive scientific meaning making has been shown to be affected by students' ability to shift between everyday meanings and scientific meanings (Nygård Larsson & Jakobsson, 2020).

In conclusion, the chemistry classroom can be seen as being in need of contextual direction (or as Kozulin, 1998, put it, individual mediation) to a high degree to promote conceptual development for students through the collaborative use of appropriate signs to mediate conceptual understanding in various contexts. Therefore, in order to understand how psychological tools can be used to mediate sensemaking in chemistry, it is necessary to investigate the relationship between the use of psychological tools and sensemaking in the chemistry classroom for students in both different classrooms and of different achievement levels.

4.1.4.3 The role of everyday and scientific concepts

The research on what Vygotsky called 'everyday' and 'scientific' concepts (the latter of which are introduced in school) was mostly carried out by his student Shif. She presented story-based problems to school-age children from second grade and fourth grade that were equivalent, but could be solved by using either scientific (social science) or everyday concepts. The stories were illustrated using pictures from social science school lessons or common everyday life (the problems were based on material from the social science courses for the second and fourth grade, respectively). The children had to finish sentences that ended with 'because' or 'although' (since children learn to understand cause and effect earlier than they do oppositional relations), and then a 'clinical discussion' took place with the child to elucidate 'cause-effect relationships[5] and relationships of implication with both scientific and real-world material' (Vygotsky, 1934/1987, p. 167). The data were supplemented with information about the children's achievement level and classroom observations. The results of the study showed that children were better at reasoning using scientific concepts than they were at using everyday concepts, but that the fourth-grade children reasoned much better with everyday concepts than the second-grade children did. Finally, second-grade children did poorly on all of the sentences using 'although', whereas fourth grade students did much better (Vygotsky, 1934/1987, p. 168); this indicates that schooling has an influence on student reasoning in everyday contexts. Hence, based on Vygotsky's experiments, the teaching of schools of thought such as scientific reasoning leads to children being able to use such reasoning in their everyday lives. This underlines the value of teaching various ways of reasoning in school to give children a wide toolbox of reasoning to use in their everyday lives.

Another part of the research undertaken by the Vygotsky group was a study of primary school children's schoolwork in relation to their understanding of certain concepts. The subjects studied were 'reading and writing, arithmetic, and natural sci-

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[5] The 1986 edition reads: 'the child's conscious comprehension of causal relations' (p. 147).

ence[6]' (Vygotsky, 1934/1986, p. 180). Three issues were explored: how mature the children's mental functions were when they started school; how instruction influenced the development of mental functions over time; and 'the nature and significance of instruction as a formal discipline[7]' (Vygotsky, 1934/1987, p. 201). The results from this research showed, according to Vygotsky (1934/1986, 1934/1987), that (1) children's thinking is not developed when they start school; (2) as children learn at school, they gain conscious awareness of what they previously have not been aware, and development follows instruction (although not directly) – for instance, as children learn to write, they gradually gain conscious awareness of sounds they produce as they speak, and they learn to be able to reflect around how they express themselves; (3) the abilities developed at school common to all subjects are conscious awareness and volition; and (4) a child's mental development (the developing functions) is indicated by what the child can do with help, not what the child can do on its own (already developed functions). In conclusion, the studies of Vygotsky and colleagues showed that schooling leads to the restructuring of everyday word meanings through the introduction of scientific concepts in all subjects, and this leads to the expansions of the child's conscious awareness (Vygotsky, 1934/1986, 1934/1987).

Vygotsky further rejected Piaget's thoughts on everyday concepts as ideas that had to be overcome in the child. On the contrary, he claimed that the scientific concept and the everyday concept had to develop mutually, but in opposite directions (see Figure 4), with both developing the other in a dialectical relationship (development through opposition within unity). Vygotsky also concluded that the child needs to have developed a basic everyday concept for instruction to be successful; hence, the child develops both concepts as they transform:

> Thus, while scientific and everyday concepts move in opposite directions in development, *these processes are internally and profoundly connected with one another*[8] [emphasis in original]. The development of everyday concepts must reach a certain level for the child to learn scientific concepts and gain conscious awareness of them. (1934/1987, p. 219).

Hence, according to the Vygotskian view of learning, in order to develop concepts in chemistry, teaching situations need to include students being able to relate to their own everyday experiences of chemical phenomena that these experiences can be

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[6] The 1987 version also mentions social science here, but no results from social science are discussed or mentioned after this point in the text.

[7] Section removed from the 1986 edition.

[8] The 1986 version says: 'the two processes are closely connected' (no emphasis) (p. 194).

viewed as practical examples of a general principle of chemistry. This, in turn, leads to a greater understanding of the meaning of the chemical principle.

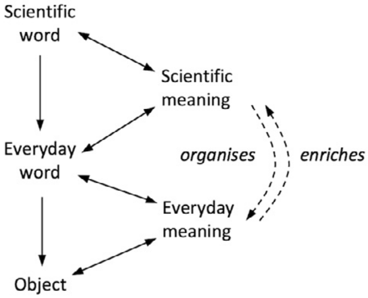

Figure 4. Scientific and everyday concepts (word meanings) and their relation to objects (based on a model by Clarà, 2017). As a child uses a word in relation to an object, a word meaning is formed. The scientific word has an indirect relationship with the object via the everyday word, but the scientific word meaning can organise meaning derived from everyday experience. On the other hand, the concrete and experiential everyday word meaning enriches the scientific meaning and is necessary for development of the scientific concept (Clarà, 2017; Vygotsky, 1934/1987, 1931/1994). For instance, the everyday word 'colour change' forms an everyday meaning (experiential meaning, such as a connection to mixing) in relation to the test tube in chemistry classroom as shift in chemical equilibrium is studied. The scientific meaning of 'shift in chemical equilibrium' has an indirect relationship to the test tube via the everyday word meaning of 'colour change', which means that the everyday meaning stands closer to the object and mediates the secondary, scientific meaning-formation in relation to the test tube. As the everyday and scientific word meanings move closer through education, the meaning of 'colour change' enriches the scientific meaning of 'shift in chemical equilibrium', and the meaning of 'colour change' becomes an example of shift in chemical equilibrium. Adapted from Figure 1 in Paper II (Hamnell-Pamment, 2023a).

According to Vygotsky, conscious reasoning in the adolescent, in terms of the ability to verbally define the scientific meaning of a concept such as chemical equilibrium, occurs quite late in the concept's development – later than being able to apply the concept to a new situation to solve a problem (Vygotsky, 1934/1987, p. 161). Cognitive research has confirmed that the use of formal (or scientific) reasoning varies from task to task and that developing metacognitive awareness is part of adolescent development (Newman & Newman, 2020).

Vygotsky also proposed that scientific concepts are part of concept systems that are crucial for the development of conscious reasoning through schooling:

> Scientific concepts have a unique relationship to the object[9]. This relationship is mediated through other concepts that themselves have internal hierarchical systems of interrelationships…And once a structure of generalization has arisen in one sphere of thought, it can – like any structure – be transferred without train-

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[9] The object is not mentioned in the 1986 version which instead only discusses 'awareness and mastery': 'Scientific concepts, with their hierarchical system of interrelation, seem to be the medium within which awareness and mastery first develop.' (p. 171)

> ing to all remaining domains of concepts and thought. Thus, *conscious awareness enters through the gate opened up by the scientific concept* [emphasis in original]. (1934/1987, p. 191)

Hence, an important part of learning the meaning of a concept such as chemical equilibrium is through its relation to other concepts such as reaction rate or concentration. An example of how a concept system in chemistry can be constructed is shown in Figure 5, where the concept (meaning) of *chemical reaction* is shown to be defined through other concepts (meanings).

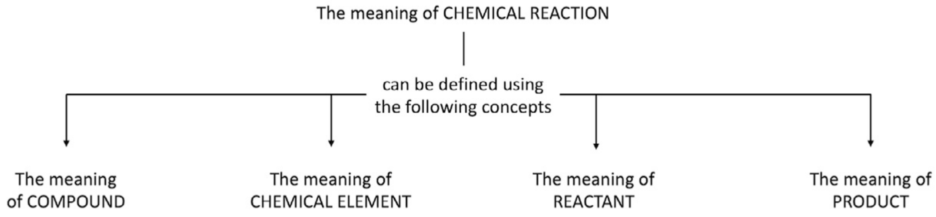

Figure 5. My example of a concept system relating to the concept *chemical reaction*. This example is based on the definition by Vygotsky of concept systems as a system of connected meanings (1934/1987), and shows the interdependence of meanings for students learning chemistry. Learning the basic principles of chemical reactions can lead to abstract thinking around chemical reactions that can be consciously applied to new situations rather than contextualised thinking bound to each specific reaction (ibid.). However, the meaning of *chemical reaction* needs to be mediated through the use of other meanings, such as the meaning of the words *compound* and *reactant*, 'just as a stitch must be seen as part of the fibers that tie it to the common fabric' (ibid., p. 193).

As previously mentioned, according to Vygotsky, the theoretical, scientific concept (or meaning) and the everyday, experiential concept (or meaning), develop mutually. The scientific meaning developed in school organises the spontaneous, everyday meaning, whereas the spontaneous, everyday meaning enriches the scientific meaning through its grounding in visual or otherwise empirical experience mediated through everyday words. In addition to sign-mediation, the types of words of signs a student chooses to use in the classroom in a learning situation determines the outcome of the students' reasoning: the use of everyday language and its lack of a concept system brings arguments that are rich in experience but poor in abstraction (Vygotsky, 1934/1987, p. 193), and the use of a language rich in chemistry concepts brings about mediated, abstract reasoning poor in experiential depth (Vygotsky, 1934/1987, p. 169). The process of learning, according to Vygotsky, meant that 'Everyday concepts are restructured under the influence of the child's mastery of scientific concepts' (1934/1987, p. 216), leading to an enrichment of the scientific conceptual meaning and a changed understanding in the student's private world. In the chemistry classroom, this negotiation of meaning occurs through the social use of words and chemistry symbols for reasoning around processes and visual phenomena that become the student's private experience. Säljö (2010, p. 101) referred to this level of learning as the *microgenetic level*, where participation in a variation of learning tasks leads to the development of reasoning. More specifically, learning at the microgenetic level involves the restructuring of the everyday meaning the student has developed through concrete experiences under the influence of the scientific meaning and its related meaning-system.

Daniels (2008) emphasised the contextual nature of the everyday concept, through which scientific concepts can find their practical application (p. 41). Views on how concepts are developed have enormous implications for educational practice and Vygotsky was highly critical of Piaget's ideas on learning, which focused on the elaboration of everyday concepts, as well as of education that only stimulated already developed functions (Vygotsky, 1934/1986, 1934/1987). Hence, Vygotsky would have been critical of such practices as unguided inquiry as a way of learning science, as this would not lead to development of children's thinking. Importantly, as Leont'ev pointed out (1997, p. 29), the idea that the use of scientific concepts in education could stimulate the development of psychological functions went against all educational theory and practice at the time. For a current perspective, Gredler (2012) suggested that the current focus in schools on covering a lot of content and requiring young schoolchildren to analyse general patterns not only undermines the development of psychological functions (as the child will be forced into acts of memorising rather than developing their everyday concepts necessary for forming concepts in adolescence), but also puts impossible demands on young children as they cannot consciously reflect on their own thought processes without help. In short, the Vygotskian view of learning can be used to explain the advantages of guided inquiry learning in science teaching where students are helped to reflect around their experiences of phenomena (Furtak et al., 2012). Guided inquiry in a science subject can give students not only the possibility to develop concepts short term, but also the opportunity to develop their ability to think and reflect, which is necessary for future studies in the subject. In the same way, students' previous lack of experience of guided inquiry in science would, according to this logic, lead to poor conceptual development and a poor ability to reason abstractly in the science classroom.

4.1.4.4 The zone of proximal development

Of the concepts in learning established by Vygotsky (1934/1986, 1934/1987), the *zone of proximal development* (ZPD) remains the most studied (Eun, 2019). Vygotsky's basic conceptualisation of the ZPD regarded the role of instruction in development. Vygotsky proposed that instruction drives development, which could be most easily seen when studying the ZPD:

> *Instruction is only useful when it moves ahead of development.* When it does, it *impels or wakens a whole series of functions that are in the stage of maturation lying in the zone of proximal development* [emphasis in original]. This is the major role of instruction in development.[10] (1934/1987, p. 212)

Following his observations on the role of the ZPD in learning, Vygotsky proposed that instruction for school-age children should be aimed at developing mental functions, not already developed ones. With functions, Vygotsky alluded to 'attention, memory and thinking' (1934/1986, p. 175), which he studied in terms of how they developed as a result of mediation by signs (Leont'ev, 1997).

According to Eun (2019), Socratic dialogue was a possible inspiration for Vygotsky when he conceptualised the ZPD as part of his theory of psychological development (p. 19). Eun (ibid.) also identified the ZPD as a unifying concept for mediation and interiorisation, concepts that are central to Vygotsky's theory of learning. In short, learning within the ZPD involves the collaborative negotiation of word meaning (mediation using psychological tools with the help of a more competent other), as well as the individuals learning cultural practices of psychological tool-use through dialogue and later including them as part of their thinking (interiorisation of the use of psychological tools) (ibid.).

Because the ZPD includes negotiation of word meaning, this means that collaborative work within the ZPD is focused on concept (word meaning) formation. According to Vygotsky's writings (1934/1987), as a child progresses through school and develops the ability to mediate conscious thought through the use of words and symbols for reasoning, learning occurs within the realm of meaning formation. In this realm, concepts (word meanings) negotiated in collaboration with an adult, teacher or capable peer, are seen as nonspontaneous, whereas concepts (word meanings) formed spontaneously by the child at any level are seen as spontaneous. Spontaneous concepts are used as part of the negotiation process when relating a nonspontaneous concept to a concrete object through the mediation of signs within the students' ZPD; see Figure 6 (Vygotsky, 1934/1987; Clarà, 2017).

Clarà (2017) argued that development is driven by the child's formation of nonspontaneous meanings within instruction, as part of the mutual development of structurally related nonspontaneous and spontaneous word meanings. Vygotsky gave the example of the meaning of the word 'mammal' (a scientific word meaning that is nonspontaneous for the school-age child) and the meaning of the word 'dog' (which for the child has an everyday word meaning and is therefore spontaneous); through education at school-age (primary school) level, 'dog' becomes an example of a 'mammal' (1934/1987, p. 230; ibid.).

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[10] Section removed from the 1986 edition.

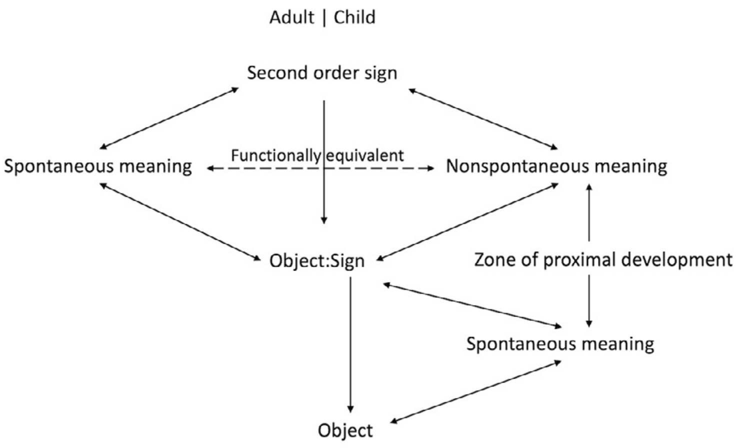

Figure 6. Clarà's reinterpretation of concept development in terms of spontaneous and nonspontaneous meanings, with regard to 'the child's formation of a nonspontaneous meaning within instruction' (Clarà, 2017, p. 57). Double arrows between meanings-signs and meanings-objects indicate that meanings are formed for the relation between the word and the object that the word refers to. For example, the second-order sign could refer to the newly introduced word 'equilibrium reaction' and the object:sign could refer to the word 'chemical reaction' (previously used by the student to describe the formation of products from reactants) when referring to a phenomenon in a test tube as an object. Through learning, the spontaneously formed meaning of the word 'chemical reaction' becomes reorganised in relation to the meaning of 'equilibrium reaction' (although some reactions mean that 100 per cent of the reactants are converted into products, this is often not the case). Image reproduced from 'How instruction influences conceptual development: Vygotsky's theory revisited' by Marc Clarà, published in *Educational Psychologist*, © 2017, reprinted by permission of Informa UK Limited, trading as Taylor & Taylor & Francis Group, http://www.tandfonline.com.

According to Clarà, many interpretations of Vygotsky's theory of concept formation have inconsistencies, as scientific concepts are being interpreted as belonging to various ontogenic stages depending on the researcher (2017). To resolve this issue, Clarà proposed an interpretation of concept formation as a dialectic between nonspontaneous and spontaneous concepts at any ontogenic stage (see Figure 6). According to this interpretation, nonspontaneous concepts are defined as meanings that children or adolescents form within instruction as part of collaborative practice, and spontaneous concepts are defined as meanings that children or adolescents can form on their own. For instance, 'mammal' could be a meaning that is spontaneous for an adolescent but non-spontaneous for the school-age child. In this way, spontaneous concepts can be related to vernacular language (see, for instance, Chapter 2.2.1.2). Within this nonspontaneous–spontaneous dialectic, the spontaneous meanings of the student mediate the relationship with the object. For instance, the dissolution of a salt as a nonspontaneous word meaning can be explained through the already known spontaneous word meanings of chemical bonds, ions and molecules. The student's nonspontaneous meaning, as it is formed, then becomes a functional equivalent of the teacher's spontaneous meaning. This, in turn, means that there will always be a partial intersubjectivity of mediated meaning in the classroom discourse while the meaning is developed. Note that the scientific concept (or meaning) as a cultural construct may have a meaning that is defined by the scientific community, but that the spontaneous meaning formed by the teacher as part of classroom discourse will be dependent on the local classroom activity (Wells, 2008).

Definitions of the ZPD vary in the research literature. According to Eun (2019), there are three major definitions:

1. The ZPD as the distance between individual and assisted performance (leading to research on scaffolding instruction).
2. The ZPD as the distance between understood and active knowledge (corresponding to scientific and everyday concepts).
3. The ZPD as the distance between individual activity and societal activity (leading to a research focus on processes of social transformation).

Clarà (2017), on the other hand, divided research about the ZPD into two approaches, based on how the ZPD is viewed:

1. The ZPD viewed as a target for assessment of maturing psychological functions (a developmental perspective).
2. The ZPD viewed as 'an interpsychological relationship' between an adult and a child where teaching and learning must involve continuous social interaction (an instructional perspective) (p. 51).

According to Clarà (ibid.), both perspectives fail to take the other perspective into account in relation to Vygotsky's theory, which is clearly aimed at the link between instruction and development (although he did not think that this relationship was linear; see Vygotsky, 1934/1987).

Smagorinsky (2018) argued that the ZPD is Vygotsky's 'best known as well as … most widely misunderstood idea' (p. 70), particularly with regard to it being used for promoting various instructional practices, such as scaffolding or peer learning, and being taken out of its sociocultural and long-term developmental context. According to Smagorinsky, this is due to superficial readings of *Mind in Society* (where it is described as 'the distance between the actual development level as determined by independent problem-solving and the level of potential development as determined through problem-solving under adult guidance or in collaboration with more capable peers'; Vygotsky, 1934/1978, p. 86), and an insufficient insight into Vygotsky's other works. Smagorinsky (2018) suggested that scaffolding interpretations have emerged due to literal interpretations of Vygotsky's use of the word 'tomorrow' when speaking of development. In Russia, 'tomorrow' is used as a metaphor for the future – in this case, the near or distant future in which the children can participate more fully in their culture's practices (ibid.).

Chaiklin (2003) underlined the fact that what is being developed within the ZPD is intimately related to children's developmental level, for instance, as defined by Vygotsky, pre-school age, school-age, and adolescence. Based on Vygotsky's writings, Chaiklin (ibid.) proposed that the ZPD's focus depends on the demands put on the child as a result of sociocultural practice, where schooling plays a large part. Within this context, the ZPD could be used to identify maturing functions in a child. For instance, school-age children develop their capability to reason using concepts, and hence, work within the ZPD of a school-age child would include his/her ability to reason using scientific concepts in collaboration with an adult through *imitation* (which, Chaiklin emphasised, is not a mindless activity according to Vygotsky, but instead implies an understanding due to maturing functions that paves the way for being able to solve a problem with some help from a teacher or capable peer).

In this thesis, I have chosen to follow the interpretation of Vygotsky's writings by Clarà (2017), in that I view the ZPD as an individual zone of development that emerges during instruction as word meanings are negotiated with a teacher or more competent peer. As word meanings are negotiated, this leads to the development of word meanings for the learner, as well as the development of conscious, structured thinking over longer periods of time (Clarà, 2017; Vygotsky, 1934/1987). Therefore, this definition of the ZPD is not solely dependent on social interaction (for example, homework can be work within the ZPD if it repeats what has been done in class), but it is always linked to educational contexts (ibid.). I also share Eun's (2019) view of the ZPD as a unifying concept of mediation through, and interiorisation of, the cultural use of psychological tools.

The definition of the ZPD as being dependent of the child's developmental level is especially relevant for studying learning at upper secondary school. According to Clarà (2017), at the higher level of education where the adolescent learns to master abstract thinking, there will be conceptual meanings that are already formed through schooling and can be applied independently and spontaneously by the student. These spontaneous conceptual meanings are different from the everyday meanings developed in early childhood at this developmental stage, and must therefore be distinguished as separate entities. However, during the early school years, everyday conceptual meanings are equivalent to spontaneous conceptual meanings in terms of their development; that is, they need to be reorganised in relation to the cultural concept system within the ZPD (Vygotsky, 1934/1987). Hence (reminding ourselves that, according to Vygotsky [ibid.], varying types of concepts coexist), when students speak in the chemistry classroom, they need to negotiate everyday, experiential word meanings from their private worlds, as well as school-developed word meanings they spontaneously understand and nonspontaneous word meanings they are in the process of developing in collaboration with the teacher to understand the object of study from a chemistry perspective. Learning, from this perspective becomes a much more complex process.

As Clarà pointed out (2017), it is important to take note of the development of conceptual meaning over time: as students utilise new ways of reasoning and master new meanings, certain scientific conceptual meanings will become spontaneous to the students; that is, meanings are formed independently and can be used for individual reasoning through the use of signs. A learning situation in an upper secondary school classroom will reasonably include students who have mastered reading and basic algebra, for instance, and the students will use words and algebraic expressions as part of their reasoning repertoire. From a chemistry perspective, a student could be expected to be able to use the word 'concentration' for reasoning while studying chemical equilibrium, for example. The student will then use these spontaneous meanings to form nonspontaneous meanings in collaboration with the teacher or a capable peer while discussing a phenomenon (Chaiklin, 2003). Furthermore, as Vygotsky pointed out, the spontaneous conceptual meaning then *changes* in terms of its relation to other conceptual meanings of higher abstraction: 'the new structure of generalization to which the child is led through instruction creates the potential for his thought to move to new and higher planes of logical operations. Since the existing concepts are drawn into these operations, their structure is also changed' (1934/1987, p. 233). Scientific concept systems can be seen as constantly changing as learning progresses through different school levels (Vygotsky, 1934/1987, p. 232), which is true for the concept of chemical equilibrium, as discussed in Chapter 2.4.

4.1.4.5 The social influence on language development

The last piece of research summarised in *Thinking and Speech* is Vygotsky's group's work on private speech (or, as he calls it, 'egocentric speech') in children. The first part consisted of a series of experiments with children, all of whom were put in situations where the social aspects of the situation was reduced, such as with deaf children, in a private corner, or in a loud environment. All experiments showed dramatic reduction in the private speech of the children. In the second part of the research, Vygotsky's group studied the composition of private speech and concluded that it consisted of abbreviated meanings – a 'flow of thought' (186, p. 249) – and facilitated the child's actions and awareness. Hence, Vygotsky concluded that private speech in children has a partly social aspect, and rather than it being a sign of egotism that disappears (as proposed by Piaget), it shows the child's speech development from socially directed talk to self-directed talk:

> Speech for oneself has its source in the differentiation of an initially social speech function, a differentiation of speech for others. Thus, the central tendency of the child's development is not a gradual socialization introduced from the outside, but a gradual individualization that emerges on the foundation of the child's internal socialization … speech is naturally reconstructed and takes on a new structure that corresponds with its new functions … Our experiments

> make it clear that the function of egocentric speech is closely related to the function of inner speech. It is not an accompaniment of the child's activity. It is an independent melody or function that facilitates intellectual orientation, conscious awareness, the overcoming of difficulties and impediments, and imagination and thinking.[11] (p. 259, 1934/1987)

Vygotsky also observed that the word is used as a tool to direct conscious attention (1934/1987, p. 159). Through the process of concept formation, the word and its developed meaning can direct the attention of the child and how the child is able to reflect about his or her reality. Vygotsky (1934/1987) proposed: 'The word functions as the means for the formation of the concept. Later, it becomes its symbol' (p. 126). Hence the cultural and collaborative use of psychological tools in the classroom will influence how children later use these tools for their own sense-making practices. Vygotsky described this change from social collaborative activity to conscious individual mental activity as 'a transition from inter-mental functions to intra-mental functions' (p. 259).

The connection between spoken word and attention was later confirmed by Galperin's studies on children's learning, where children learnt how to direct their attention during tasks correctly through talking out loud to themselves (Arievitch & Haenen, 2005). The self-talk gradually disappeared as their performance on the tasks increased, and the students were eventually able to execute the tasks quickly in their minds (ibid.). Hence, from this perspective, the language the student is taught to use in the classroom also reflects what the student is paying attention to and learning. Vygotsky proposed that words are used in order to direct the behaviour of the self or others (Vygotsky, 1930/1981, p. 137). Following this, teacher–student dialogue can be seen as the social origin from which chemistry students learn what to pay attention to in the laboratory classroom, and how to reason in relation to that experience.

Wertsch (1991) pointed out two important implications from Vygotsky's theory regarding the relationship between *intermental* (social) and *intramental* (individual) activity. Firstly, intramental activity will contain traces of the intermental activity from which it developed. Secondly, reasoning can be both individual and social, where intermental activity is a joint activity in which the thinking is produced socially by the participants. According to Davydov (1995), the idea of *internalisation*, or *interiorisation*, was critical to Vygotsky's ideas on development, namely that collective activity is internalised through the use of cultural signs. This underlines the importance of taking a holistic approach to understanding Vygotsky's theory of development, and including both the study of social interaction and individual reasoning when trying to understand sensemaking in chemistry.

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[11] In the 1986 version, this section is heavily summarised.

In relation to this final study presented in the book *Thinking and Speech*, Vygotsky's last works included suggestions for incorporating the child's emotional experience in his theory of development, as a determining factor for promoting developmental change, a fact that Daniels (2009) claimed has been neglected in most post-Vygotskian research. According to Vygotsky, the child's development becomes shaped by his or her individual emotional experience of the context (*perezhivanie*) (Vygotsky, 1934/2020). He exemplified this by referring to how differently siblings develop in the same family conditions, which depends on how much they understand and respond emotionally to their surroundings (ibid.). However, the concept of *perezhivanie* was not elaborated further on in *Thinking and Speech*. According to Lantolf and Swain (2019), '*perezhivanie* was perceived as an emotional experience that motivates thinking and that thinking in turn always implicates an emotional reaction to objects and events' (p. 529). They also underlined that the 'emotion-intellect dialectic' reflects that emotions are never distinct from thinking, but that both develop within unity (ibid.). This means that because emotions affect, for instance, attention, memory, cooperation and commitment, thinking and emotion cannot be seen as separate (ibid.). The aspect of the emotional experience will be further addressed as part of the theoretical section on sensemaking (see Section 4.2).

4.1.5 Definitions

4.1.5.1 How concepts are defined in the thesis

The focus in this thesis is on the study of the use of psychological tools, such as words and their representations as part of scientific discourse, and their influence on sensemaking. This thesis utilises the framework for the development of scientific concepts, or word meanings, proposed by Clarà (2017). Showing that current interpretations of Vygotskian theory vary in their classifications of word meaning in concept development, especially regarding the Vygotskian terms *spontaneous* and *nonspontaneous*, Clarà proposed a more elaborate definition of word meanings, which allowed for theorisation that was congruent with Vygotskian theory and, at the same time, allowed for the study of concept development at any school level. Clarà (2017) differentiated between three types of word meanings:

1. *Everyday* word meanings formed through everyday experience during childhood (meanings lacking a concept system). These word meanings are both spontaneous (spontaneously formed by the child) and experiential (grounded in experience).
2. *Spontaneous* word meanings, which students can form on their own and use for reasoning. These word meanings include everyday word meanings, but also scientific word meanings that students have learnt to form on

their own through schooling. What is spontaneous depends on the student's ability to form a meaning on their own.

3. *Nonspontaneous* word meanings, which students are in the process of learning to form. These meanings are formed in collaboration with, or through imitation of, a teacher or capable peer. Nonspontaneous meanings are scientific meanings formed through the use of words/symbols that students use to form spontaneous meanings as part of learning within the ZPD. The ZPD emerges when meaning is developing for an individual student.

These definitions have consequences for development of word meaning within the ZPD. During early school years, children will negotiate everyday word meanings in relation to nonspontaneous, scientific word meanings (Clarà, 2017). However, in later school years, the ZPD will more likely involve negotiation of nonspontaneous, scientific word meanings with spontaneous, scientific word meanings formed as a result of schooling (ibid.). An example could be the negotiation of the meaning of 'equilibrium reaction' (nonspontaneous concept) in relation to the meaning of 'chemical reaction' (spontaneous, scientific concept) defined as the formation of products from reactants for the students in the present study.

According to Clarà's reading of Vygotsky, spontaneous word meanings mediate the relationship with the object around which the nonspontaneous meaning is formed. For instance, the meaning of shift in chemical equilibrium (nonspontaneous meaning) of iron thiocyanate could, for a student, be mediated through the meaning of colour change (everyday meaning) or the meaning of 'reaction' as formation of products from reactants (spontaneous scientific meaning), or both (see Figure 6).

In order to maximise the clarity of what is being studied, these three different definitions of types of concepts, or word meanings, will be used in the thesis. Since the study takes place at upper secondary level, spontaneous concepts will be scientific word meanings that students can form on their own (already learnt concepts), such as 'concentration' or 'reaction rate'. Everyday concepts will be word meanings with an experiential connection, such as 'colour change', and nonspontaneous concepts will be concepts being learnt, such as 'equilibrium'.

4.1.5.2 The definition of the social-individual relationship in the thesis

The theoretical perspective on learning in this thesis can be said to be dialectical, as it defines the social and the cognitive as separate entities of analysis, developing through interaction within opposition, but part of a continuous whole (Daniels, 2008). As argued by Valsiner (1998), this does not mean that the social and the cognitive are regarded as completely separate; rather, as Hicks (1996) pointed out, they stand in a dialectical *relationship*, where the individual utilises cultural psychological tools to facilitate a 'reconstruction of social meanings' as she takes part in collaborative practices (p. 123). The individual, in turn, can influence the sociocultural setting in a reciprocal relationship (Daniels, 2008). This stance stands in contrast to some approaches in the research field more focused on activity, such as those of Rogoff (1990) or Wenger (2009), that argue that social and psychological factors are inseparable (for an in-depth analysis, see Sawyer, 2002).

Within this definition of the social-individual relationship, the individual student can be regarded as an individual agent available to reflect around chemical processes through the use of interiorised psychological tools that belong to the scientific language of chemistry. From this perspective, the language that the student uses and how it is used becomes vital for mediating the sensemaking process and explaining why such a process may succeed or fail. In turn, how this language use is taught indirectly through collaborative sensemaking practice with the teacher also becomes another important aspect for understanding how and why classroom sensemaking is, or is not, accomplished.

I will now continue to give an overview of the theoretical perspectives on sensemaking used in the thesis.

4.2 Sensemaking

In this section I will elaborate on the construct of sensemaking used in the thesis, and relate it to research in chemistry education.

4.2.1 Sensemaking in science education as a conceptual construct

According to Odden and Russ (2019a), sensemaking has for a long time been a fragmented construct in science education. Based on the science education literature, they proposed a definition of sensemaking as:

> A dynamic process of building or revising an explanation in order to 'figure something out' – to ascertain the mechanism underlying a phenomenon in order to resolve a gap or inconsistency in one's understanding. One builds this explanation out of a mix of everyday knowledge and formal knowledge by iteratively proposing and connecting up different ideas on the subject. One also simultaneously checks that those connections and ideas are coherent, both with one another and with other ideas in one's knowledge system. (pp. 191–192)

According to this definition, sensemaking is built within tension: not only tension between the known and the unknown or two seemingly inconsistent ideas (which causes the individual to feel puzzled or surprised, ibid. p. 192), but also dialectical tension between everyday experiential concepts and formal scientific concepts as they become part of the process of sensemaking.

Based on the research literature, Odden and Russ (ibid.) proposed that sensemaking has been researched (and thereby defined) from three perspectives in science education:

1. Sensemaking as an approach toward learning in science. Participation in sensemaking depends on the expectations and goals of the students, and how the activity in which they take part is *epistemologically framed* (that is, their idea of what the activity is all about, which can be memorising, discussing or having fun). This 'e-frame' (Odden & Russ, 2019a, p. 193) can change on a moment-to-moment basis.
2. Sensemaking as reasoning. Sensemaking involves knowledge integration, which means that previously learnt models of reasoning are connected to new models for reasoning in science, which involves working with different representations such as equations, particle models or graphs.
3. Sensemaking as a language practice. Sensemaking involves the tension between building and refining an explanation through critique, and this is a language practice whereby students must use their own words or own language to be able to participate meaningfully. This language practice can be a practice with others or a personal reflection practice.

From the viewpoint of these three perspectives, sensemaking in science education involves both social and cognitive aspects, which is similar to Vygotsky's theory of learning.

4.2.2 Weick's definition of sensemaking

According to Weick (1995), sensemaking is driven partly by a need to maintain a positive self-image in puzzling situations that pose a problem for the individual in terms of a gap being observed between reality and what is expected. Following this logic, sensemaking is retrospective, making sense of an event that has occurred, and social, as it depends both on previous experience (socialisation and cultural influences) and how others (real or imagined) react to the sensemaking being presented (ibid.). Hence, to Weick, sensemaking must be grounded in experience. Another aspect of sensemaking is its ongoing nature, as people's observations and reflections are triggered by an interruption to a flow of events that embody what is perceived by them as normal (ibid).

Hence, sensemaking occurs 'in the middle of projects' (Weick, 1995, p. 45) and if the gap is not resolved, this leads to an emotional response, and can feel threatening to the individual. Weick argued that sensemaking involves being 'shocked into attention' (ibid., p. 85) for various reasons regarding some discrepancy being observed (although attention can also be raised through another person pointing out the discrepancy). Shock can also occur from confusion that arises when experiencing a highly complex event (ibid.). This jolt to attention can lead to a narrowing of perception, selective attention toward what is familiar, and loss of meaning (ibid.). Hence, Weick's definition of the emotional aspect of sensemaking lies very close to Vygotsky's concept of *perezhivanie* and its influence on learning.

According to Weick (1995), the outcome of sensemaking will be decided partly by which cues are at hand to the individual; that is, the context within which sensemaking takes place. Weick concluded that sensemaking will take the shape of a 'good story' (1995, p. 61); that is, something plausible and reasonable will be constructed that is congruent with previous experience, entices agreement from peers and is both logically and emotionally satisfying.

According to Weick, paradigms with a high degree of consensus regarding how the world is viewed (such as chemistry) can function as frames for sensemaking, where examples such as experiments make sense through being 'stories that exemplify frames' (1995, p. 131). Through the telling of stories that integrate an event within a larger frame, enable discussions about and connect between events, guide action and convey shared values, the complexity of reality and the stress therein is reduced (ibid.).

Weick argued that issues with sensemaking can be more than just the narrowing of perception and reliance on the familiar during events that cause confusion. People's expectations of a situation can also limit what they are able to perceive, especially in novel situations where people have higher needs both for predictability and a sense of order in the world (Weick, 1995, pp. 148–153).

Weick's description of sensemaking can, in many ways, expand on the definition of sensemaking in science provided by Odden and Russ (2019a) in a Vygotskian sense, as it includes experiential, emotional, social and perceptive aspects. A difference between Weick's framework and that of Odden and Russ is the concept of frame, where Weick interpreted Goffman's definition of frame as 'the structure of context' that is mainly a provider of cues (1995, p. 51). These are cues for what is being noticed by the participants and cues that give expectations for behaviour. People can guide others regarding what to pay attention to, and thereby influence the process of sensemaking (ibid). Therefore, Weick's concept of framing in sensemaking is related to influencing the actual process, whereas the framing in sensemaking described by Odden and Russ (2019a) determines whether a student takes part in the process of sensemaking.

I argue that it is necessary to involve both aspects of framing in an analysis of sensemaking in response to the question 'what is it that is going on here?' (Goffman, 1974, p. 25), as Goffman included both ideas in his view on frames (frames as cues for sensemaking and frames as codes for behaviour; see Persson, 2018, p. 63).

4.2.3 Self-concept and face-work in sensemaking in chemistry

As mentioned previously, Weick (1995) stated that sensemaking is partly driven by a need to maintain a positive self-image. Within science learning, self-image can be related to the *academic self-concept*, which can be described as students' own perceived ability to perform an academic test and a description/evaluation of the self in terms of academic ability in relation to others, as well as to their own ability in other subjects (Bong & Skaalvik, 2002). This is a slightly wider concept than the concept of *self-efficacy*, which is a student's self-judgement of their ability to perform a task based on experience from individual events (ibid.). The academic concept seeks to define the overall self-estimation of the student in a defined area, whereas the self-efficacy concept seeks to define students' expectations of their own performance (ibid.). However, the concepts are related; an increase in student self-efficacy leads to higher engagement on task, greater persistence, and greater performance, which over time leads to improvement in academic self-concept (ibid.). At the same time, the academic self-concept is a reliable predictor of academic achievement, as the relationship between the academic self-concept and academic achievement is reciprocal over time (Wu et al., 2021).

When it comes to the academic self-concept in chemistry, student-perceived ability to speak the scientific language of chemistry has a significant positive impact on the chemistry self-concept (Rüschenpöhler & Markic, 2020). The chemistry self-concept (belief in one's academic ability in chemistry) is dependent on student persistence with regard to engaging in chemistry tasks, their self-perceived ability to understand the scientific language of chemistry, and, to a lesser extent, enjoyment in reasoning and feeling of teacher support (ibid.). Therefore, the student self-concept that drives, and is maintained through, sensemaking, is an important factor within the sensemaking process, as positive progress on the task and a feeling of making sense through language leads to continued involvement in chemistry learning and has a positive impact on future achievement in chemistry.

The need to maintain a positive academic self-concept in sensemaking can be related to Goffman's concept of maintaining *face* within an interaction (1955). According to Goffman (1955), in all social interactions people tend to act out patterns of behaviour that express both how they view the situation and how they evaluate the participants in the interaction. This evaluation tends to be particularly focused on self-evaluation, as the social interaction supports an image of self to which people are emotionally attached (ibid.). Goffman refers to *face-work* as the work in social interactions that is done to avoid threats to the face of the interacting participants (ibid.). Hence, according to Goffman, a person's self-concept arises from social interactions in which the person takes part (ibid.), and the self is defined both as an actor and as a construction:

> So far I have implicitly been using a double definition of self: the self as an image pieced together from the expressive implications of the full flow of events in an undertaking; and the self as a kind of a player in a ritual game who copes honorably or dishonorably, diplomatically or undiplomatically, with the judgmental contingencies of the situation. A double mandate is involved. (1955, pp. 237–238)

Following this, it can be expected that threats to student self-concepts in sensemaking will give rise to tension in conversation and compensatory face-work by the participants.

Based on the literature described above, I propose that the definition of sensemaking in science education may need to be expanded on in relation to tension in interaction and participant evaluation in conversation. This issue is further explored in Paper IV.

4.2.4 Sensemaking in relation to research in chemistry education

As I have previously summarised in Chapter 2.1.3, the chemistry triplet is a model for thinking commonly used in chemistry education research. The triplet involves three aspects, or knowledge domains of chemistry, involved in sensemaking: the macroscopic (experiential), the symbolic (the representational) and the submicroscopic (the theoretical) domain (Johnstone, 1991). These can be said to represent the nature of chemistry (Taber, 2013). As mentioned in Chapter 2.1.3, the triplet model has been a successful framework for studying both chemistry comprehension and communication and has become almost paradigmatic in chemistry education research (ibid.). This is likely due to its focus on the role of models and modelling and use of symbols in interpreting chemistry phenomena, which is both a focus for chemistry educators and a challenge for students (Taber, 2010). I also mentioned previously that researchers interpret the chemistry triplet from different perspectives. Therefore, in terms of relating sensemaking in chemistry to the chemistry education research, it is necessary to discuss (a) how the triplet has been defined previously, and (b) how the triplet model can be used as a framework for studying sensemaking in chemistry.

4.2.4.1 Problems arising from attempts to define the chemistry triplet from various perspectives in chemistry education research

I will begin by outlining two problems that are faced in using Johnstone's theory. The first is that establishing how to define the levels of the triangle is not clear-cut. Various researchers have used the triangle in different ways. For instance, all three knowledge domains have been described as 'representations' by some (Gilbert & Treagust, 2009), while others have claimed that only the symbolic level can be seen as a representation (Taber, 2013). In the latter argument, a model of an atom would belong to the symbolic level, but in the former, the submicroscopic. Hence, there is a problem of definition depending on whether the triplet is being interpreted as types of representation of different chemical knowledge or as different conceptualisations from the perspective of the student. For instance, pH is a representation of an experimental, macroscopic property, a chemical equation is a representation of a symbolic nature, and a drawn model of an atom is a representation of a submicroscopic entity. On the other hand, the student can have an experience of a macroscopic phenomenon and can conceptualise this phenomenon either through a macroscopic model (through, for instance, describing acids or bases using scientific terminology) or submicroscopically (such as through describing the interaction between acid and base particles), and communicate this through the use of symbols. From this latter perspective there is also the problem of defining what is to be included in the experiential 'macro' level in an age where images of molecules can be produced experimentally and therefore be experienced (Talanquer, 2011).

If the triplet is not defined properly, a problem also arises when deciding how to classify concepts according to the three knowledge domains, which is how to categorise more complex concepts such as 'amount of substance' and 'energy'. These concepts are macroscopic and abstract. For instance, 'amount of substance' is a concept constructed for the purpose of *function*; that is, to manage macroscopic entities on the basis of proportionality to the number of particles (Pekdağ & Azizoğlu, 2013). Therefore, to say that it is descriptive of a macroscopic property comparable to, say, 'temperature' is insufficient since 'amount of substance' is inherently *not* experiential (which was the definition in Johnstone's original model [1991]). However, 'amount of substance' could be used by the student as an experimental property and not as a conceptualisation of an event. Hence, any definition of knowledge domains becomes difficult because concepts in some context change meaning depending on their use.

4.2.4.2 Recent triplet re-conceptualisations and their usefulness in relation to student sensemaking

Attempts have been made to solve the issue of defining the three triplet knowledge domains. Talanquer (2015) suggested that separating the macroscopic level into an empirical macroscopic sub-level and a macroscopic sub-level based on models might be more useful pedagogically, and Taber (2013) suggested separating everyday perceptions from conceptualisations within either the macroscopic or the submicroscopic levels. As mentioned previously, Taber also suggested that shifting between levels might be gained through the use of symbolic representations, and recommended proposing three new levels: an experiential (everyday) level, a theoretical descriptive level, and a theoretical explanatory level, where the symbolic level is utilised as a resource to transfer between the different levels through the use of everyday and subject-specific language (see Figure 7).

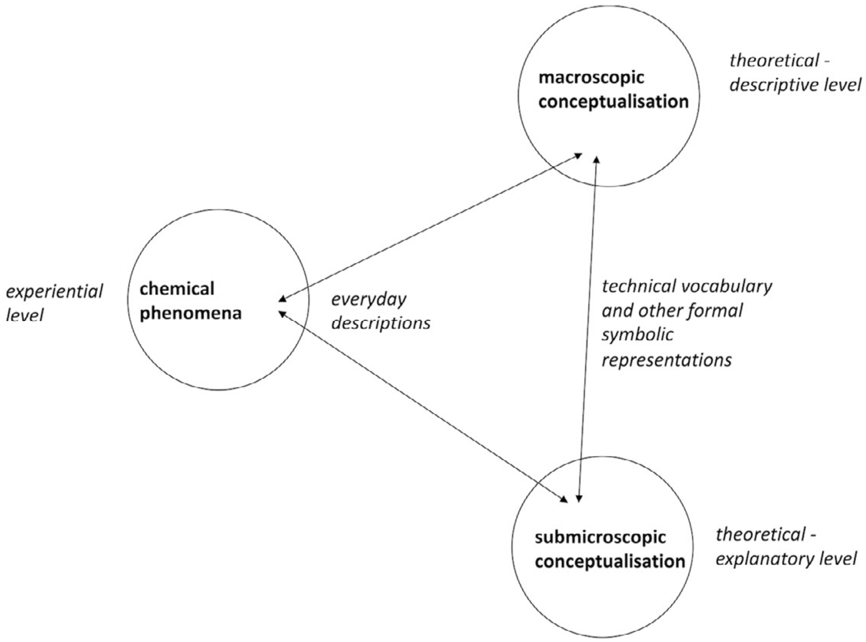

Figure 7. Learning model for chemistry proposed by Taber (2013, p. 165). According to Taber, learners use scientific and everyday language to traverse between the different scientific and everyday concepts through 're-descriptions' (ibid., p. 165). Used with permission of The Royal Society of chemistry, from 'Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education', Keith S. Taber, *Chemistry Education Research and Practice*, 14(2), © 2013; permission conveyed through Copyright Clearance Center, Inc.

Taber's model pays homage to the original ideas of Johnstone, by including the idea of an experiential level of thought, and proposes that learning 'involves re-descriptions (represented by the arrows) between everyday language of direct experience and formal representations of the subject at two distinct levels' (p. 165). This model also is a much more accurate depiction from a sensemaking perspective, involving both scientific models and everyday experiences and the path between. However, it does not fully resolve the issue of known concepts being used to describe new concepts in chemistry, such as the use of 'rate of reaction' and 'concentration' in describing 'chemical equilibrium'. It also does not resolve the issue of the same words being used for experimental properties or conceptualisations depending on the context. For instance, you can measure concentration in an experiment, and you can conceptualise changes in concentration as part of a theoretical model; therefore, 'concentration' has different meaning in terms of sensemaking in the different contexts.

4.2.4.3 *Reconceptualising the triplet fully in terms of sensemaking*

To solve the issue of meaning when interacting with students, it might be possible to reframe the chemistry triplet from the perspective of student actions in the chemistry laboratory. A research study was recently conducted on student reflections on the triplet that involved collaboration with a teacher at the International Baccalaureate Diploma programme (Thomas, 2017). In this study, the chemistry triplet as presented by Johnstone (1991) was defined from the perspective of student reflections about their own thought actions; that is, observing, communicating or explaining (Thomas, 2017). Specifically, students were asked to explain different chemical phenomena using triplet discussion prompts over a period of 20 weeks (see Figure 8). Most students found the exercise useful and all were able to follow the prompts to describe knowledge at the different levels of the triplet.

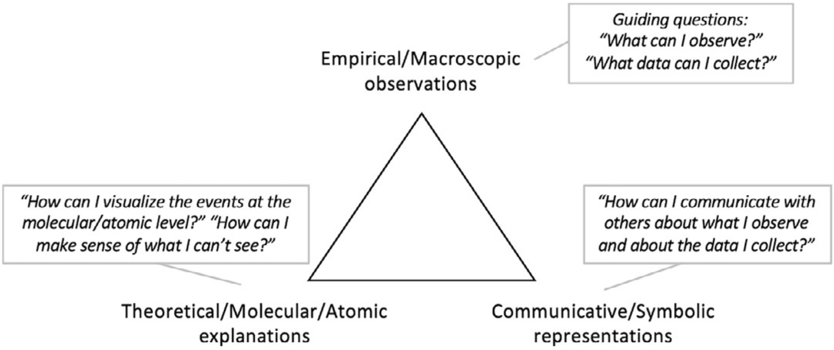

Figure 8. A representation of the triplet based on the perspective of Thomas, showing the original reflective questions given as prompts to the students to promote reflection about the tree knowledge domains of chemistry (2017, p. 540). From Paper III (Figure 1, Hamnell-Pamment, 2023b).

In conclusion, in order for an accurate analysis of student triplet use to take place, it is less useful to use the current theoretical models of chemistry to analyse student use of concepts, as a concept could have multiple meanings for the student within the act of sensemaking. It appears to be more useful to let students describe their own actions by themselves through sorting concepts representing different aspects of the triplet according to how they use them while making sense of phenomena. Hence, for the purpose of this thesis, the model of Thomas (2017) was utilised in defining different aspects of the chemistry triplet based on student actions during sensemaking.

To frame the analysis of sensemaking in this thesis, a clearer definition was made of the chemistry triplet based on student actions during sensemaking in chemistry, shown in Figure 9. To relate to the sensemaking concept defined so far in this section, the macroscopic observations can be related to the experience, which makes the student pay attention to an inconsistency or a gap in knowledge (Weick, 1995). The theoretical explanations (combining the submicroscopic theoretical and the macroscopic theoretical knowledge domains; Taber, 2013) can be related to the theory the student relates to as known and new concepts are connected in relation to the experience to build an explanation (Odden & Russ, 2019a). Finally, the symbolic communications can be related to the connecting to and between the different representational forms necessary for sensemaking in science (ibid.).

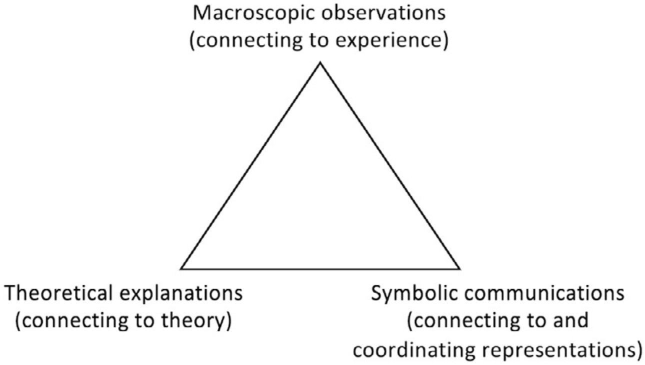

Figure 9. My interpretation of the chemistry triplet in relation to student sensemaking actions, based on Johnstone's (1991) original model, the sensemaking definition presented by Odden and Russ (2019a) and Thomas' (2017) action-based perspective. For each observable chemistry phenomenon, the student can make a typical observation, explain this observation using theory, and communicate this using the symbolic language of chemistry. For instance, when making sense of shift in chemical equilibrium, a student might observe a colour change, explain it as changes in concentration of the different species due to changes in rates of reaction, and express this information as a graphical representation, which can then be connected further to the double arrow in the chemical equation.

4.3 Sensemaking in chemistry from a Vygotskian perspective

I will end this theoretical section by connecting the concepts of sensemaking in chemistry to Vygotsky's theory of learning and development.

4.3.1 Sensemaking in chemistry and adolescent reasoning

According to Vygotsky and later research (Newman & Newman, 2020; Vygotsky, 1934/1987), adolescents can fluctuate between scientific, organised, reasoning using models and everyday associative reasoning. Hence, from this perspective it cannot be expected that sensemaking (connecting formal thought and everyday reasoning; Odden & Russ, 2019) is always accessible to students at upper secondary level. Following Vygotsky's theories, some guidance within the ZPD (such as showing students a model on how to solve a problem that they then use to solve similar problems on their own; Vygotsky, 1934/1987, p. 216) is needed for students to develop formal reasoning over time. This can help ensure that students participate in sensemaking and, over time, can make sense of chemistry phenomena on their own. In this context it is relevant to comment on chemistry as a cultural practice within a paradigm (Weick, 1995). From this point of view, chemistry concepts can be regarded as cultural constructs, where sensemaking according to the chemistry triplet needs to be explicitly guided through scaffolded sensemaking, supporting sensemaking in all three knowledge domains, which has also been recommended by others (Taber, 2013). Paper I, which is a pilot study, investigates how concept mapping can be used to look into how upper secondary school students relate to the triplet knowledge domains. Paper III (another concept mapping study) investigates how student language use and achievement level (that is, the available psychological tools) relate to how students structure their sensemaking in chemistry; in other words, how they organise the knowledge domains in relation to the triplet model.

4.3.2 Mediation and sensemaking at upper secondary school

As Gredler (2012) has argued, the adolescent develops reasoning that moves away from context-bound reasoning to the abstract, although this is by no means a uniform process (Newman & Newman, 2020). Therefore, from a Vygotskian perspective on sensemaking in the classroom, upper secondary school students should be helped to purposefully utilise different models and different representations in order to mediate different perspectives of meaning in relation to observed chemical phenomena. The models and symbols included in the chemistry triplet can be used as tools for communication of meaning and mediation of thought, leading to the development of structured thinking, or ‘expert’ practice, which is also outlined by the triplet framework (Johnstone, 1991; Schönborn & Anderson, 2008). This process needs to involve the students using their own words – that is, vernacular (Brown & Spang, 2008) – and shifting between scientific and everyday meanings (Nygård Larsson & Jakobsson, 2020; Odden & Russ, 2019a). However, as abstract reasoning is still developing for the adolescent (Newman & Newman, 2020; Vygotsky, 1934/1987), teacher provision of contextual cues for sensemaking (Weick, 1995) is expected to be necessary in order for students to mediate these perspectives of meaning. At the same time, as the students’ personal experience influences their emotional cognitive dialectic (Lantolf & Swain, 2019; Vygotsky, 1934/2020), students need to maintain a positive academic self-concept in the interaction in order to promote further engagement (Rüschenpöhler & Markic, 2020). A lack of confidence in their scientific language use to make sense of events can lead to a threat to their self-concept and future achievement, whereby face-work may be needed to resolve tension in interaction (Goffman, 1955; Rüschenpöhler & Markic, 2020; Wu et al., 2021). Paper IV investigates the interactional work teachers do to promote sensemaking in teacher–student interaction.

4.3.3 The role of scientific and everyday concepts in chemistry sensemaking at upper secondary school

As discussed above, development according to Vygotsky arises from the tension produced as everyday and scientific concepts related to chemical phenomena relate dialectically in the chemistry classroom. For instance, a student's experiential meaning mediated by the word 'colour change' (a macroscopic level word) will stand in contrast to the scientific meaning generated when colour change is observed as part of shift in chemical equilibrium (the theoretical explanation). As everyday meanings and scientific meanings are contrasted during sensemaking about a puzzling event, the students can be helped to describe the event using vernacular language (for instance, concentration change or rate of reaction change communicated through a graph), thereby making sense of the observed phenomenon through connecting known concepts to the concept being learnt (Odden & Russ, 2019a). As sense is being made, the student connects the triplet knowledge domains. As the concepts are connected, this leads from a Vygotskian perspective to a reorganisation of the chemistry meaning system accessible to the student through mediated thought, where, for instance, concentration change of iron thiocyanate becomes an example of shift in chemical equilibrium. Paper 2 explores the influence of language as a psychological tool for contrasting everyday and scientific meanings, and proposes a possible use of concept maps to facilitate this process.

4.3.4 The ZPD in chemistry sensemaking at upper secondary school in relation to concept development

I now arrive at the thorniest issue regarding concepts and sensemaking. As part of learning activities within the ZPD, meanings are communicated and developed in dialogue through mediation using psychological tools (for instance, chemistry symbols and models), leading to the interiorisation of cultural thought practices (Eun, 2019). Concept formation mediated by psychological tool use occurs as part of problem-solving activities (Vygotsky, 1934/1987), such as relating the observation of a phenomenon to chemistry theory. Concept formation from a Vygotskian perspective involves relating spontaneous and nonspontaneous concepts at various levels of child development (Clarà, 2017). However, as Vygotsky himself pointed out, it also means overall that everyday, experiential concepts and scientific, organised concepts approach one another (Vygotsky, 1934/1987). On one hand, Clarà's (2017) argument for the use of spontaneous and nonspontaneous concepts as contrasting within the ZPD for the adolescent is reasonable and convincing. On the other hand, the sensemaking process (Odden & Russ, 2019a) and making sense of chemistry (Taber, 2013) clearly involves relating to experience using everyday words, and using both everyday words and known scientific words to describe phenomena. One way to understand this contradiction of ideas is to pay attention to Vygotsky's description of adolescent reasoning as often context-bound, and abstract, formal reasoning as only one of several ways of reasoning accessible to the individual (1934/1987). From this perspective, a learnt scientific concept cannot be expected to be stably spontaneous. In other words, the everyday meaning mediated by the everyday word is most likely necessary to also, on occasion (or often, depending on the student's previous knowledge), mediate the relationship between the object and the unstable spontaneous meaning mediated by the spontaneous scientific word, before a nonspontaneous meaning can be formed. This means that the sensemaking teaching situation from a Vygotskian perspective involves three concepts: the stable, spontaneous everyday meaning; the unstable and sometimes spontaneous scientific meaning; and the nonspontaneous scientific meaning that needs to be formed. Paper II illustrates ways in which students connect these different meanings in concept maps, and Paper IV illustrates how teachers can guide students through sensemaking.

In the results section, I will elaborate on what my research shows on how student language use is related to sensemaking in chemistry in the upper secondary school chemistry laboratory. First, however, I will delve more deeply into the methodology and methods utilised for the thesis.

5 METHODS AND METHODOLOGY

5.1 Methodological approach

5.1.1 Choosing the qualitative research approach

At the beginning of my PhD studies, the main question I wished to seek the answer to was: what kind of learning happens in the chemistry laboratory? From the research that I initially read (Abrahams & Millar, 2008; Hofstein, 2017; Hofstein & Lunetta, 2004; Lunetta et al., 2007), it seemed that there is limited research on what makes the laboratory environment particularly useful for learning compared to other forms of practice, leading to questions about the reasonableness of spending money on practical lessons (Hofstein, 2017). Having spent several years in chemistry labs, including teaching, I felt that there is something crucial that happens when a student encounters chemistry through practical learning, although I could not quite define what it was. Not being willing to limit myself to pre-defined answers within deductive methodology, I turned to qualitative methodology in trying to find out the answer to my question.

Qualitative research methods concern understanding a phenomenon by studying contextual data, natural settings and the point of view of the individuals involved (Cohen et al., 2018, p. 288). Hence, the researcher focuses on the subjective accounts of the participants, searching for causes or consequences, often using an inductive method for authenticity of data and generation of ideas (Cohen et al., 2018, p. 289). Some examples of qualitative, interpretive research methodologies are action research, ethnographic research, ethnomethodological research, and the case study approach, all of which belong to the branch of naturalistic research (Cohen et al., 2018). Whereas action research includes participants as collaborators for authentic change or is even driven by the participants themselves through several cycles of development of some issue important to them, the other research methodologies include the researcher as more of a passive observer of participants and are perhaps less biased towards an agenda (ibid.).

The case study method is special in that it uses a range of approaches to study a real-life project or system (for instance a policy or an education reform, or a learning event) in depth, with a focus on an individual or a group of actors, with the aim of capturing as much contextual data as possible to provide a holistic view of the case (Cohen et al., 2018). A good example is the case study by Hughes and Greenhough (2004) on two students' approaches to homework; the study elegantly demonstrated how contextualised the efficiency of homework can be by the narrative description of two contrasting cases. The researcher generally chooses several methodologies to gain multiple perspectives, and might use both ethnography and survey, for instance, as an approach (case studies are usually non-interventionist; Cohen et al., p. 188). The methods used in a case study could be both qualitative or quantitative and depend on the nature of the case or cases being studied; however, observation is usually used (Cohen et al., 2018, p. 385). Hence, the case study could be regarded as having a pragmatic methodological approach rather than being driven by a particular philosophy, and could therefore include, for instance, elements of experiment and ethnographic research, as long as it is focused on a case (or several cases in the case of comparative case studies). The case is defined by its context and boundaries in time and space (Cohen et al., 2018, p. 377)

Apart from different qualitative research variants representing different views and assumptions regarding the researcher, the worlds being studied, and the participants, all essentially naturalistic methods have drawbacks due to their focus on particular events or individuals, which gives rise to low generalisability that is only applicable to certain contexts (Cohen et al., 2018, p. 289). What they gain, however, is an understanding of individuals acting in and responding to context, which is usually lost in quantitative research due to the need for simplification and statistical comparison that is not always successful in dealing with the more complex issues of human behaviour. Qualitative research is also interpretive in nature, and naturally dependent on the researcher's philosophy and world views when data are being analysed, as well as being open to bias. Reflexivity is an important part of the work ethic of the qualitative researcher, as no observation can be said to be devoid of theoretical basis (Cohen et al., 2018, p. 648), and the researcher must be continuously aware of being biased. Hence, respondent validation and using a range of methods are critical to ensure the validity and reliability of the research (see also Cohen et al., 2018, p. 649), especially if the data are purely qualitative.

In working with case studies, a wider generalisability can be achieved by appropriate sampling in a multiple case approach, where the researcher strives to cover a wide range of variables in the subjects, and validity and reliability can be achieved by triangulation and multiple perspectives, transparency, a sound theoretical basis, thick description and remaining true to the natural contexts (Cohen et al., 2018, pp. 249–250, 381–382). Hence, although the case study might abandon some authenticity if long-time immersion is not attempted, this might well be compensated for by some sound methodological planning.

In my research study, I opted for a multiple case study approach to look at the learning of shift in chemical equilibrium in the chemistry laboratory at upper secondary school from several angles. Only some of the data ended up in this thesis, which focuses on analysis of concept maps and teacher–student dialogues captured on video. I taught concept mapping to the school classes that I visited so that they could map out their knowledge of chemical equilibrium before and after the practical lesson that I observed and filmed. Neither the teachers nor the students involved felt that the concept maps themselves were agents of any active change, and this was also not the intention of using concept maps. Rather, their role was to ask questions to students in a similar way to other ways of collecting research data such as interviews or surveys. I chose concept maps over interviews to map student knowledge due to the general theoretical stance of the thesis being that thinking is inherently social (Vygotsky, 1934/1987). From this standpoint, it can be hard to differentiate between contextualised, social thinking and individual thinking in interviews, as cues for sensemaking from the interviewer can lead to contextualised collaborative reasoning that is hard to compare across data. Concept maps, on the other hand, provide the same contextualised cues for sensemaking for all students. In this case, these cues included a focus question, a scaffold, and five given concepts (for more information on concept mapping, see Section 5.4.1). The given concepts guaranteed that the use of psychological tools by the students for sensemaking could be compared across the different contexts. Writing is also beneficial for students while they reason as it off-loads working memory and gives the opportunity to visualise reasoning using drawings and representations, thereby encouraging reflection (Chen et al., 2016).

Although collaboration was allowed when the students were learning to construct concept maps, the concept maps produced for the research study were individually constructed. In addition to the concept maps, I also collected other data, most importantly the video data, which was used for conversation analysis (I was a passive observer during filming). In addition, I collected interview data and survey data (see questions in Appendix A and Appendix B, respectively). For the pilot study only (which focused on 11 students studying at the International Baccalaureate Programme in a city in Sweden), I included a survey question regarding the students' experienced understanding of the chemistry triplet and of concept mapping (see Appendix C). It is worth mentioning that I collected the data before my theoretical framework was developed, so not all of the data were used. I later added focus group interviews for two of the case studies; however, these data were also not used, other than for the illustrative quotes given in Chapters 1 and 8. An overview of the setup of the study is shown in Figure 10.

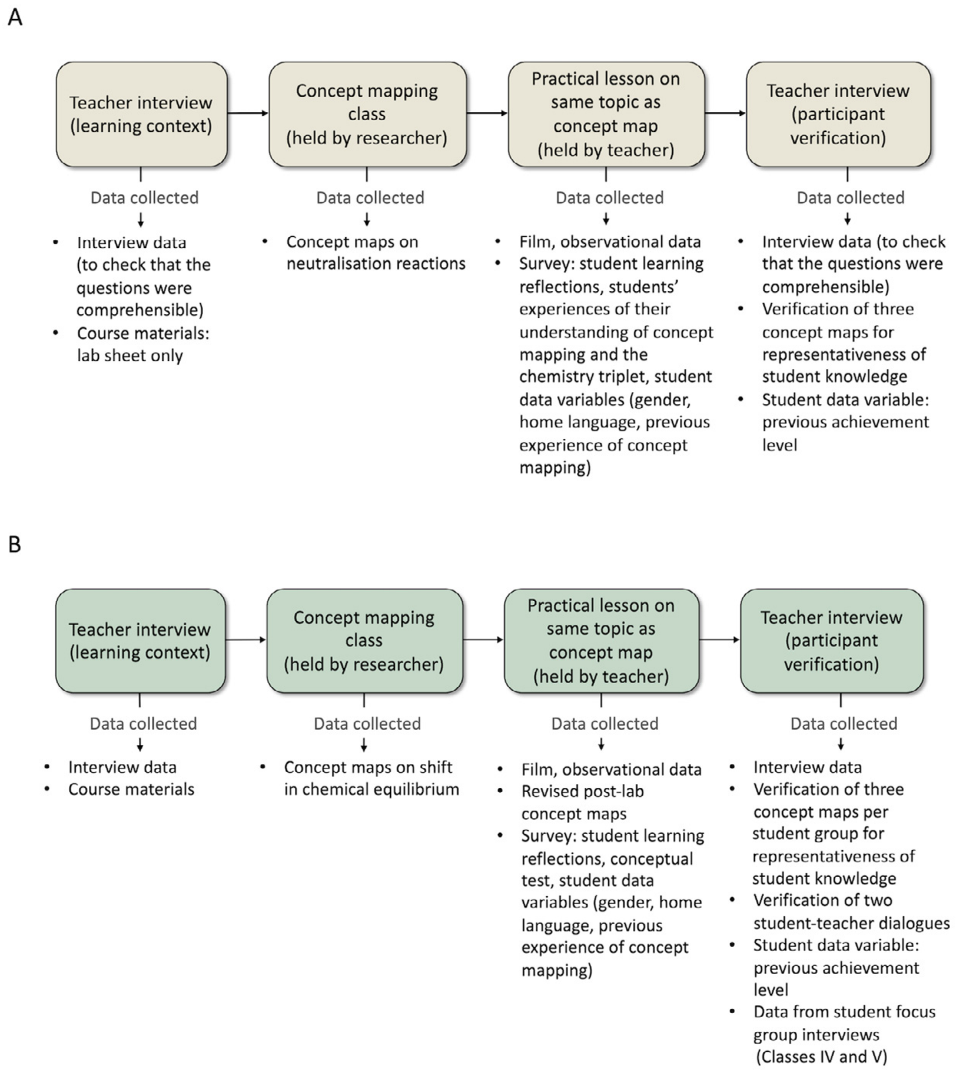

Figure 10. Overview of the case study setup for the pilot study (A) and the five cases (B) from which the data used in this study were collected.

Qualitative studies of selected student populations can be criticised in that they are not representative and therefore carry low reliability in their interpretation. However, the investigation of multiple or typical cases can still bring a contextualised, nuanced view of reality not achievable through statistical analysis (Flyvbjerg, 2001). To achieve a maximally differentiated student sample for the purpose of collecting a wide range of scientific language in the data, a maximum variation sampling strategy was utilised in choosing schools to participate in the study. Such a strategy can be very successful at generating descriptions of typical contexts (Abrahams & Millar, 2008), and carries higher reliability (Cohen, Manion, & Morrison, 2018, p. 157).

I chose to provide the students with psychological tools for their concept maps. As these tools can be regarded as 'hints', in the same way as the teachers give hints to their students as they build explanations about chemical equilibrium (Vygotsky, 1934/1987), the study as a whole can be regarded as being focused on the ZPD; that is, what the students are learning rather than what they have already learnt.

I will now move on to discussing the sampling for the multiple case study, and then describe the participants and the data collection for this study.

5.1.2 Choices made regarding sampling

As the purpose of the multiple case study was to examine language use and sensemaking at upper secondary school level, it was necessary to use purposive sampling to make sure to include the representation of a wide range of student achievement levels as well as learning contexts in the data. Maximum variation sampling (including two different school systems taught in two different languages, and urban/small town/academic areas) was utilised both to increase the transferability of the study results between contexts (Miles, Huberman and Saldaña, 2014), and to make the data as rich as possible to ensure the applicability of its interpretation (Cohen et al., 2018, p. 157). Five school classes in Sweden were chosen; this was considered an adequate number for descriptive statistical analysis while maintaining qualitative analytic depth in terms of interpreting the concept maps, although it needs to be noted that any comparisons of qualitative data need to be based on the similarity of the local contextual factors (Miles et al., 2014). To increase the comparability, a choice was made to collect data from similar educational contexts; that is, the practical study of shift in chemical equilibrium at upper secondary school.

Four schools were approached and chemistry teachers were asked to volunteer for participation in the research study, which included a concept mapping class, observation and filming of a practical lesson in shift in position of equilibrium, two interviews with the teacher about the students and the lesson, possibly a group interview with a few of the students, and the collection of student materials including concept maps, a qualitative survey, and student achievement levels. The teacher was asked to prepare the students as usual in the lead-up to the practical lesson, and then give up the lesson prior to the practical lesson to the researcher for the teaching and construction of student concept maps. Because of the low number of students in the classes at one of the schools, two classes led by two different teachers were studied at this school (Classes III and V; see Table 2).

Table 2. A summary of the contexts surrounding the students participating in the multiple case study. From Paper III (Hamnell-Pamment, 2023b).

Class	School system	School type	School area	Number of participating students	Year	Teacher's description of class during interview
I	Swedish	Municipal	Inner city	18	2/3	Disengaged, but motivated during practical work
II	Swedish	Municipal	Small town	21	2/3	Mostly motivated, calm and quiet
III	IB	Municipal	University town	12	1/2	Motivated and hard-working
IV	Swedish	Private	Inner city	28	2/3	High-achieving and disciplined, very concerned about grades, poor in conceptual knowledge
V	IB	Municipal	University town	10	1/2	Dedicated and engaged in the subject*

A limitation in the sampling was that only very experienced teachers at supportive schools chose to participate in the study. Hence, the student sample cannot be regarded as typical of students in Sweden; rather, it is a data sample produced in optimal student conditions in a variety of settings. However, Flyvbjerg (2001) argued that there is a particular value in the investigation of favourable cases, in that they represent a best-case scenario and therefore carry inherent generalisability to less favourable cases.

Methodologies and perspectives were triangulated, with the aim of achieving convergent validity in the interpretive analysis (Cohen, Manion, & Morrison, 2018, p. 381). Analysis of video recordings (teacher–student learning dialogues) and student concept maps formed the basis of the analytic work. To further understand the collaborative management of social interactions in the laboratory classroom, as well as student individual reasoning in the concept maps, semi-structured teacher interviews were conducted before and after the practical (for questions, see Appendix B). I could have collected more contextual data, through such means as observing the teaching of the classes prior to the practical class, rather than relying on teacher interviews. Then, contextual inferences could perhaps have been made about the social origin of the language in the concept maps, which was not possible based on the chosen methodology.

While students' conceptions of chemical reactions in Sweden do not appear to differ significantly from those of other countries, they may still be influenced by local teaching practices or textbooks used (Andersson, 1990a). Teachers in the sample also used different textbooks from each other (except for the teachers of Classes I and II, who used the same book; see Table 2 for a summary of the sample), but the general outline of the teaching of chemical equilibrium (taking a qualitative kinetic approach, proceeding from reaction rates to chemical equilibrium) was very similar across contexts in the study, and has been shown to be a general practice in chemistry teaching at upper secondary school (Driel & Gräber, 2002). Common issues with understanding chemical equilibrium shown in international studies (Driel & Gräber, 2002; Piquette & Heikkinen, 2005) were also represented in the sample, which indicates that the way the students reasoned in the sample would likely be transferable within an international research or teaching context.

The practical lesson related to shift in chemical equilibrium in Swedish schools is usually not very complicated in terms of equipment, and is focused on eliciting student reasoning about shift in chemical equilibrium. Hence, since the concept mapping class took place just before this practical lesson, it was reasonable to assume that all teachers had prepared their students theoretically before they were asked to produce the concept maps (which was also the case, more or less, according to the interviews).

Previous research shows that speaking a different language at home to the school language is negatively correlated with science achievement, whereas reading comprehension proficiency is correlated with higher science achievement (Van Laere, Aesaert, & van Braak, 2014). The developing segregation in the Swedish school system has led to increased inequality in schooling (Yang Hansen & Gustafsson, 2016). This means that, to understand causality, it is important to study what is happening to learning in multicultural classrooms where students struggle with literacy. To allow for comparisons between different student groups within the study, contextual factors that have previously been shown to be related to science achievement – that is, previous achievement level (Lopez et al., 2014), gender (Martin et al., 2000; O'Reilly & McNamara, 2007), and whether the students spoke the school language at home (Van Laere, Aesaert and van Braak, 2014), either fully, partially, or not at all – were collected from the students as part of a survey at the end of each case study.

5.2 Comments on the participants

Students (N=88) aged 16 and 17 from five upper secondary school classes participated in the multiple case study, with achievement ranging from low-achieving to very high-achieving, as judged by previous course grades or term grades (grades from the course of Chemistry 1 [Kemi 1] for the Swedish school system or achievement levels for the International Baccalaureate [IB] school system[12]). Most students had little or no previous concept mapping experience before the study. The inner-city school class (Class I) had a high proportion of students who speak a different language at home from the school language (Swedish), and so did both of the university town IB school

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[12] In the Swedish school system, students taking science at upper secondary school take a three-year programme with two years of mandatory chemistry courses (Chemistry 1 and Chemistry 2) usually taking place during Years 1 and 2, respectively. Chemical equilibrium is part of the Chemistry 2 curriculum. In the International Baccalaureate Diploma Programme in Sweden, which consists of two years of study and is usually taken after a preparatory year (Pre-DP), chemistry is taken as a continuous course running over two years and chemical equilibrium is usually studied during the spring of the first year.

classes, for whom the school language was English (Classes III and V). Thirty-six per cent of the students spoke a different language at home than the school language.

The highest grades (A or 7) were slightly overrepresented in the sample.[13]

A significant proportion of students, whose previous grades were mostly in the mid-range (D/C or 4/5; but also, occasionally, E or B or 6), did not wish their grades to be connected to their work or their personal information. This group is presented in the results graphs in a separate column as ‘x’. An overview of the distribution of previously assessed achievement levels or grades in the sample is shown in Figure 11.

The teachers involved in the study all had 15–30 years of experience teaching chemistry.

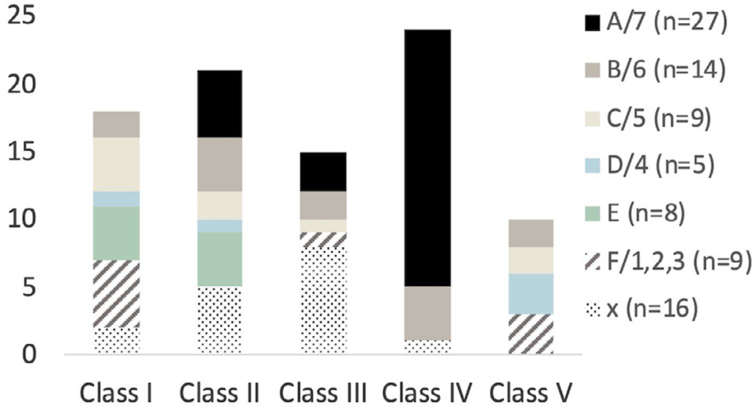

Figure 11. Distribution of previous grades (Swedish school system) in the student sample in terms of number of students in each grade or achievement level, here shown divided over the five student groups (I: municipal, inner-city, Swedish school system; II: municipal, small town, Swedish school system; III: municipal, university town, International Baccalaureate school system; IV: private, inner-city, Swedish school system; V: municipal, university town, International Baccalaureate school system, during COVID-19 pandemic). F or 1, 2 or 3 represent failing grades in the Swedish or International Baccalaureate school system, respectively, and x represents students who did not wish for their grades to be connected with their work or their personal information. From Paper III (please note the addendum to the figure legend compared to the article: x[n=16] instead of x[=12]; the graph itself has not been affected by this article error).

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[13] In the Swedish grading system, the highest grade (A) can be said to correspond to extensive and nuanced reasoning, a C to extensive reasoning, an E to synoptic but satisfactory reasoning and an F to not fulfilling the requirements for E. A B grade fulfills the requirements for grade C; also, to a large extent, Grades A and D work equivalently as a grade in-between E and C (Skolverket, 2010); the IB grades range from 1 = fragmentary to 7 = comprehensive knowledge (International Baccalaureate Organization, 2017).

5.3 Data analysis

5.3.1 Description of the coding process

All materials were transcribed or otherwise digitised and imported into NVivo (concept maps, interviews and documents) or Transana (video recordings and video transcripts), where the materials were subjected to several waves of coding from an ethnographic content analysis perspective, meaning that each document or transcript statement was viewed and interpreted as part of a sociocultural context (Altheide & Schneider, 2013). Hence, interpretation of student–teacher talk was done in reference to the contextual information found from collected documents, video recordings and interviews, as well as the researcher's own insight into the chemistry teaching context. When analysing the video recordings, purely practical conversations between the students and the teacher that were not relevant to visual interpretation or reasoning (such as, 'Where can I find the water?' 'Over there') were not coded.

Constant comparison analysis (Parry, 2004) was utilised to code the data, which meant all concept maps or video transcripts were coded on the basis of the focus of each sub-study, with the codes being constantly compared, merged and generalised where appropriate in a gradual process. As the video materials and concept maps were analysed, a focus on different perspectives of sensemaking gradually emerged. Hence, both the choice of sensemaking as a framework and the more specific research questions for the thesis emerged inductively from the data.

5.3.1.1 Coding of the concept maps

The concept maps were coded using a first wave of coding based on some of the definitions from the theoretical framework as well as concept-mapping literature. This meant that the chemistry triplet, Vygotskian concepts and types of language use all were theoretical concepts that guided how the concept maps were interpreted. These initial codes were then refined inductively in relation to the data. For example, in terms of the analysis of the language use in the concept maps, the research literature guided the definition of categories during the first wave of coding (where different numbers indicated different degrees of explicitness and precision of student language; Section 5.4.1.2 outlines the previous research that guided the coding). However, following the example of Besterfield-Sacre et al. (2004), these categories were then refined inductively during the second wave of coding through describing different categories and subcategories of overall language use in the concept maps. For a full definition of the final categories of language use in the concept maps, and for coding examples, see Papers II and III.

Framework analysis was utilised to facilitate constant comparison of the concept map codes, which meant that relevant text summaries in the participants' own words were charted into a thematic matrix with coding labels. This enabled an overview of the data for contrasting and comparing groups of codes, refining of the codes into categories, and providing an overview of the trends in the codes. As part of the framework analysis, codes were grouped into dimensions within typologies or themes, where each concept map could only be classified as one particular dimension of a theme (Ritchie, Spencer and O'Connor, 2014). This analysis was also done in NVivo. Coding was accompanied by regular memoing (Cohen, Manion and Morrison, 2018, p. 719), and theme dimensions were explored for interactions across themes and variables (Ritchie, Spencer and O'Connor, 2014) using the NVivo query function. Codes in various constellations were run through searches against the variables collected from the students (previous chemistry grade, language spoken at home versus school language, gender and concept mapping experience) to look for further patterns. To optimise the analysis, any patterns found were re-verified in the original materials (Cohen et al., 2018, p. 719). As the data sample was quite large (88 students), quantitative analysis, in the form of descriptive statistics, using SPSS, was performed to illustrate the trends in the data codes.

During the concept map analysis, the codes changed only in minor ways as data from Case Studies IV and V were added, indicating some data saturation (Cohen et al., 2018, p. 601).

5.3.1.2 Coding of the video recordings

The approaches to coding of the video recordings were two-fold: A first wave of descriptive coding was followed by a second wave containing three coding perspectives: in vivo coding, coding based on previous research (viewing the conversation from the perspective of the chemistry triplet), and process coding. Initial codes were developed from coding a subsection of the data (a detailed transcription and coding of all longer teacher–student interactions in the video data), and then used as a starting point to code the rest of the data. Codes were refined as an iterative process and explored for dimensions and patterns (Miles, Huberman, & Saldaña, 2014). A codebook was developed to maintain code definitions throughout the coding process. All the video transcripts were analysed through going back and forth between transcripts and videos in Transana.

5.3.2 Analytical considerations regarding the text analysis

Framework analysis using a constant comparison approach can be an effective way of dealing with large amounts of qualitative data because it generates possibilities of constant review (Gale et al., 2013). A notable aspect of framework analysis is that closeness to the original data is kept for as long as possible during the analysis, enabling an overview of the themes at the same time as some of the original data are visualised (Ritchie et al., 2014). This means that the researcher can make comparisons across as well as within cases, which can highlight instances of uncoded data, contradictory coding, or deviant cases (Gale et al., 2013). A possible drawback of the method is that the coding matrix generates an illusion of quantitative analysis, skewing the focus toward counting codes rather than looking at variability within themes (ibid). Another drawback is that framework analysis is time-consuming (ibid.).

According to Altheide and Schneider's ethnographic approach to document analysis (2013), documents can be regarded as cultural artefacts generated as part of social processes situated within a certain context. This means that documents produced within a context cannot, from this perspective, be interpreted through pure content analysis. Instead, the ethnographic analyst asks questions such as: How does this text relate to its larger cultural context? How does the text relate to the setting? Who is the text produced for? What representational choices have been made? What perspectives of interpretation of the text can be taken? (Altheide & Schneider, 2013, p. 12). This type of analysis is consistent with a symbolic interactionist perspective and focuses on the meaning being produced in the activity, as well as underlining the importance of interaction between people (ibid.). In order to perform ethnographic analysis of documents of sufficient quality, the researcher must be familiar with the context within which the documents are produced (ibid.). This can be achieved through immersion in the field or immersion in documents (ibid.).

Although I am a chemistry teacher, and therefore familiar with the contexts I have studied and able to conduct relaxed interviews with other chemistry teachers to complement my classroom observations, it is likely that some of the contextual information was lost when I collected my data, as I did not observe the classes I visited for longer periods of time. For instance, I cannot say a lot about the social milieu of the classrooms or individual student learning journeys in relation to the concept maps or conversations studied. In order to study the relationship between social interaction and learning as *change in sensemaking over time*, another study would be needed that focused on studying individual student learning journeys in different social contexts. However, the use of the language of chemistry studied in this thesis has been analysed as a cultural construct that mediates a certain meaning within the teaching context from which it originates. According to Vygotsky (1934/1987), this meaning reflects both its originating social context and the individual's thought process.

5.3.3 The use of conversation analysis to study teacher–student classroom interaction

In Paper IV of this thesis, conversation analysis (CA) was utilised to study teacher–student sensemaking. CA is a method used by ethnomethodologists that focuses on how interactions are managed in conversations (Heritage, 1984). These conversations can be both general (as in everyday conversations) or institutional such as in clinics or schools (ibid.). According to Heritage (ibid.), conversational interactions are, from an ethnomethodological perspective, both '*context-shaped* and *context-renewing* [emphasis in original]' (p. 242). This means (1) that a conversational action can only be understood within the context it is being produced, especially with regard to the preceding actions within the interaction; and (2) that each action will bring context and thereby understanding of the actions that follow. Hence, less attention is paid to assumptions about the interaction by the researcher, meaning that CA is largely based on the actions of the conversation participants (Heritage, 1984). The focus of CA then becomes the turns taken within conversation; what these turns say about the overall structure, or organisation; and conducts that the participants agree on reproducing and the actions give evidence to (ibid.). Hence, CA focuses both on the common actions by which conversationalists reflexively manage their interactions in various ways, and on the overall norms that are maintained through the use of these actions (Heritage, 1984; Hutchby & Wooffitt, 2008). These actions are often organised in specific ways. Schegloff referred to *sequence organisation* as the organisation of different actions, or moves, enacted through orderly, turn-based talk (Schegloff, 2007). Hence, turns of talk can be examined in terms of what they achieve and what their overall goal is (ibid.). The structure of interaction also provides a basis upon which the interactants can manage sensemaking within that interaction (Heritage, 1984). According to Peräkylä (2016), 'the uniqueness of CA…resides in the way in which it shows how "action", "structure" and "intersubjectivity" are practically achieved and managed in talk and interaction' (p. 1).

The basic unit of analysis for CA is the *adjacency pair*. According to Schegloff (2007), an adjacency pair can be defined as follows: (1) It contains two turns at talk; (2) it involves two speakers; (3) These turns of talk are adjacent – that is, next to each other; (4) these turns of talk have an order, which means the first part (*first pair part*) involves an initiation of some sort and the second part (*second pair part*) is a response to the first part; and (5) these turns of talk are interrelated – for instance, a question requires an answer. Because of the relation within the adjacency pair, the first pair part imposes a constraint on what can be addressed through the second pair part, whereby the second speaker must either comply with the provided direction or be noted to not comply.

Institutional conversations, to which teacher–student conversations belong (Hutchby & Wooffitt, 2008), tend to have a stricter order of interaction than everyday conversations, and often contain chains of question-answer sequences. They can be interpreted as embodying a stricter set of normative rules than everyday conversations, where the exchange of speaker is instead open for negotiation between the conversational participants (ibid.). The character of institutional conversations is especially clear in the example of American courtroom talk, where the order of the conversation is highly structured and a breach of this order leads to sanctions (Drew, 2016). Of special interest in some institutional conversations is the asymmetry of position of competency of the interactants, which can be seen clearly in doctor–patient conversations, where the doctor's diagnosis takes precedence over the patient's own opinion (Hutchby & Wooffitt, 2008, p. 159). In American courtroom talk, there is a presentation of two parallel realities in front of a jury (Drew, 2016). In the latter context, *maximum expectations* regarding what has been said become important; that is, the version of reality presented by the witness implicitly becomes a block towards other, more discrediting interpretations (ibid.). Hence, a certain presentation of reality by the one being questioned can block the questioner's goals in the interaction. A similar phenomenon of alternative interpretations of reality can arise when intersubjectivity is negotiated in science education, which was shown, for instance, through Mortimer and Wertsch's (2003) study of a middle-school science classroom. In that study, the students resisted the move from everyday language to scientific language as the loss of the everyday context made the conversation irrelevant to them (ibid.), and their everyday explanations thereby took precedence over the model introduced by the teacher. In this way, despite being questioned, the students could resist the threat of irrelevance to their everyday experience that the science lesson at that point represented. Mortimer and Wertsch (2003) also showed, in another conversation, when the everyday experience was connected to the scientific model, that the students were perfectly able to make sense of chemical phenomena but that they were doubtful of the utility of the scientific model compared to their own everyday reasoning. Mortimer and Wertsch (ibid.) concluded that there is always an inherent conflict between everyday meanings and scientific meanings in the science classroom, which must be addressed if science education is to be made meaningful. The balance between asymmetry of position and alternative interpretations of reality in institutional conversation can also lead to the formation of spaces of both resistance and autonomy, which can be seen in primary school, where young children use the conventionalised ways of resolving conflict in the presence of the teacher and use their own conflict-resolving strategies in the teacher's absence (Hutchby & Wooffitt, 2008, p. 198). In conclusion, student–teacher conversations in chemistry classrooms can be expected to contain alternative presentations of realities and asymmetry in the positions of competency, which can lead to threats to student academic self-concepts, as well as a feeling of irrelevance. In these situations, spaces of resistance and autonomy can arise where students can instead rely on their own ways of solving problems in the absence of the teacher.

Although CA sometimes focuses on single cases, it more commonly searches for general patterns of interaction in several cases, via thorough descriptions of conversational turns in interaction (Hutchby & Wooffitt, 2008). In this way, the goal of CA is to maximise the generalisability of the conclusions from the analysis by showing the robustness of the proposed model of conversational action (ibid.). Close attention is also paid to deviant cases and their impact on the model of action (ibid.).

In Paper IV, CA was chosen as a method to study sensemaking in interaction between students and teachers, based on the method's affordance in terms of mapping how sensemaking is managed in teacher–student interactions. The analytic method was regarded suitable as a method for exploring teacher's actions in terms of guiding sensemaking in the classroom and as a method that could explore tensions in conversation arising from threats to students' academic self-concepts. Following the basic tenets of CA, all conversations containing what appeared to be sensemaking aspects (that is, some kind of explanation being built in order to resolve a student knowledge gap; Odden & Russ, 2019) were analysed in order to find common patterns of interaction.

5.4 Considerations regarding the methods

In this section, I will use the opportunity to elaborate further on the methods that I have used for data collection and the considerations I made when I planned my research project.

5.4.1 Considerations regarding concept mapping as a method for studying sensemaking

5.4.1.1 Concept mapping: an introduction

First introduced by Novak and Gowin (1984), concept maps are metacognitive tools that are used for learning and assessment (ibid.; Novak, 2002). According to Novak (2002), concept maps are effective tools for evaluating how an individual organises knowledge into a concept-system, which means their construction also has relevance to a Vygotskian analysis of concept development. Concept maps (for an example, see Figure 12) typically have a structure that includes *concepts* and *linking words*. According to Novak (2002), concepts are '*perceived regularities in events or objects, or records of events or objects designated by a label* (usually a word)' (p. 550; author's own emphasis). This definition of concepts is closely related to Vygotsky's definition of a concept as a generalisation (for instance, a 'chair' is a generalisation for a type of furniture), although the Novakian definition puts less focus on the social influence on conceptual meaning (ibid.). According to the Novakian definition, conceptual meaning is derived from how the concepts are linked to other concepts in a hierarchical structure (a definition very similar to Vygotsky's system of meanings, but more explicit) (ibid.). This can be visualised in a concept map, where concepts can be connected using linking words. The linking words are placed on arrows or lines that tie the concepts together (ibid.). Together, the concepts and linking words form *propositions*, which can be either only read in one way (in which case they are labelled using an arrow) or in both directions (in which case they are shown as a line) (ibid.). Several connected propositions make a concept map. The propositions, or semantic units, can then be evaluated in terms of their quality, and the overall structure of the concept map is also evaluated. (ibid.; for a detailed description of concept mapping, see Novak & Cañas, 2008). Common patterns exist in concept maps in terms of how knowledge is presented by the author of the map and can reflect, for instance, rote learning or expertise in an area (Kinchin, 2020).

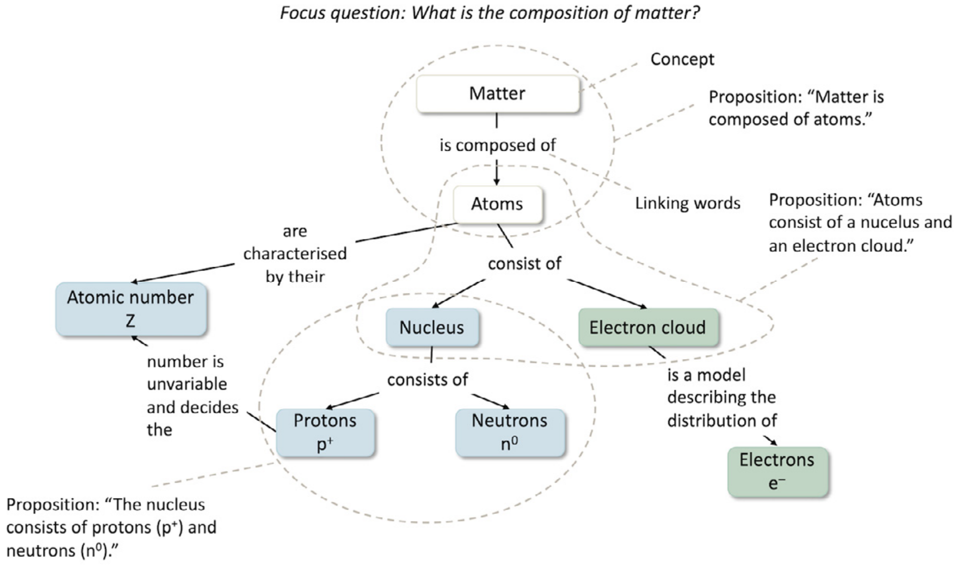


Figure 12. An example of a concept map. In a concept map, concepts are connected with linking words to form propositions, or 'meaningful statement[s]' (Novak, 2002). These propositions are connected into a concept map, where the meaning of a concept is visualised through its connections and position within the knowledge domain represented by the concept system shown by the map (Novak, 2002). Note that only three out of six propositions are circled in the concept map above. Based on an example given by Chevron, 2014, p. 50.

Concept mapping was originally based on Ausubel's assimilation theory of learning, which states that meaningful learning of a concept means establishment of the concept's relationship to other concepts already known to the student, as a result of school instruction (Ausubel et al., 1978; Novak & Gowin, 1984). Hence, the construction of concept maps has the potential to show the learner's current conceptualisation of an idea formed as part of a learning event.

According to Cañas, Novak and Reiska (2015), an 'excellent' concept map has '*high clarity*, a *clear message* and *communicates key ideas* [emphasis in original]' (p. 15), although the quality of the proposition appears to be more important to differentiate students for the purpose of assessment than the overall structure on its own (Ruiz-Primo et al., 1997; Ruiz-Primo, Schultz, et al., 2001; Srinivasan et al., 2008).

Although concept maps are often constructed with no more guidance than the concepts given as words, they can also be constructed to provide guidance for the learner in different ways: Scaffolded maps, or 'skeleton' maps, give a pre-defined structure for learners to work with through a few connected beginning concepts (Cañas et al., 2012, p. 252), and knowledge integration maps have been used in biology to connect different levels of information (genetic, cellular, organism) about evolution processes (Schwendimann & Linn, 2016). Given that a connection has already been shown between non-verbal reasoning skills (measured by the Raven's Progressive Matrices test) and concept mapping in science (Mercer et al., 2004), I deemed that concept mapping was a reasonable choice for studying variations in student sensemaking.

5.4.1.2 Assessment of learning using concept maps

This section discusses concept map assessment in detail. Good (2005) claimed that three central ways of defining scientific understanding are '*Explaining science concepts in terms of other concepts, predicting the outcomes of changes in systems, and solving problems that involve more than simple, algorithmic recall* [emphasis in original]' (p. 345), where concept mapping is used to define the first of these central ways of understanding science. Concept maps were chosen in this study because they have been documented to focus students' attention to main ideas and the structure of knowledge (Donnell et al., 2002), a focus that, as mentioned previously, is often lacking during chemistry lessons in the laboratory (Johnstone, 1991). Because of the focus on main ideas intrinsic to concept mapping, the use of concept maps could provide students with the support they need to reflect about domains of knowledge in a way that may not be otherwise possible. This reflection could be considered a supported reflection within the student's ZPD, helping the students think about their own sensemaking (Vygotsky, 1934/1987).

Concept mapping will provide different outcomes depending on how many concepts are given, whether students get to choose concepts from a list, or whether all the concepts are predetermined (Regis et al., 1996; Ruiz-Primo & Shavelson, 1996). For instance, pre-given concepts are useful for studying the growth of links between concepts, whereas a list of concepts to choose from enables the study of which concepts the students find more relevant to use (Regis & Albertazzi, 1996). Finally, giving the students the opportunity to choose their own concepts can lead to students choosing less relevant concepts for the subject area, complicating concept map comparative assessments (Kinchin, 2014; Ruiz-Primo & Shavelson, 1996), but it can also give students the opportunity to introduce new, more overarching concepts to better show their understanding (Regis et al., 1996).

The quality of the concept maps produced by students can differ depending on the overarching subject and the level of the learner, as biology majors can produce highly complex hierarchical maps (Martin et al., 2000; Pearsall et al., 1997), whereas upper secondary school students studying chemistry have been observed to mostly produce non-hierarchical maps of much lower quality in terms of structure and propositions

(Ruiz-Primo et al., 1997), and even when given concepts have been observed to not always connect them using valid propositions (Ruiz-Primo, Schultz, et al., 2001). Low-achieving upper secondary school students have also been observed to take a more random approach when constructing their maps (ibid.).

Because of the reduced bias in quantitative assessments, the evaluation of concept maps in the research literature is often quantitative (e.g., Boujaoude & Attieh, 2008; Derbentseva et al., 2007; Francisco et al., 2002). When used to assess student knowledge, overall propositional quality in concept maps is an indication of theoretical understanding of chemistry, as shown in a case study at university level comparing concept maps with interview answers during a problem-solving event in organic chemistry (N. L. Burrows & Mooring, 2015). The quality of the concept map propositions (connections) also indirectly predicts course grades through predicting student problem-solving capacity, as shown by another study comparing concept maps to course grade in organic chemistry at university level (Lopez et al., 2011). In that same study, the authors showed that comparing quality of propositions made it possible to identify gaps in student knowledge.

When it comes to practicality and ease of assessment, the Shavelson group (Ruiz-Primo et al., 1997; Ruiz-Primo, Schultz, et al., 2001) developed an effective procedure for teaching concept maps to high-school students of chemistry that focuses on quantitative assessment of propositions rather than hierarchy. Ruiz-Primo et al. (1997) showed that the quantitative evaluation of the quality of propositions between a set number of concepts is a good indicator of student performance on concept maps from students studying at upper secondary level chemistry, regardless of which topic is being taught. However, there appears to be a difference between students in terms of whether they get to choose their own concepts or not – some do better when they choose their own concepts and others do better when concepts are selected for them (Shavelson & Ruiz-primo, 2005). Because of the nature of quantitative assessments, some students may benefit from producing well-developed propositions, including concepts with low relevance to the topic of the map when they choose their own concepts, which complicates the analysis (Kinchin, 2014). However, it would appear that, overall, selecting the right concept for concept maps is an important aspect of student knowledge, as it has been noted that the ability to pick relevant concepts is correlated with propositional quality (Ruiz-Primo et al., 1997).

In Martin, Mintzes and Clavijo's (2000) study of concept mapping by biology students at university, *interconnectedness* – that is, the number of cross-links per number of concepts expressed as a percentage – was instead proposed as a possible measure of the quality of a knowledge framework. Using this type of quantitative assessment, a decrease in the interconnectedness score over time was used to demonstrate general rote learning in the class, observed for both rote learners and meaningful learners (classified by a self-report questionnaire on study habits) (ibid.). The authors proposed that the measured decrease could be due to the students learning new concepts but not integrating them well enough (Martin, Mintzes & Clavijo, 2000).

As these examples have shown, several quantitative methods have been described for assessing knowledge growth using concept maps. The quantitative analysis of propositional quality in analysing concept maps has been particularly well established (Cañas et al., 2015; Ruiz-Primo et al., 1997; Ruiz-Primo, Schultz, et al., 2001; Srinivasan et al., 2008). The quantitative analysis of propositional quality in settings where all concepts are given to the students has been shown to correlate highly with convergence scoring, which is a scoring based on a comparison of student propositions to that of an expert reference concept map (Ruiz-Primo, Schultz, et al., 2001). The most developed propositional scoring method is a six-level evaluation method developed for medicine (Srinivasan et al., 2008). However, perhaps due to practical and subject suitability issues, the four-level ordinal scale used, for instance, by Lopez et al. (2011; 2014) is encountered more often in the literature (see Table 3).

Table 3. Proposition analysis on a four-level ordinal scale from Lopez et al. (2011). Alternatively, a five-level scale can be used, where Level 4 denotes 'outstanding'; that is, a complete and deep understanding (Ruiz-Primo, Schultz & Shavelson, 1997). This type of scoring scale is usually used for quantitative analysis (propositional scoring).

Quality of proposition	Descriptions
3	Scientifically correct and scientifically/precisely stated
2	Correct but scientifically 'thin' or vague (that is, technically correct but too general or too vague)
1	Partially incorrect
0	Incorrect or scientifically irrelevant

When students learn concept mapping, there may be some variability in concept mapping scores depending on both the improvement from practice and the occasion ('learner-occasion-domain interaction effect'; Srinivasan et al., 2008, p. 1202). The improvement could be related to the number of concepts used; in the study by Srinivasan et al. (ibid.), an improvement through practice of around 10 per cent of the total score was noted when learners were given many concepts to work with (50–60). However, when fewer concepts are used at upper secondary school level, this variability has not been noted (Ruiz-Primo, Shavelson, et al., 2001; Yin et al., 2005). In Srinivasan et al. (2008), map scores also varied depending on what day concept mapping took place (possibly related to personal factors and fatigue), and high variability was noted between subject areas.

Despite being the most popular approach in the research literature (de Ries et al., 2022), quantitative methods for assessment of concept maps all have limitations depending on how the concept mapping session is planned in terms of freedom or structure. For instance, if students are given a concept map in which they are asked to fill in the blanks, this will provide a less accurate result than if they construct a map on their own. At the same time, it is difficult for novice concept mappers to construct a concept map from scratch (Cañas et al., 2012). In addition, assessment of concept mapping must consider that the concept maps only represent one facet of the student's knowledge in a subject area (Shavelson & Ruiz-primo, 2005).

Understanding a subject topic can be regarded as having interconnected knowledge, continuously progressing into higher levels of understanding (Entwistle & Nisbet, 2013). Therefore, it may be more useful to study concept maps *qualitatively* in terms of content and overall structure. It has been suggested that the most useful application of concept maps as an evaluation tool for chemistry teachers at upper secondary school is for the qualitative studying of alternative conceptions; that is, the study of concept map content and organisation over time (Regis et al., 1996). In the same study, students also appreciated concept mapping as a learning tool (ibid.). Change over time seems to be a particularly good use of concept mapping for teachers. Longitudinal studies in biology, where concept maps were drawn every 4–6 weeks during university courses, have shown that free-drawn concept maps grow in complexity over time, with more concepts, valid propositions and crosslinks added (Martin et al., 2000; Pearsall et al., 1997). In one of these studies, a difference between rote learners and meaningful learners (classified according to a self-report questionnaire on study habits) was shown, where meaningful learners constructed more developed concept maps (Pearsall et al., 1997). Also, alternative understandings appeared to inhibit growth in certain knowledge areas, and free use of concepts enabled the researchers to see simple initial concepts being transformed into more scientific expressions as learning progressed (Martin et al., 2000). Hence, the qualitative assessment of concept maps in terms of organisation, content and change appears to be useful for studying learning in science from a more holistic perspective.

It may also be valuable to study the quality of the connections in the maps that are produced by students in terms of the overall structure of the map. Kinchin (2020) described ways of differentiating different types of concept maps based on their structure in terms of interconnectedness and branching, identifying aspects of reasoning displayed in the maps such as superficiality, rote learning, dynamic thinking, knowledge integration, lack of knowledge and unreflective thinking on behalf of the learner. Overall structural analysis of concept maps can also be used to qualitatively assess differences in how concepts are connected and integrated in novice compared to expert reasoning (Kinchin, 2020; Kinchin et al., 2019; Schönborn & Anderson, 2008).

When comparing quantitative and qualitative assessment of concept maps, qualitative assessment of concept maps has been shown to be more useful for evaluating student reasoning in science education research (Zele, Lenaerts and Wieme, 2004). However, despite the benefits of qualitative assessment of concept maps, the evaluations are interpretive and dependent on the expertise of the assessor (Zele, Lenaerts and Wieme, 2004). Because of this issue with interpretive assessment in the qualitative assessment of concept maps, a balance needs to be struck between enabling student self-expression and ensuring the possibility of comparative analysis. Comparisons between students creating structured and less structured concept maps have shown that students reveal their understandings better when they construct their own maps; however, this also leads to high map variability where some maps may be less relevant to the subject topic (Ruiz-Primo, Shavelson, et al., 2001). To remedy the issue of difficulties with meaningful comparisons of student concept maps, and to introduce a better model for concept map assessment in terms of quality, Besterfield-Sacre et al. (2004) inductively developed a holistic scoring rubric for the qualitative assessment of concept maps. According to this analysis (ibid.), the three categories necessary for a complete evaluation of the quality of concept maps were: *comprehensiveness* (students' ability to define the subject topic at their knowledge level), *organisation* (ability to organise and connect the concepts), and *correctness* (accuracy as well as level of knowledge). The scoring rubric of Besterfield-Sacre et al. (2004) also included the possibility of ranking concept maps into nine different levels (see Table 4).

Table 4. Conversion rubric for holistic scoring. From Besterfield-Sacre et al. (2012). This rubric was used as a model to differentiate between concept maps of similar character in terms of language use, as part of the inductive coding process.

Holistic Score	**1-**	**1**	**1+**	**2-**	**2**	**2+**	**3-**	**3**	**3+**
Converted Score	1	2	3	4	5	6	7	8	9

For the present thesis, the holistic scoring of Besterfield-Sacre et al. (2012) was utilised as a model to define the different aspects of the qualitative analysis of the concept maps. As methods used to compare the quality of propositions have been well researched (Lopez et al., 2011; Ruiz-Primo, Schultz, et al., 2001; Ruiz-Primo, Shavelson, et al., 2001; Yin et al., 2005), categorisations utilised in quantitative analysis of concept maps were also used to inform the coding that laid the basis for qualitative comparisons between concept maps.

5.4.1.3 Concept maps from a Vygotskian perspective

As mentioned previously, concept mapping is based on the cognitive research of Ausubel, and concept maps have been proposed to be presentations of learner knowledge structures (Novak, 2002). Based on this supposition, concept maps have been suggested to be useful to evaluate knowledge growth and development (Novak & Musonda, 1991). Another common way to evaluate student conceptual knowledge is through interviews (Treagust and Duit, 2008), which is particularly prominent in science education. Standardised testing can also be used (see, for instance, Gieske et al., 2022). Hence, the alternatives available to assess student knowledge in chemistry are based on a cognitivist view of knowledge as existing independently in the mind. The evaluation of knowledge expressed in interviews with students has been criticised within the sociocultural field (Mercer, 2008; Schoultz et al., 2001), as knowledge production is seen as interactive and dialogical. Prescribing to a dialogistic (interactive) rather than a monologistic (input/output) view on learning and communicating, a sociocultural perspective on human interaction views dialogue as a reciprocal construction that is contextualised and has a sequential organisation, where the production of meaning is reflexive between the participants (Linell, 2001). In addition, a sociocultural perspective regards expressed knowledge as a result of reasoning through the use of mediational means, such as words or symbols (Vygotsky, 1934/1987; Jakobsson, 2012). Hence, from this perspective, the type of mediational means used determines the outcome, which is why a Vygotskian analysis of teaching and learning needs to focus on the types of mediational means used as well as how they are used to produce an outcome (an expression of knowledge). In the initial considerations for this thesis, I chose concept mapping as a less intrusive option to study student learning, where the students could access the same mediational means. I chose the evaluation of student language expressions in concept maps because concept mapping was less likely to produce a mutual knowledge construction compared to interviews, and much more likely to show an extensive view of the student's reasoning compared to standardised testing. In addition, as the thesis looked at language use rather than knowledge, the fact that the mediational means (or the psychological tools) are given to the students becomes less important in relation to *how* they are used to produce meaning. Indeed, concept mapping has been proposed to be an act of exploration of meaning and generalisation from a Vygotskian perspective (Aguilar-Tamayo & Aguilar-García, 2008). Student concept mapping is also more likely to produce an expression of conceptual meanings that might otherwise be ambiguously expressed in interviews or free writing (Andersson, 1990a), as it is possible in concept maps to clearly differentiate between integrated reasoning and rote learning (Novak, 2002). Hence, concept maps were an advantageous choice in terms of qualitatively evaluating student sensemaking from a Vygotskian perspective in the study.

In the context of this study, the expression of sensemaking in the concept maps must be viewed as a response to the framing of the activity; that is, the presentation and explanation of the triplet scaffold, and the given concepts. Hence, the student sensemaking produced should be seen as reasoning using mediational means within a framed context rather than a response that is continuously produced in interaction with another person. In this case, the framing of the activity as a *scaffolded* mapping activity was judged to be more useful for comparative analysis than the use of free concept mapping, where students decide the shape of their own maps. The directed framing of the concept map activity through the shape of the scaffold and a selection of concepts important for the study could also guarantee analysis relating to conceptual connectedness and tripled knowledge domains. From a Vygotskian perspective, the collaborative, pre-instruction on concept mapping, the scaffold and the given concepts of the mapping activity can be seen as an invitation to work within the ZPD when learning how to concept map (Chaiklin, 2003). In addition, when the students were creating their individual concept maps, they were invited to form a concept system about chemical equilibrium using the mediational means available (given concepts and scaffold) in order to solve a problem that involved relating this concept system to an everyday concept steeped in experience ('colour change'). This meant that the individual concept maps can also be regarded as having been created as a response to an invitation given to the students to both form a concept and make sense of a phenomenon within the ZPD.

In conclusion, although originally a cognitivist method (Novak & Gowin, 1984), concept mapping can be interpreted, from a Vygotskian perspective, as a tool for meaning formation (Aguilar-Tamayo & Aguilar-García, 2008), and, if concepts and scaffolds are given, meaning formation within the ZPD. Utilised for the present study, the execution and analysis of the same was contextualised, holistic and meaning-based rather than quantitative or seen as being representative of a mind framework. From a Vygotskian perspective, concept maps describing and explaining phenomena can be viewed as holistic products of sensemaking mediated through the use of the language of chemistry and often emerging from collaborative work within the ZPD.

5.4.1.4 Choices made for the concept mapping data collection

I chose to assess meaning formation within the ZPD, as chemical equilibrium cannot be regarded as a concept that is, or will be, fully learnt at upper secondary school level (Yan & Talanquer, 2015). Hence, a tension emerged between making sure the students were invited to form meanings within the ZPD, and making sure the concept maps could be assessed for research purposes, and it was within this tension that the choices formulated below were made.

Kinchin (2014) pointed out the importance of being 'justified and explicit' when it comes to designing the freedom of the concept map exercise (p. 46). Because the studies in this thesis were explorative, it was considered important to give the students freedom as well as support. Although they should ideally be given the opportunity to choose their own concepts and connections, as well as how many of these they wished, the lack of support involved in free mapping is not expected to generate good results from novices at this level (Cañas et al., 2012). Indeed, novice students at this level are expected to need a starting scaffold as well as a small list of starting concepts, as these students benefit from some structure in drawing their maps for topics that are considered difficult (ibid.). However, students should still be encouraged to build on this map using their own concepts. By not using a limited number of concepts, I accepted that a comparable, quantitative estimation of the students' knowledge level would not be completely possible. I concluded from the literature that, when assessing concept maps, restricting the concept use to enable reliable comparisons between students would partially prohibit the students from free expression in terms of meaning formation; but also that giving some concepts to the students would still enable comparative analysis in terms of the quality of the propositions from a qualitative, holistic perspective.

To make sure that the students' use of the knowledge domains of chemistry was properly investigated, I deemed it suitable to use a concept map design similar to Schwendimann and Linn's (2016) knowledge integration map, but using a scaffold based on the triplet sensemaking heuristic of Thomas (2017); see Figure 13.

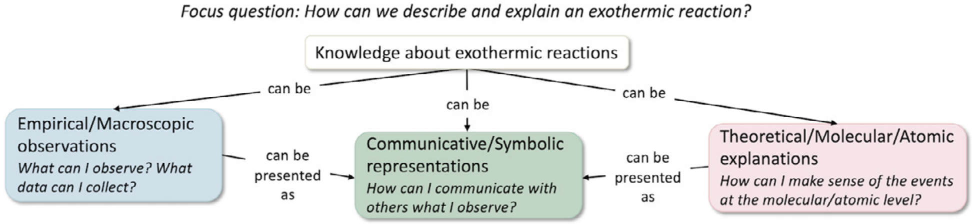


Figure 13. The concept skeleton prepared by the author for the practice concept maps (original colours were purple, blue and peach). The design of the skeleton was based on the reflection exercise by Thomas (2017), where the italicised words are quotes from the original exercise prepared for the International Baccalaureate Diploma Programme (p. 540).

I considered it essential to assert whether the students had learnt concept mapping before they constructed their concept maps on chemical equilibrium. Therefore, I used a similar procedure to the 50-minute training procedure in Ruiz-Primo, Schultz, Li and Shavelson (2001), with the modification that only five pre-determined concepts were used (compared to 20 in the original study), and students were given free choice of any other two concepts. This is because the three knowledge levels (macroscopic, symbolic, and submicroscopic) were already pre-chosen and pre-structured concepts in the map, giving a total of eight pre-given concepts and two 'own' concepts (the 'knowledge of chemistry' concept is not counted because its connections were pre-decided; see Figure 13). In this way, students could practice choosing their own concepts while the efficacy of the concept map teaching session could still be evaluated, and the learner-occasion interaction effect could be kept to a minimum. Giving an initial list of concepts to the students from the beginning was not regarded as something that is negative for the quality of the maps produced, or the quality of the analysis, since the propositions are the essential aspects of the maps (Cañas et al., 2012). However, a limited number of concepts could force students to add invalid connections rather than come up with their own (Ruiz-Primo et al., 1997). Hence, five initial concepts with the option of adding more 'own' concepts were given as the conditions for the study as well as the practice session.

As the concept map in the study has a hierarchical structure (knowledge domains given by the scaffold), a hierarchical group training session was decided on, although examples were given of hierarchical, non-hierarchical (Walker & King, 2002), as well as cyclic concept maps (Derbentseva et al., 2007), as concept maps in chemistry can take different shapes depending on the topic (see, for instance, Aguiar & Correia, 2016; Burrows & Mooring, 2015; Markow & Lonning, 1998); this can be explained by the fact that different disciplines in chemistry may either have a central concept, several interconnected concepts that can be learnt independently (Green & Rollnick, 2006), or concepts belonging to a process (Derbentseva et al., 2007). These examples were given to provide the students with an element of freedom when they constructed their maps, as it was not expected that they would follow the hierarchical structure to a large degree (Ruiz-Primo, Shavelson, et al., 2001). Also, allowing for cyclic substructures could possibly increase the explanatory level of the maps (Derbentseva et al., 2007), as well as allowing for dynamic aspects (Safayeni et al., 2005). The examples shown during the concept-mapping session were colour-coded for clarity, which has been shown to be beneficial for the study of finished maps (Aguiar & Correia, 2016; Nesbit & Adesope, 2006). They were also all on the subject of chemistry. The rationale of keeping the teaching within a chemistry context came from the sociocultural perspective of participating in scientific reasoning as 'participating in a socioculturally situated speech genre' (Mortimer & Wertsch, 2003, p. 233); that is, a way of speaking and reasoning that may not always transfer well between school subjects or different life situations (Wertsch, 1991; Wertsch et al., 1993).

The concepts given for the study were (Swedish words in parenthesis): 'colour change' ('*färgförändring*'), '$\rightleftharpoons$' ('$\rightleftarrows$' was used for Swedish students, being the most common notation in the books for Swedish upper secondary school), 'reversible' ('*reversibel*'), 'K_c' ('K' was used for Swedish students, being the common notation in the books) and 'concentration' ('*koncentration*'). The concepts were chosen based on (a) the content of the IB Diploma Programme syllabus (International Baccalaureate Organization, 2014) and the content of the Oxford IB Chemistry Course Companion (developed with the IB; Murphy et al., 2014), as well as (b) the content of three major course books for Swedish upper secondary school (Borén et al., 2012; Henriksson, 2012; Sonesson et al., 2013) The students were encouraged to add whichever other concepts they liked in order to construct their maps (Le Châtelier's principle is not included in all books for Swedish upper secondary school, so it was not included here as a concept, but it was expected to show up in some of the maps; in the end, 'reaction rate' was the most common additional concept chosen by the students). Based on the previous research, I assumed that the use of these beginning concepts should not significantly influence the language used by the students, nor how they sorted the concepts as belonging to one of the three knowledge domains. Based on low-achieving students previously being able to choose simple concepts for university-level biology (Martin et al., 2000), as well as for high-school-level chemistry with a similar training procedure (Ruiz-Primo et al., 1997), it was assumed that having to come up with some own concepts would not inhibit the students from adding to the maps in the study, and that having a consistent beginning list of concepts for all students would help the comparative analysis of propositions from a holistic perspective.

In their comparative study of six different concept map assessment methods, McClure, Sonak and Suen (1999) noted that the mapping task must be kept simple to keep the instruction time down. The use of a scaffold and few pre-given concepts to fit the level of the students ensured that the concept-mapping session fulfilled this criterion. To ensure the production of maps of high explanatory quality, it is also essential for the central concept or focus question to have a dynamic aspect; that is, to contain an element of change (a process) (Derbentseva et al., 2007). Cañas et al. (2012) also pointed out that the choice of conditions, such as the focus question, central concept and the list of concepts given to students, all restrict the topic of the map and will affect the quality of the maps being produced. In this study, all three of these factors were deemed to have been properly considered, as a reaction (a chemical process) was being studied, the focus question was about describing and explaining this same process, and students were given a partly structured map with a list of pre-given concepts since they were novices and would benefit from some structure in drawing their maps for topics that are considered difficult. In addition, as knowledge integration maps have not been utilised in the subject of chemistry, but have been successful in promoting learning in biology (Schwendimann, 2011; Schwendimann & Linn, 2016), the design of the knowledge integration scaffold was deemed to have support in the literature.

As mentioned in Section 5.3.1, I utilised coding that was theoretically informed and framed using previous research in combination with inductive coding in order to code the concept maps analysed in the thesis. As mentioned previously, the holistic analytic framework of Besterfield-Sacre et al. (2012), with its three aspects of analysis, was used as a model for the qualitative holistic analysis of the relationship between language use and sensemaking. The concepts of c*omprehensiveness* and *correctness* (ibid.) were reformulated based on an inductive analysis of the concept maps as *explicitness* (using scientific rather than more vague, deictic words) and *precision* (learning to use scientific concepts in a nuanced manner) of scientific language use, respectively, aligning the research analysis with studies on science learning for English language learners (O. Lee et al., 2019). In this thesis, *organisation* was interpreted as organisation of concepts in relation to the triplet knowledge domains and organisation of concepts in relation to everyday and scientific meanings within the ZPD. Research on propositional analysis (see Table 3) was used to inform the coding on the *explicitness* of student scientific language use. A similar conversion rubric to the one in Table 4 was used when explicitness and precision of language use were coded, but only when needed to define the categories of scientific language use further. The results of the coding in terms of scientific language use can be found in Papers II and III, and contained language use divided into categories 0, 1-, 1+, 2-, 2+ and 3 (description of each inductively coded category can also be found there). This meant a reduced nuance in concept map variability for this rubric compared to the framework developed by Besterfield-Sacre et al. (2004) (six levels instead of nine). The reduced nuance can be viewed in relation to the fact that the framework of Besterfield-Sacre et al. (ibid.) was developed for the analysis of learning within the subject of industrial engineering as a whole, whereas the concept maps for this study concerned a subtopic of chemistry with less overall complexity.

5.4.1.5 *Finalised concept mapping procedure (lesson held by researcher)*

Students were taught concept-mapping by the researcher in the school language (Swedish or English depending on the school) during an 80-minute class according to the method by Ruiz-Primo *et al.* (1997; Ruiz-Primo, Schultz, et al., 2001), modified to only show examples from chemistry concept maps. At the end of the instruction on how to concept map, the students were instructed on the basic idea of the 'triplet' concept and constructed triplet-scaffold practice maps collaboratively in pairs on the subject of exothermic reactions, using five given concepts and any two concepts of their own (see examples of student handouts in Appendix D). The scaffold was adapted from the 'triplet' concept upper secondary school metacognitive exercise provided by Thomas (2017). During this time, the researcher walked around the classroom and answered any questions that arose during mapping, except during Study V, where the regular teacher helped answer questions, due to pandemic restrictions.

At the end of the lesson, the students were given 20–25 minutes to construct individual, scaffolded 'triplet' maps on the subject of chemical equilibrium, using five concepts: 'colour change'; 'reversible'; '⇌' or '⇄' for the IB and the Swedish curriculum, respectively; 'K_c' or 'K' for the IB and the Swedish curriculum, respectively; and, finally, 'concentration'. The students were instructed to first sort the concepts into the three different types indicated by the scaffold, and to then connect them with links. It was noted during the classes that the students took a long time placing the concepts (up to 15 minutes for some students). When constructing their maps on chemical equilibrium, the students were allowed to use as many of their own concepts as they liked in addition to the five given concepts for the final map. For the pilot study, the topic of this final concept map was neutralisation reactions (concepts given to students were 'colour change', 'pH', 'acid particles', 'base particles', and 'proton transfer').

It was particularly important to establish that the students at this level had learnt the principles of concept mapping, so a previously established evaluation procedure was utilised to assess student learning of concept mapping as a technique (Ruiz-Primo, Schultz, et al., 2001). This evaluation showed that 91 per cent of the participants used all the concepts provided, 99 per cent used labelled lines, and 99 per cent provided one or more valid propositions, with no significant difference between the different student groups (I–V). This result was in line with previous research (ibid.) and it was concluded that the students had learnt how to construct concept maps in all the classes.

5.4.1.6 *Considerations regarding the use of concept maps as a representation of student sensemaking*

According to de Ries et al. (2022), there are four methods of assessing knowledge in concept maps produced in research studies: (1) counting propositions, cross-links and categories and using them to calculate, for instance, map complexity or interconnection; (2) comparing maps to a reference map and focusing on correctness; (3) judging overall quality using a rubric; and (4) qualitatively (that is, inductively) focusing on map content or overall morphology. Each type of analysis carries advantages and disadvantages. For example, counting propositions allows for reliable comparisons of map complexity but can say very little about the quality of the map (ibid.). Usually, a combination of methods are utilised for evaluating concept maps for research purposes (ibid.). Qualitative analysis has previously been used as one of the best methods for representing all of the concept map data, and for focusing the analysis on the nature of student thinking (ibid.). I chose this method because it best aligned with my research question. For the present study, I chose to code both the overall language use in the concept maps using coding informed by research (using previous research on assessment of concept maps as a guide to code the concept maps in terms of explicitness and precision of language use), and inductive coding to identify patterns of language use in the data. These patterns of language use were then related to inductively coded map morphology (also initially informed by theory, as Vygotskian concept relations and triplet concept relations were explored). Hence, no judgement of, for instance, overall map quality or complexity was made compared to a reference; rather, I described and compared the types of student expressions in relation to different variables. Although correctness was judged as part of the holistic assessment of the scientific language use, this was only done to describe the concept maps in terms of dimensions of language use.

An objection to this framework for analysing students' scientific language use through concept mapping could be that the data gathered would be a snapshot of student reasoning and not representative of their knowledge. Students slowly make sense of the abstractions within speech that make up a concept, which they gradually learn to form on their own through scientific language use (Lemke, 1990). Hence, a classroom artefact collected at a specific point in time can only be taken for what it is: a sensemaking product that the student produced at a specific point during learning. However, comparisons of sensemaking *between* students of different achievement levels and language use, as they study the same science topic, can illuminate how students of different abilities and backgrounds are able to make sense of phenomena in class. Such studies are important for improving classroom equity in science, and illuminating student differences in reasoning can be helpful to teachers who struggle with teaching differentiated classes (Kousa & Aksela, 2019). Concept maps are regarded as representative of at least part of a student's knowledge construction on a particular topic (Novak & Gowin, 1984; Shavelson & Ruiz-primo, 2005).

Affective variables, learning identities and student epistemologies might all affect what students actually write in their maps. Even though concept mapping has the benefit of being associated with higher motivation and improved confidence in students (Nesbit & Adesope, 2006), it is still important to be aware of the possible influence of the above factors, such as by observing how the students interact with the maps in terms of engagement. During the data collection for the research study, it was observed that all the students who chose to participate were greatly engaged during the concept mapping sessions.

The learner-occasion interaction effect cannot be measured in the present study since the practice concept map and the study concept map are of different subject areas. Instead, the validity of the results was evaluated based on qualitative measures. Poorly taught concept mapping can lead to a discrepancy between the students' spoken words and what is written in the concept maps (Jin & Yoong Wong, 2010). Therefore, sensemaking was triangulated (to establish concurrent validity; Cohen et al., 2018, p. 265) by teacher verification of a sample of the concept maps, and a comparison was also made between a sample of the student–teacher dialogue during the classes and the concept maps of the students involved (in terms of which concepts the students used, and how they connected them to reason about chemical equilibrium). No large discrepancies were found between sensemaking in the concept maps, the teachers' knowledge of their students, and the classroom dialogues. Most dialogues developed to a higher level than displayed initially in the concept maps, which is to be expected from teacher-led sensemaking dialogues. One teacher commented on a high-achieving student being quite brief in his concept map, just like he was when he spoke in class (Teacher 1, Interview 2), and another teacher commented that the disconnected reasoning in one of the concept maps was typical for that particular student (Teacher 5, Interview 2). One teacher commented on the type of elaborate explanation being given in one of the concept maps as being typical for that student (Teacher 3, Interview 2). Based on these spontaneous comments on the randomly sampled concept maps, my impression was that they were not only representative, but could also reflect student classroom mannerisms.

5.4.2 Considerations regarding the use of video recordings to study classroom activities

A qualitative observation is sensitive to context and uses thick descriptions that are later used to generate hypotheses (Cohen et al., 2018, p. 544). However, it can be argued that there is some inherent structure in any observation, as the observer pays more attention to certain events depending on the underlying theoretical framework (Cohen et al., 2018, p. 542). Video observation can be used to overcome the inherently selective eye of the researcher (Cohen et al., 2018, p. 556) and is particularly useful for validation during analysis by, for instance, multiple viewings by several researchers (Erickson, 2006). However, with the opportunity for increased validity from thick descriptions comes a risk of data overload, and the importance of the researcher having suitable expertise to interpret the rich material correctly (Cohen et al., 2018, p. 557). For validity in observation, triangulation is recommended (Cohen et al., 2018, p. 279); for instance, by confirmatory interviews and other data sources.

Video recordings have several advantages over observations: (1) they can be viewed several times from different perspectives; (2) they allow for detailed observations of social interaction; and (3) they allow for member-checking – that is, participant verification of their authenticity (Blikstad-Balas, 2017). However, some aspects of video recording in research can pose challenges for the researcher, which will be discussed in this section.

5.4.2.1 The issue of reactivity

One issue with video recording in classrooms is whether the camera affects the social interaction it records. According to Blikstad-Balas (2017), the camera is forgotten after a short period of time in classroom studies and only remembered intermittently. However, Cowan (2014) regarded the researcher behind the camera as more of an intermittent participant, with whom children in classrooms can occasionally interact as part of their social interaction, but that this can be clearly evidenced from the video material itself. My experience from data collection was that I had some limited effect on the classrooms I visited. An example was at the beginning of one lab, where one of the students clearly acted as if he had an audience and spoke to an invisible third part about his conversation with the teacher. However, this awareness was not present during the second and third times the teacher spoke to him, and no one else in the class displayed this type of behaviour (although the teacher reported that the students in this class were unusually quiet compared to when the camera was not there). This 'film set' effect on the students was only noticed once, and can be countered with several instances of students being completely unaware of my presence as an observer (for instance, whispering about their poor understanding or copying their friends notes in secret in front of the camera). In conclusion, for most of my studies, the students largely ignored the camera, but there was one study in which there appeared to be some awareness of my presence in the classroom. On the other hand, it is unlikely that this would lead the students to reason about chemical equilibrium in a way that they otherwise would not. In the case where the students were unusually quiet, the teacher described the situation as being slightly harder to get the students to talk during the introduction to the lab, but that they otherwise behaved as normal (Teacher 1, Interview 2).

The teachers seemed to have a more intermittent awareness, possibly because they were wearing a lapel microphone. This awareness was made obvious by glances at the camera, such as when one of them commented on the quality of the chemicals. Other glances were made in relation to them remembering the time and finishing the class so the students could modify their concept maps and complete the surveys. However, these incidents were intermittent, as evidenced by the fact that one teacher walked around with the camera outside the classroom, talking with the microphone on, and another commented that she forgot that the camera was in the room.

In conclusion, I believe the camera only had a minor effect on this research study, and mostly affected the teachers, but not enough to significantly influence the progression of the sensemaking dialogues in class (which occurred much later than the introductory sections, as the students usually took about 20 minutes to get started with the practical lessons). Blikstad-Balas (2017) pointed out that observations and interviews also affect the participants, and that the special case of reactivity in the case of video recordings may be exaggerated.

5.4.2.2 Connection between data collection and analysis

Blikstad-Balas (2017) also pointed out two other issues with using video recordings in educational research. Firstly, data gathering with video is always limited by how much the video camera can capture. Secondly, the more material is gathered, the more time demands are put on the researcher. An effect of these issues is that a lot of the video research in education produces in-depth investigations of short segments of video, which risks missing data dealing with the sequencing of events and overemphasising events that may not be typical for the setting (ibid.).

How data are collected and sampled for analysis depends on the interest of the researcher. Some learning events may require longer timescales than others, and then the researcher must sample a series of important events for learning from a large corpus of data (Derry et al., 2010). Hence, depending on how the data were collected, there will always be limitations regarding what conclusions can be drawn from them (ibid.).

When dealing with a collection of video recordings, Derry et al. (2010) suggested that it can be helpful to plan in advance what to search for informed by previous research. Establishing research questions grounded in theory and literature can also help in the planning of the collection of artefacts, such as photos and documents involved in classroom interactions, which can help with triangulation (ibid.).

Because of the difficulty in managing large amounts of video data, Derry et al. (2010) suggested several ways of organising the video data to aid the analysis: indexing the data on site using field notes, creating flow-charts, writing narratives of the recordings and transcribing a portion of the events. They also suggest a workflow that involves exploring a few clips in depth to generate tentative explanations for events, after which more clips are viewed and the explanations are gradually revised to fit the data through several analytical cycles (ibid.). Finally, the same authors noted that transcripts and videos should be shared with other researchers, both to elicit multiple interpretations of events and analytical dimensions and to validate their quality (ibid.). Regarding which transcription method to use to transcribe video, Cowan (2014) showed that multimodal analysis of video can have advantages to purely text-based transcription, in that it can open up for analysis of complex social interactions that become obscured when only the talk of the interaction is transcribed.

5.4.2.3 Final video recording choices for the thesis

The lessons studied were practical lessons on chemical equilibrium, where I was a passive observer. The data collection was focused on teacher–student interaction between students and their regular teachers. Therefore, two cameras were used in the classroom: one that covered the writing on the board for the whole-class interaction and one that filmed the whole classroom that I controlled. I sat at the back, in the corner of the classroom, controlling the camera as well as the sound recording and taking notes. The teacher carried a lapel microphone, and a second microphone recorded the background noise in the classroom. This choice was based mainly on the facts that I only visited the classes for short periods of time and that I wished to minimise the presence of the camera in the room. This slightly limited data collection also helped reduce the time spent going through video recordings. As my focus was on language use and sensemaking, I felt that it meant I would focus on data pertinent to the study. As the analysis later revealed, it would have been useful with close-up cameras on student lab sheets as they were often used as references to conversation. To find out how they were used, I had to instead deduce their implied use from the conversation and from the collected materials (for instance, I would deduce from the conversational context whether a quotient or a chemical reaction was pointed at). However, bench cameras would have brought much more attention to the filming and possibly greater reactivity from the students.

Another issue was ethics, in that students who did not wish to be filmed still had the right to participate in class. Therefore, I had to limit the view of the classroom to give them space to learn unrecorded. Other setups could have been used, such as a camera in the ceiling recording the students from the front. However, having control over the camera helped me navigate when students who did not wish to be recorded walked across the classroom and into the camera view (after this had happened three times, I changed the consent forms to inform the students of their personal responsibility to stay on their side of the room). Hence, having control over the camera helped me be more flexible when unexpected challenges arose. Also, it is possible that recording the students from the front of the room would have made them much more self-conscious, and perhaps unwilling to participate in the study.

During the filming, I chose to index the data using field notes in order to easily find suitable conversations for transcription later. This meant that I noted the topic of the conversation and the approximate time of the conversation on a pre-made schedule that divided the recording into five-minute sections. This aided me in selecting longer conversations for transcription.

When transcribing, I initially used verbatim transcription before later moving into conversation analysis with a multimodal component. The reason for this choice was the utility of conversation analysis in studying intersubjective agreement in interaction (Heritage, 1984), which I felt was essential for the study of teacher–student sensemaking. The use of conversation analysis was elaborated on in Section 5.3.3.

5.4.3 Considerations regarding the use of interviews to complement video recordings of classroom activities

The qualitative interview is regarded as a social encounter in which participants are allowed to discuss their world view (Cohen et al., 2018, p. 506). To fully utilise the interview as method, the researcher should use it for complex issues and must be an active listener who takes responsibility for the conversation quality as well as being responsive to the social situation as it develops (Cohen et al., 2018, p. 518). Face-to-face interviews can be more reliable than telephone interviews in this case, as the respondent might be more encouraged to confide in an interviewer they can interact with freely, and the interviewer will be more responsive to social cues (Cohen et al., 2018, p. 275). Researcher bias (the interviewer having certain expectations that influence the conversation), as well as aspects of the researcher-respondent relationship (such as different status or ethnicity), can affect the validity of the interview, as well as the risk that the respondent feels threatened by the questions or simply does not understand them, although this bias can be reduced by careful wording of the questions (Cohen et al., 2018, p. 272–273).

Interviews can have varying degrees of structure, which also affects reliability and authenticity. While unstructured interviews using an interview guide allow the researcher to be responsive to the interviewee and the unique situation that develops, this reduces the comparability of the responses, as all topics might not be covered (Cohen et al., 2018, p. 510). Semi-structured interviews can be flexible in terms of the wording and the sequence of questions to maintain a natural-feeling conversation (Cohen et al., 2018, p. 511); however, even with increased comparability, these types of interviews are not as reliable as interviews with pre-given answers as choices. However, with greater reliability comes greater superficiality, as well as the risk of annoying the interviewee (Cohen et al., 2018, p. 513). A middle road in this case could be to use the same wording in every interview, but no pre-given answers, which would give higher reliability (Cohen et al., 2018, p. 273); this was the preferred choice in this research study considering the comparative case study approach. Cohen et al. (2018) pointed out that questions and probes for an interview must be planned in detail, even for a semi-structured interview (p. 514). They also suggested using open-ended questions for more authentic answers (p. 513) and emphasised the importance of being an active listener (by paying attention and summarising), being polite (not interrupting, being transparent in actions such as checking the time, thanking the respondent, etc.), and establishing good rapport (pp. 518, 521–522). Sometimes, a member of a certain community (such as a teacher) could gain greater rapport within a member of the same community, and rapport could also be established by using less threatening, easy questions at the beginning of the interview (Cohen et al., 2018, p. 519). The use of video materials and artefacts can also build rapport and empower participants (Cohen et al., 2018, p. 633).

All of these aspects of conducting interviews were considered and implemented for the contextual and confirmatory interviews conducted prior to, and after, the video recordings of the practical classes. The interviews were piloted on teachers twice, once in Swedish with a native Swedish teacher and once in English with a native British teacher. As the interviewer, I made sure to present myself as both a chemistry teacher and a researcher and I conducted teacher-related small talk before and after the interviews. I also had a semi-structured interview guide with pre-planned follow-up questions, where most of the questions were open-ended. I did not take more than a few words of notes and instead gave my full attention to the interviewee, relying on the two recording devices I had brought. The first (contextual) interview started with an easy question (regarding the plan for the practical lesson) and the second (participant verification) interview started with the viewing of a video clip from the lesson – both were good conversation starters. The use of the sample concept maps to ask the teachers for their representativeness of the students' knowledge also engaged all the teachers greatly in the interview. After each interview, I summarised my impressions in a document and kept this to inform later analysis.

5.5 Ethical considerations

5.5.1 Collection of data

For this study, no sensitive data were collected from the participants, and the participants were at no risk of psychological injury in participating, which meant no ethical permit was required for the research according to Swedish law (SFS 2003:460). Instead, ethical considerations were made according to the general guidelines of the Swedish Research Council (2011). Participation was voluntary, participants were fully informed of the purpose of the study and the handling of the data collected, and the participants could choose to quit at any time. All participants were offered an opportunity to participate in the study but not be recorded on video, and the camera angle in the classroom was modified accordingly. As all students were over the age of 14, no additional parental permission was required (SFS 2003:460 18§). As concept mapping could be considered a benefit in terms of learning for the students, it was deemed ethical that all students in the class participated in the concept-mapping part of the study as well as the practical, but that data from these students were not collected. Following GDPR, all student data was digitised and pseudonymised during data handling, and the code lists for identification and the consent forms were locked in a safe. Video and audio recordings were stored on a separate, password-protected hard drive, which was also stored in a safe when not in use. As per mutual agreement between the participants and the researcher, the data will be fully anonymised when the research project is finalised and before the data are archived.

5.5.2 Ethical reflections

Apart from following general procedural ethical guidelines, such as the honouring the participants' right not to be observed in the classroom (Cohen et al., 2018, p. 557), there are also general ethical considerations to be made when a research project actively interferes with education. Although educational science has the potential to improve how science is taught in classrooms, an intervention, such as an experiment, might have side effects such as psychological or emotional effects that could affect the involved students' future life and education. In this regard, studies in education could be compared to clinical trials (Cohen et al., 2018, p. 400), so their ethical aspects should be given due consideration. For instance, it is not advisable to have a control group in a study that looks at active learning, where efficacy is well established (Freeman et al., 2014). The use of concept maps in education is an example of such practice. Based on these arguments, the studies undertaken during this project needed to include the availability of teaching of the educational component (concept mapping) to all participating students, and control groups should not be used. It was also important to make sure that participation in the study remained voluntary throughout.

With participants giving up some personal information to the study (such as previous achievement grades, whether they speak the school/university language at home and reasoning ability in terms of concept map result), there is also important to consider the cost/benefit ratio to the students (Cohen et al., 2018, p. 113). Teaching concept mapping to the students involved can be considered beneficial to them on a personal level, but the societal impact of the qualitative research can also be considered. According to Geertz (1973), it is important to consider the risk contained in cultural analysis so as not to 'lose touch with the hard surfaces of life' while studying the small and particular (p. 30). Although the present study was not strictly ethnographic, Geertz' recommendation to look further than description and find the themes of life (such as urbanisation, status or morality [ibid.]) still applies in terms of what should be looked for in the analysis to give the project more relevance than simply educational, to make up for any potential embarrassment students might feel when they are challenged to express what they know. To keep the mind open to larger, moral issues can also make the contribution to the research field more significant (Cohen et al., 2018, p. 290). In this case, questions I have sought to answer on a higher level from my study are: Which students benefit from instruction in the chemistry lab, which students do not, and why?

6 THE RESULTS OF THE THESIS

6.1 Overview of the results from the different sub-studies

6.1.1 Paper I

The pilot study was the first study I conducted for my thesis work and it involved 11 students studying acid-base chemistry. In this study, I tested teaching concept maps to the student group before a practical lesson, let them draw triplet concept maps on acid-base chemistry, and then piloted a video recording of the practical lesson.

The goal of the pilot study was to examine the utility of triplet concept maps in being used for the support of knowledge integration (a sensemaking act implied by the connection between concepts situated on knowledge domains in concept maps) in chemistry at upper secondary school, and also how the students related to the triplet concept in their concept maps. Furthermore, I had an opportunity to pilot a video recording, and I distributed a survey in which the students answered questions about their experiences of the concept mapping exercise and the aim of the practical lesson.

In the study, the students showed a range of interactivity with the triplet scaffold. Some students actively connected to the scaffold using their own words in a meaningful way to show that they grasped (or did not grasp) the triplet concepts, whereas others interacted passively through copying statements from the example I gave out in class. Other students only used arrows with no linking words on them to connect to the three knowledge domains, but still used linking words to connect the rest of the concepts. Later, in the larger data, I saw that students who organised and connected their knowledge domains also interacted actively with the triplet scaffold (unpublished data). In the pilot study data, the main difference in how the students related to the triplet knowledge domains related to their definitions of symbolic concepts as they described and explained a neutralisation reaction.

Four out of the 11 participants in the pilot study said that they found the idea of the knowledge domains hard to grasp. A range of how symbolic meaning was defined was also shown in the sample. Symbolic meaning could be defined as both observational and symbolic; symbols could be defined as observations, particles could be defined as symbols, or there could be a generally poorly defined symbolic meaning in the concept maps. Students with poorly symbolically defined maps found the concept mapping exercise particularly useful.

In the study, an attempt was made to look at gender differences in triplet concept mapping. Although some differences were found in this pilot study, they were later not found in the full material. However, it was noted in this pilot study that the methodology used made it possible to compare different variables or contextual data in relation to the qualitative concept map analysis. Also, the method utilised to teach concept mapping was regarded as successful.

It was noted that concept mapping possibly cued a theoretical focus regarding the practical lesson that followed after the concept mapping lesson, as shown by the high theoretical focus self-reported by the students after the titration lab. However, this effect needs to be confirmed in further studies.

In conclusion, it appears that triplet concept mapping worked as a support for sensemaking, especially for students who did not construct defined knowledge domains in their concept maps.

6.1.2 Paper II

In this paper, I analysed concept maps constructed by 88 students at four upper secondary schools in the lesson before they participated in a practical lesson involving shift in chemical equilibrium (Swedish and International Baccalaureate Diploma Programme). I used a Vygotskian definition for concept development within the ZPD to define concept formation as the students' integration of the everyday concept into a scientific concept system as part of mediated thought within collaborative practice. This concept system needs to be based on already developed concepts; that is, known word meanings (Vygotsky, 1934/1987). I also defined this type of concept formation as a sensemaking practice. Finally, I defined concept mapping as a type of collaborative practice that guided this reconstruction of word meaning for the students. As words mediate meaning formation (ibid.), I then wished to explore how the scientific language use of the students influenced their concept formation within the ZPD as part of sensemaking.

In the data, I found five different ways that students organised the scientific concept system in relation to the everyday concept:

1. The everyday concept was integrated into the scientific concept system for chemical equilibrium.
2. The scientific concept system for chemical equilibrium was placed as a separate section, and the everyday concept was isolated from all other concepts.

3. The everyday concept was integrated into a separate experimental concept system, and the scientific concept system formed a separate theoretical section in the concept map.
4. No scientific concept system for chemical equilibrium was shown and the everyday concept was integrated with the learnt concept of 'concentration' (one concept map).
5. No connection was shown between the concepts.

The integration of the everyday concept into the scientific concept system outlined by the students was then compared to the students' language use (defined as more or less explicit and precise; Lee et al., 2019). As shown by descriptive statistics, students using more precise and explicit scientific language in the data sample more often incorporated the everyday concept into the scientific concept system compared to students using vaguer language. Examining how students who spoke another language to the school language at home fared in this data, a comparison was then made between school-language native speakers and school-language non-native speakers regarding how they managed to incorporate the everyday concept into the scientific concept system. Students who spoke the school language at home also integrated the everyday concept into the scientific concept system significantly more often than students who did not. The conclusion from the study was that students' language use influences their capacity to participate in sensemaking and learning within the ZPD.

6.1.3 Paper III

In this study, I analysed the same concept maps as in Paper II, but with regard to how the knowledge domains of the triplet (defined as observational/empirical, communicative/symbolic and explanatory/theoretical) were connected in the concept maps as part of student sensemaking. I did this because of the strong evidence in the chemistry education literature that students find it problematic to connect these knowledge domains as part of sensemaking in chemistry. At the same time, managing to effectively utilise and traverse these knowledge domains is referred to as an expert practice in chemistry (Johnstone, 1991; Kozma & Russell, 1997; Kozma & Russell, 2005; Taber, 2013) and lays the foundation for learning the subject meaningfully (Taber, 2013). In the study, I wished to explore how student language use and previous achievement level was related to students engaging in this type of expert sensemaking in chemistry. In the data, I found four different concept map types regarding how the students connected the three knowledge domains:

1. Concept maps that had structured knowledge domains, language that was generally clearer than the other concept maps, and more cross-linking connections between concepts.
2. Concept maps in which the scaffold was connected to in a meaningful way, showing understanding of the knowledge domains, but where the rest of the concept map was not completely structured into knowledge domains. Instead, the students produced linear or branched, parallel narratives from the scaffold.
3. Concept maps in which symbols were used as observations and/or explanations and where the knowledge domains were less defined. These concept maps also had linear or branched narratives in parallel.
4. Concept maps showing no structure of knowledge domains. These concept maps mostly had vague language in them, although some had explicit and precise language. The way the concepts were connected was mostly associative; that is, producing statements instead of an overall coherent structure.

When I compared these ways in which the students connected observable phenomena with symbols and theory to student achievement level, I observed a general increase in explicitness and precision of student language with higher assessed achievement level. This meant that students with higher achievement level significantly more often (as shown by the high correlation between the variables) used appropriate terminology, chose appropriate concepts and were more elaborate in their connecting words between concepts. However, the language use of the students was not related to how they connected the triplet knowledge domains.

I also observed group differences in the construction of concept maps, where some school classes contained students that were, overall, more adept at defining knowledge domains in chemistry than others. This difference was not dependent on achievement level. One group with a high assessed achievement level average produced a majority of Type 1 and Type 2 maps, whereas another student group with a very high assessed achievement level average showed an overall poor definition of the triplet knowledge domains in their concept maps. Instead, these concept maps often showed an associative manner of making sense of chemical equilibrium, where several statements were produced in an unstructured manner. According to their teacher, this latter student group was poor in conceptual knowledge and very concerned about grades.

In conclusion, although a well-developed scientific language in terms of explicitness and precision was highly correlated with previously assessed achievement level in this study, this language use was not related to how the students organised the triplet knowledge domains in their concept maps. Students with higher assessed achievement levels could express linear, parallel narratives indicative of rote learning (Kinchin, 2020), and students with lower assessed achievement levels could express well-structured and integrated concept maps indicative of deep learning (ibid.), and vice versa. Hence, assessment of achievement level in chemistry in Sweden may not always include sensemaking, despite it being part of both the Swedish and International Baccalaureate curricula.

6.1.4 Paper IV

In this study, I looked at how sensemaking was managed by four experienced teachers during practical lessons on the topic of chemical equilibrium. As student experience, described in everyday words, was connected to the scientific concept system of chemical equilibrium in all the teacher–student dialogues studied, this study can also be viewed as a study of how teachers guide concept formation within the ZPD.

The sensemaking dialogues had the same overall structure, which included students first expressing their pre-knowledge to the teacher in some way (such as a question or an attempt to make sense of the phenomenon they were observing), and then teacher–student sensemaking, which included teacher clues for sensemaking and student responses.

The three major actions that the teachers used to help students make sense of phenomena in all conversations were:

1. Connecting theory with experience (physical, observational or indirect), such as connecting a colour change with concentration change
2. Connecting to other means of reasoning through the introduction of alternative concepts (either theoretical or the symbolic representation of the chemical equation), such as the teacher suggesting that the students think in terms of reaction rates
3. Managing the conversational tension arising from exposing the students' knowledge gaps, for instance through pointing out that observing a colour change can be difficult.

The chemical equation was used as a double referent in some conversations to link theory and experience and thereby mediate the progression of sensemaking, and sensemaking was noted to be context-specific; that is, cued by a certain framing provided by the teacher.

Teachers used various actions to maintain student displays of competency while managing sensemaking. These actions included:

- Steering the conversation away from the knowledge gap by introducing alternative concepts to the sensemaking interaction

- Providing explanations when students expressed their difficulties in sensemaking, which meant the teachers took over the sensemaking act from the student, avoiding further displays of lack of competence
- Using inclusive pronouns to affirm the student's belonging to the scientific community
- Using humour or direct statements to confirm the difficulty of a task
- Confirming a response as valid from a different perspective
- Giving hints to the students through gestures and reformulation of student contributions.

Sometimes, these actions also simultaneously included cueing alternative concepts, such as hinting toward the chemical equation. Hence, the teachers managed to uphold sustained sensemaking in dialogue through balancing the threat to the student self as presented in the interaction (Goffman, 1955; Weick, 1995). This was achieved through various actions that promoted the student being presented as competent while bringing the sensemaking forward on the basis of the student's knowledge gap.

In conclusion, the present study has shown how the teachers worked to guide sensemaking for the students through connecting back and forth between theory and experience. It has also shown that chemistry teachers showing students as competent in the interaction despite their knowledge gaps was an integral part of the chemistry sensemaking practice. Hence, based on both the literature (Criswell, 2012; Oliveira, 2010; Weick, 1995), and the results of the study, I have proposed that the emotional component of sensemaking needs to be accounted for when studying sensemaking in a chemistry education context.

7 DISCUSSION

The research project presented in this thesis utilised a qualitative analytic focus to explore different aspects of student sensemaking in chemistry, thereby trying to explain why sensemaking in chemistry might be difficult for some students. Therefore, the aim of the present study is not to generalise, but to investigate examples of student sensemaking. The results of the study can be utilised for the purpose of pointing out causes of differences in student learning and can then be compared with student learning in other contexts. In this section, I will discuss the results from the research project, and point to possible implications for teaching as well as further research.

7.1 A Vygotskian perspective on sensemaking in chemistry

In this thesis, I have attempted to develop a Vygotskian holistic approach on the study of language, social interaction and sensemaking in the chemistry classroom. Looking back on Carlsen's (2007) definition of the different research traditions (Vygotskian, conceptual change, sociolinguistics/sociocultural theory and situated learning) with their various emphases, it would seem that the Vygotskian approach I have chosen to adopt is more wide-ranging than Carlsen's definition (ibid.). According to Vygotsky (1934/1987), language use and meaning is central, but the word use in itself reflects the social interaction from which it was interiorised. To Vygotsky, the meaning of concepts change via social discourse, and the mediation of meaning through this discourse is situated (Eun, 2019). Hence, a Vygotskian holistic perspective can be said to contain all of Carlsen's aspects, but only in relation to Vygotsky's theoretical framework. For instance, the idea of conceptual change becomes a problem in relation to how this change is defined. In the Vygotskian perspective, concepts change as their meanings develop and become connected to other meanings through collaborative mediation in the ZPD (Clarà, 2017; Vygotsky, 1934/1987), which means that students' alternative conceptions can never really be contrasted against more convincing societal conceptions and be overcome. Rather, as spontaneous (that is, everyday and experiential) and nonspontaneous (scientific and systematic) conceptual meanings are placed in opposition through education, they both grow and connect (leading back to Vygotsky's original problem with Piaget's view of child thinking as something egocentric that becomes socialised through education; Vygotsky, 1934/1987). Comparing sociolinguistics/sociocultural theory and situated learning to Vygotskian theory, their action-based focus becomes a problem with regard to Vygotsky's original focus on the development of consciousness and self-directed action, as others have observed (Kozulin, 2003; Miller, 2011; van der Veer & Valsiner, 1994). Hence, the theory of Vygotsky as a framework is needed for the study of language use (the use of psychological tools for mediation of meaning) and the development of sensemaking as an interiorised, cultural practice that helps students consciously (rather than without conscious awareness and action) make sense of their world over time. Thus, this Vygotskian definition of sensemaking is also very different from a sociolinguistic or social semiotic practice that focuses on the shaping of or conveying of meanings on a moment-to-moment basis in social settings.

One could argue that the Vygotskian definition of sensemaking presented in this thesis is too broad. Each of the perspectives presented by Carlsen (2007) could be viewed as a framework that is more suited to its individual focus. However, the Vygotskian framework focuses on the connections among the conceptual, the discourse, the cultural and the situated, which enables the study of connections rather than isolated events on their own – this was, of course, Vygotsky's purpose from the start (which emerged as a response to what he viewed as a problem in psychological research in general; Vygotsky, 1934/1987). When different aspects of learning and development are studied in isolation, their connections are not considered, which has implications on the research produced as well as the practices in schools. For example, teaching focused on the development of the child is very different from teaching focused on overcoming a student's alternative conceptions. Given the increased focus on the influence of context on learning in science education (Duit & Treagust, 2012), the Vygotskian perspective on sensemaking developed in this thesis can be a useful framework for researchers who find the 'cognitive-situative divide' (Vosniadou, 2007) hard to overcome.

7.2 The structuring of sensemaking and meaningful learning in chemistry

The results from this thesis, especially evidenced in Papers I and III, have shown that the many students participating in the study struggled to make sense of chemistry in a meaningful, integrated manner, by which I refer especially to connecting and navigating the triplet knowledge domains in a structured manner, which is the definition used by Taber (2013). This was shown in the small pilot study, through some students who did not connect to the triplet scaffold and self-reporting difficulties understanding the concept of the three knowledge domains, as well as in Paper III, where comparatively few students in the five student groups structured and integrated these knowledge domains. It is important here to separate integration in terms of knowledge domains, referred to in the concept mapping literature as *cross-links* between domains of knowledge within a hierarchy of knowledge (Novak & Gowin, 1984), and links between concepts in general, which can be arbitrary or more meaningful depending on the overall structure of the concept map (Novak, 2002).

Navigating the cultural language of chemistry for sensemaking appears to be about more than relating concepts. All the types of ways of organising the connection between the knowledge domains in the concept maps involved the students connecting concepts with linking words according to previous definitions in the literature (Novak, 2002; Ruiz-Primo, Schultz, et al., 2001). Comparatively few concept maps (six out of 88) were completely incoherent in terms of language use. Despite concept connections, a notable proportion of the concept maps (Types 2, 3 and 4 in Paper III) contained sections that were linear and/or parallel (see Figure 14).

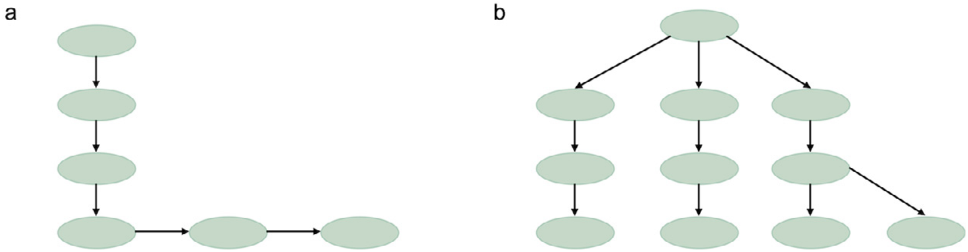


Figure 14. Examples of how (a) a linear connection pattern (that is, a chain; Kinchin, 2020), and (b) a branched, parallel connection pattern (an unreflective pattern; Kinchin, 2020) could look in a concept map. Whereas the linear pattern can be seen as one long string of thought and indicative of rote learning (in contrast to a structured concept system), the branched pattern instead shows several strings of thought fanning out from a common concept. Branched patterns in concept maps usually contains both more and less relevant concepts to the topic, and lack connections between each strand of thought (Kinchin, 2020). These types of concept maps can be developed toward greater knowledge domain interconnectedness through reflective, collaborative work within the ZPD (ibid.).

As the connecting concept of the parallel pattern was often the scaffold given to the students, the parallel patterns could be interpreted as the students using linear reasoning for sensemaking for each section of the scaffold. Linear types of patterns in concept maps have connected to rote learning (Kinchin, 2020). Another pattern that was observed was branching, which has been connected to unreflective mapping, where the concept mapper can mix in concepts that are less related to the topic and thereby build a larger map, but still not sufficiently describe or explain the topic (ibid.). Hence, it would seem that many of the students in the study (1) learned aspects of chemical equilibrium by rote learning, and/or (2) were not able to focus on connecting the main ideas of the subject topic when constructing their maps. As the same pattern has been seen in concept maps produced by prospective chemistry teachers (Kibar et al., 2013), it would appear that this way of learning chemistry is not unusual. Both these types of concept maps contained either poor structuring of knowledge domains and/or poor connectedness between knowledge domains. Hence, both these types of concept maps indicate that the students who made them had a hard time making sense of phenomena on their own in terms of mediating sensemaking that was in line with the cultural practice of chemistry.

As student language use in this thesis was related to integration of the everyday concept into the scientific concept system, as well as previously assessed achievement level, it would seem that students could use their language repertoire to manage sensemaking in terms of connecting everyday and scientific concepts in their maps, as well as influence their achievement level as assessed by their teachers. However, the scientific concept system that they produced in relation to the everyday concept would sometimes be associative, sometimes somewhat disconnected, and sometimes would appear to be based on rote learning. Rote learning, evidenced by chain-like structures, usually impeded further development of the concept system (Kinchin, 2020). In conclusion, it would seem that evidence of rote learning and associative thinking was quite common in these concept maps, either partially (such as in the Type 2 and Type 3 concept maps in Paper III) or fully (such as in the Type 4 concept maps in Paper III). In addition, no connection was found in the data between the incorporation of the everyday concept and different ways of meaningfully connecting between the three knowledge domains of chemistry (unpublished data).

In the pilot study, some students expressed confusion over the triplet knowledge domains. This aligned with the students having difficulty separating representations, such as the chemical equation, with explanations, such as relating the concepts of ‘acids’ and ‘bases’ within the context of neutralisation. Hence, although the students appeared to have some trouble identifying concepts as belonging to a certain knowledge domain, the way in which they used the different concepts to build explanations for sensemaking was clear in the concept maps. Whether the students connected to the triplet knowledge domains could also be seen in the concept maps through whether the students related to the scaffold by connecting with it in their propositions as part of their concept maps. It is not surprising that some students found it difficult to reflect about knowledge domains, as it is confirmed by ample research in the chemistry education research field that students have trouble traversing domains themselves and following teachers’ explanations when they move between the different domains (Andersson, 1990a; Ben-Zvi et al., 1988; Gabel et al., 1987; Johnstone, 2006; Stieff et al., 2013; Talanquer, 2008; Treagust et al., 2003). However, the way in which the symbolic meanings were expressed in these concept maps indicated that some students may have difficulty mediating meaning according to the cultural norms of chemistry, or manage quite well in class through other mediational means, despite struggling to form symbolic meanings in their concept maps (this has been confirmed to be an issue with chemistry learning in general; Liu & Taber, 2016). As indicated by the student questionnaire in this study, these students did find the concept mapping particularly useful. Therefore, triplet concept mapping could be a potentially useful exercise for students who have difficulty making sense of chemistry through navigating the three knowledge domains of the triplet. However, this would need to be confirmed by further studies, possibly conducted over longer periods of time (such as Thomas, 2017).

7.3 The role of language in chemistry sensemaking

A second aspect that was covered in the thesis was the role of language in chemistry sensemaking. Scientific language use in concept maps was related both to previous achievement level (Paper III) and participation in sensemaking, defined as meaningfully connecting everyday and scientific concepts (Paper II), or concept formation within the ZPD from a Vygotskian perspective (Clarà, 2017).

Hence, it would seem that the development of student scientific language is necessary for sensemaking, at least as evidenced by the data in this thesis. Generally, highly developed language meant a greater connection between concepts, a more relevant use of concepts, and a more complete definition of the process being given in the student concept maps. Concept formation was defined from a Vygotskian perspective in this thesis as reorganisation of an everyday concept (or meaning) in relation to a scientific concept (or meaning) within a scientific concept system, thereby enriching the scientific concept with experience (Clarà, 2017). It would seem that the students in the present study who had a less developed scientific language – that is, less developed mediational means – found concept formation harder. This subgroup of students included the group of students speaking a different language from the school language at home.

Previous literature has shown that when students use words meaningfully during instruction, they find it easier to learn the concepts being studied (McDonnell et al., 2016; Ryoo, 2015). This could be the reason for the results observed in Paper II; that is, students who lacked psychological tools were less likely to form a concept system to which they could relate their everyday concept. However, this was not an either-or situation; rather, students mediated the formation of various concept systems using the psychological tools at hand. The systems could be purely theoretical systems, partially theoretical systems and partially experimental systems with the everyday concept integrated, and fully integrated systems. As the definition of explicit and precise language use included being able to choose and use relevant concepts in relation to chemical equilibrium, it would seem that the students who had highly explicit and precise language relied largely on previous concepts being formed (as they were able to consciously choose them, define them within the concept system, and use them; Vygotsky, 1931/1994) in order to mediate the formation of the concept system related to shift in chemical equilibrium. Hence, one can see how, during concept development, language use and concept formation would both depend on the development of the other in a social context with the help of a competent other. Specifically, concepts defined explicitly and precisely in collaboration with a competent other would eventually lead to the formation of solid concept systems, at the same time as a solid concept system would lead to the spontaneous use of explicit and precise language.

Another aspect of student language use and sensemaking that both emerged in Paper I and in Paper III is that the students used symbols to convey meaning in various ways. Sometimes, symbols were viewed by the students as representational devices, and sometimes they were used as a means of explaining a process. Hence, the students sometimes appeared to have more of a mathematical approach to explaining chemistry. This type of thinking can be beneficial to students, as it opens up new ways of solving problems, but, depending on the instruction, can also lead to a disconnect from the underlying theory (Zhao & Schuchardt, 2021). As mathematical explanations for theory in the absence of other explanations existed in this subsample of concept maps, this finding is interpreted as a disconnect from the theory for these students. The various ways of symbol use that were observed in the concept maps (signifier, mathematical explanatory device, or mediator of a theoretical explanation) can perhaps be seen as stages where students moved from using pseudoconcepts (that is, using concepts in the ZPD using the same words and symbols as the teacher, but only being able to form their meaning in collaboration; Clarà, 2017) into fully developed concepts.

It would seem that, in many concept maps, the connection to chemical symbolism was also more associative rather than structured. As can be seen from the examples in the articles, students sometimes utilised symbols as signifiers – that is, bearers of inherent meaning – as part of an explanation, and sometimes they utilised symbols directly to explain theory. Although the students spent a long time sorting the concepts before connecting them (about 15 minutes on average), it would seem from the data that it was difficult for the students to form a structured overall sensemaking narrative in their maps where the symbolism was clearly explained. Hence, symbols were treated both as signifiers and mediational means in the data, and often as part of an association inside a sensemaking narrative.

As shown in Papers II and III, language use was connected to student sensemaking, in that students who had a higher previous achievement level used a more explicit and precise language for mediation of sensemaking, and in turn more often connected the theory of chemical equilibrium with a potential experience (represented by the incorporation of the everyday word of ‘colour change’ in their concept maps). This indicates a relationship between language use and sensemaking, which has also been implied by previous studies on language use and reasoning (Mercer, 2013; Mercer et al., 2004). Implied in this analysis of explicitness and precision of language use is that such language use mediates the use of a well-integrated concept system as the student explores a phenomenon in class. Another result that hints at the importance of the language of chemistry to concept formation are the observations in Paper IV, where the chemical equation, when introduced to the teacher–student dialogue, could mediate the connection between theory and experience for the students.

In Paper III, explicitness and precision of language use was moderately correlated with achievement, which is also supported by research showing that students who feel that they understand the chemistry language are more likely to have a better estimation of their future competence in chemistry, and are more persistent in their studies (Rüschenpöhler & Markic, 2020). However, as language was not related to the structuring of sensemaking in relation to the chemistry triplet, it would appear that improved student scientific language use in itself did not mean that the students utilised their psychological tools for sensemaking according to the cultural practice of chemistry. As mentioned previously, this structuring of sensemaking according to cultural norms appeared to vary between classrooms.

As the data also indicated a relationship between the students' home language and participation in sensemaking, it may be that language support is particularly important for low-achieving students taking chemistry at upper secondary level. This importance is underlined by the fact that the subject of chemistry, at least in Sweden, involves a dramatic rise in language demand when students transition from compulsory to upper secondary school (Ribeck, 2015). Furthermore, as the chemistry academic self-concept is influenced by how competent the student feels using the chemistry language (Rüschenpöhler & Markic, 2020), and since students' academic self-concepts predict further engagement in class (Bong & Skaalvik, 2002; Raufelder et al., 2015), as well as long-term achievement (Jansen et al., 2014; Wu et al., 2021), there is strong support in the literature for supporting students' language skills in chemistry. Based on the results of the present thesis, I propose that the reason why the development of chemistry language skills is so important for chemistry students is that the words and symbols of chemistry mediate sensemaking. Specifically, the connection between theory and experience is mediated, which can lead to a feeling of both understanding and belonging in the chemistry classroom.

7.4 Sensemaking in the ZPD

7.4.1 Teachers' work within the ZPD

Paper IV gave clear examples of work that teachers do to promote sensemaking during practical lessons, such as bringing theory and experience together and cueing thinking through guiding the students' attention to chemical symbols such as the chemical equation. In the interactions studied, the students' knowledge gaps became the central point for the teachers to act upon and attempt to fill, ideally through student contribution in a collaborative practice. As some of the examples in this study have shown, if student contribution failed, teachers would attempt to elicit student responses through such means as reformulating the question in concepts known to the student. At the same time, the students' sense of self as competent contributors needed to be encouraged as part of the interaction. Hence, the knowledge gap of the student became the trigger for sensemaking and work within the ZPD, furthering the students' development toward abstract thinking (Vygotsky, 1931/1994).

Paper IV showed that the teachers worked continuously to display their students as competent in the teacher–student interaction while probing for gaps in their students' knowledge in order to promote and guide sensemaking. This is in line with sensemaking involving a gap in a person's knowledge that, if left unresolved, can threaten the person's sense of self (Weick, 1995), which in the case of the present study has been interpreted as the student's chemistry self-concept. Given that the academic self-concept is related to future achievement (Wu et al., 2021), this could explain why all of the teachers participating in the study seemed to be at least implicitly aware of the importance of maintaining student feelings of competency throughout the student–teacher sensemaking dialogue. Based on the results of this study, I propose that managing tension in interaction may be an important aspect of sensemaking in chemistry. This can be connected to Vygotsky's notion of *perezhivanie*; that is, how the student learns and develops depends on how the student 'is aware of, interprets and relates to a certain event' (Vygotsky, 1934/2020, p. 71). At the same time, the student's development is driven in relation to the modelling represented by the teacher and through the collaborative interaction (ibid.).

The study of the work that the teachers did in the study to achieve sustained sensemaking hence indicates that collaborative learning involves students being presented as competent contributors. As evidenced by the limited and disconnected concept systems in many of the concept maps, most students in the study would need support in their sensemaking through teacher interaction in order to connect knowledge domains, scientific concepts and everyday concepts. Only four of the 88 concept maps showed a complete definition of chemical equilibrium in relation to what had been taught, as well as a structured organisation of the three knowledge domains. Hence, based on the data, the students working in pairs in the laboratory classrooms studied might only have been able to give each other limited support when it comes to sensemaking and meaningful learning. This is notable since about half of the students in the study were high-achieving with grades or achievement levels in the ranges of B-A/6-7.

According to Garfinkel, conversational moves are both '*context-shaped* and *context-renewing*' (Heritage, 1984, p. 242). As teachers invite collaborative sensemaking in the classroom, they also become responsible for maintaining the focus of the talk on the topic at hand. This was seen clearly in Paper IV, when a student did not follow the contextual cues given by the teacher, the whiteboard, and the lab sheet, and his presentation of competency by the teacher was withheld at the same time as the student was directed to the lab sheet. Hence, another aspect of teachers' work within the ZPD seen in the study was to provide contextual cues for sensemaking.

In conclusion, the teachers' work within the ZPD in this study involved continuously eliciting contribution from students in their own words in order to collaboratively work towards defining a shift in chemical equilibrium. This work involved a sustained sensemaking practice in which the cultural practice of chemistry sensemaking was implicitly shown again and again through the teacher's conversational moves. This was achieved at the same time as the students were presented as competent contributors. Teachers providing alternative psychological tools – that is, alternative theoretical concepts for sensemaking – in order to help students resolve their knowledge gaps in collaboration, was apparent in all of the teacher–student sensemaking conversations. Another ubiquitous part of sensemaking dialogues was teachers helping students link theory and experience. It can be concluded from the research, both the concept maps and the teacher–student conversations, that very few students were able to reason on their own during practical lessons on chemical equilibrium, even at high achievement levels.

At this point, one may ask whether the teachers are aware of their sensemaking practices. According to Heritage (1984), Garfinkel stressed that ordinary social interaction is grounded in life experience, achieved in a routine manner, and that the norms underlying the interactions are not really noticed unless a breach against normal conduct occurs. The actors 'are typically interested in getting their ordinary tasks done' (ibid., 118). According to Macbeth (2003), teacher–student discourse is a device that teachers routinely use to make the lesson content 'evident and visible' through a both collaborative and competent practice (p. 258). Hence, although classroom conversational turns may be routinely produced and managed by teachers, their purpose in bringing about a learning conversation between teacher and student is evident based on previous research and the research presented in this thesis. In the present study, as the teachers were not interviewed specifically with regard to sensemaking, their complete awareness of all the aspects of their sensemaking practices could not be confirmed. However, a certain awareness of sensemaking goals of the interactions can be seen in the in the interviews, through teacher phrases such as 'when you do something concrete, it is easier to get the students to talk chemistry' (Teacher 1, interview 1, line 464), 'It is not that I explain to the students … I also want them to try and put words themselves on what they have seen … and then you confirm: 'precisely, it is the way you have thought'' (Teacher 2, interview 2, lines 118–123), and, '… to think, what is it that happened, to reason about it. And then I think they can access some of it [the theory] without being given the answers' (Teacher 4, interview 1, lines 163–164). Therefore, it is reasonable to assume that the teachers had a goal of sensemaking to happen in their classes, and some idea of how to proceed in making it happen based on previous experience.

7.4.2 The structuring of sensemaking as a social practice

In Paper III, disconnected sensemaking was shown in concept maps with indicators of rote learning or unreflective learning, consistent with student surface approaches to learning (Biggs et al., 2001; Marton & Säljö, 2005; Schneider & Preckel, 2017). It would seem that the structuring of student sensemaking was also influenced by which group the student belonged to. The practice of sensemaking established in a group of students could possibly be attributed to classroom norms for sensemaking (Becker et al., 2013). However, in teacher–student conversations that contained sensemaking components studied as part of this thesis, the teachers were constantly encouraging connections between the knowledge domains. This practice occurred in four out of five classrooms, where, in the fifth classroom, the reason for focusing more on practical handling during the lesson was a particular focus by the teacher on safety during practical lessons (Interview 1, Teacher 3). This focus on practical handling was not accompanied by low student sensemaking, as evidenced by the student concept maps; rather, these students were quite proficient in structuring sensemaking (see Paper 3, Class III, Figure 9); hence, guidance of sensemaking probably occurred elsewhere in this particular teachers' lessons. In conclusion, rather than classroom norms being the decider for whether student sensemaking occurs or not, I propose that it is more likely that in some student groups, the reason for not participating in sensemaking could be (1) pressure to perform (which encourages rote learning [Cipra & Müller-Hilke, 2019; Postareff et al., 2017]), and/or (2) difficulties with the chemistry language leading to an inability to participate in learning within the ZPD at the required level (necessary for the development of structured thinking over time; Vygotsky, 1987). In the latter case, this does not mean that learning does not occur. According to Vygotsky, social interaction can promote learning at different levels, and the learning that does take place will depend on the student's emotional experience and understanding (*perezhivanie*; Vygotsky, 1934/2020).

Structured sensemaking was also unrelated to achievement level, indicating that some students succeeded in their studies through surface approaches that involved rote learning and unreflective practices, as evidenced by the shapes of their concept maps (Kinchin, 2020). From my observations of the teachers in the study, I propose that sensemaking according to the norms of chemistry is a social practice that is being explicitly taught in at least some chemistry classrooms. The utility of teaching sensemaking explicitly is supported by other research in chemistry education (Becker et al., 2013; Yaman, 2020). However, as shown in both the concept maps and in the dialogue studies of this thesis, the nature of chemistry symbolism and how it is used in sensemaking may make it hard for students to differentiate between (a) symbols being used as a cue for sensemaking provided by the teacher (Weick, 1995), (b) symbols being presented as a possible mediational means for achieving alternative paths of reasoning (Zhao & Schuchardt, 2021), and (c) symbols being used as a communicative device; that is, as representations of events communicated within a scientific community (R. Kozma & Russell, 2005). These may be types of communication that have to be more explicitly expressed by teachers.

7.5 Limitations of the study

Apart from the limitations already mentioned in the Method chapter, there are two aspects of the data gathering I would like to discuss further: (1) the use of concept maps as a research tool, and (2) limitations regarding contextual data.

There is general agreement that concept maps can be useful as tools to show students' development as learners, as long the way the concept maps are assessed is suited for the purpose of the researcher (de Ries et al., 2022). For instance, different quantitative scoring methods tend to focus on different aspects of the concept maps (for instance, organisation or correctness) (ibid.). Qualitative analysis, on the other hand, is more focused on content (ibid.). Based on a study on the usefulness of concept mapping in representing student knowledge of the atom, Zele et al. (2004) concluded that qualitative analysis based on structure and content of concept maps is by far the preferred concept mapping method for studying student learning. However, qualitative analysis is also heavily dependent on the interpretation and knowledge of the analyst (ibid.). In this study, the coding procedure was verified by external researchers; however, coding in collaboration might have given even more insight into the data.

From a cognitivist perspective, concept maps are seen as representations of students' knowledge structures (Novak, 2002). However, when examining concept maps from a Vygotskian perspective, the analysis becomes more problematic. On one hand, it would seem that concept maps have clear advantages over free-response questions when it comes to gathering data about student understandings of a certain concept (these understandings can be corroborated by student interviews; Zele et al., 2004). On the other hand, the concept maps generated can also be seen as context-dependent classroom products; that is, mediated through the use of certain psychological tools and cues, rather than a representation of a students' knowledge as 'in the mind'. The concept maps must also be seen as being generated from each individual's personal experience of the subject and their personality (Vygotsky, 1934/2020). For instance, two teachers in the study explicitly noted in the interviews that the concept maps reflected aspects of their students' personalities, and one of these aspects was a tendency to not be very expressive despite showing high competence in the classroom. Hence, a full understanding of a student's learning would require a much more in-depth study than was undertaken for the present thesis project. For instance, understanding why some students picked certain concepts for their concept maps instead of others would require a long-term classroom study in which all the concepts used in class over a period of, say, a month, could be compared to the concept maps produced by the students. The classroom interaction between the teacher and the students would also need to be studied over time to understand classroom norms for sensemaking and how these related to the concept map shapes. Also, cues such as gestures can be important for the continuation of sensemaking, as they can clarify what is being talked about and be used to bridge theory and experience (Ngo et al., 2022; Roth & Lawless, 2002). Therefore, I would also recommend bench cameras for a more thorough study of how sensemaking is sustained by students and teachers in the laboratory environment. As the present study did not cover these aspects of the learning context, I am not able to draw any conclusions on the sensemaking norms in the classes I studied, nor on the importance of gestures (or other cues such as physical tools) in sensemaking. Further research would be needed to clarify these aspects of sensemaking.

For this thesis, I chose to study meanings mediated using cues; that is, learning within the ZPD (Vygotsky, 1934/1987). Concept maps are often regarded as tools for learning in their own right that promote, among other things, conceptual learning, knowledge integration, critical learning, and reflection (Machado & Carvalho, 2020). For this reason, it is hard to reach conclusions on what meanings the students would be able to mediate if they were not given the same psychological tools. On one hand, Vygotsky only regarded the conceptual meaning formed without help as spontaneous (ibid.), which means that the concept maps drawn by the students in the present study could be viewed as a representation of what they are currently in the process of learning and are able to reflect on (assuming that they did not find the concept mapping in itself too challenging, which could also be a possibility; Kinchin, 2014). On the other hand, it can be clearly seen in these concept maps what the students have *not* learnt and do not know (Zele et al., 2004). In addition, typical shapes that have been previously established in research to be indicative of different types of learning are seen as reasonable ways to interpret the maps (Kinchin, 2020).

Other research in favour of the scaffolded setup of concept mapping utilised in this study shows that second-language students are particularly dependent on cues for understanding assignments (Lee & Orgill, 2022), which means that a decision not to include cues could have possibly meant a loss of data from this subpopulation of students. It should also be added that chemical equilibrium is a concept that takes a long time to learn (Yan & Talanquer, 2015), so trying to look at students mediating its spontaneous formation at this level of schooling might be a futile endeavour.

7.6 Conclusions

For this thesis, I utilised a Vygotskian perspective on sensemaking to define sensemaking as an integral part of the ZPD, and to study the connection between sensemaking and student language use. In the concept maps studied in this thesis, I have seen a snapshot of how students make sense of chemistry at upper secondary school. I have seen fragmented conceptual frameworks being produced in concept maps as well as integrated ones, varying ways of using symbols as part of sensemaking, and I have noted the importance of explicit and precise language use for participating in sensemaking and concept formation within the ZPD. I have also noted that the overall structure of the nature of chemistry was not expressed in a structured, integrated way by a large proportion of the students in their concept maps. A connection was observed between disconnect between the triplet knowledge domains and rote learning, as well as associative thinking. Therefore, the data indicate that learning in the chemistry laboratory requires that the teachers support students' use of the language of chemistry for mediation of concept system formation, which in turn is supportive of deep approaches to learning in chemistry (Sinapuelas & Stacy, 2015).

In the study of teacher strategies to maintain sustained teacher–student sensemaking during practical lessons, I also found that the teachers all maintained a balance between their sensemaking practice (finding out student knowledge gaps, providing alternative concepts and connecting theory and practice) and the presentation of the student in the interaction as competent. This balance promoted student learning within the ZPD; however, student development over time, such as thinking related to the chemistry triplet, could not be studied for the current data set.

A summary of the conclusions from the data is shown in Figure 15.

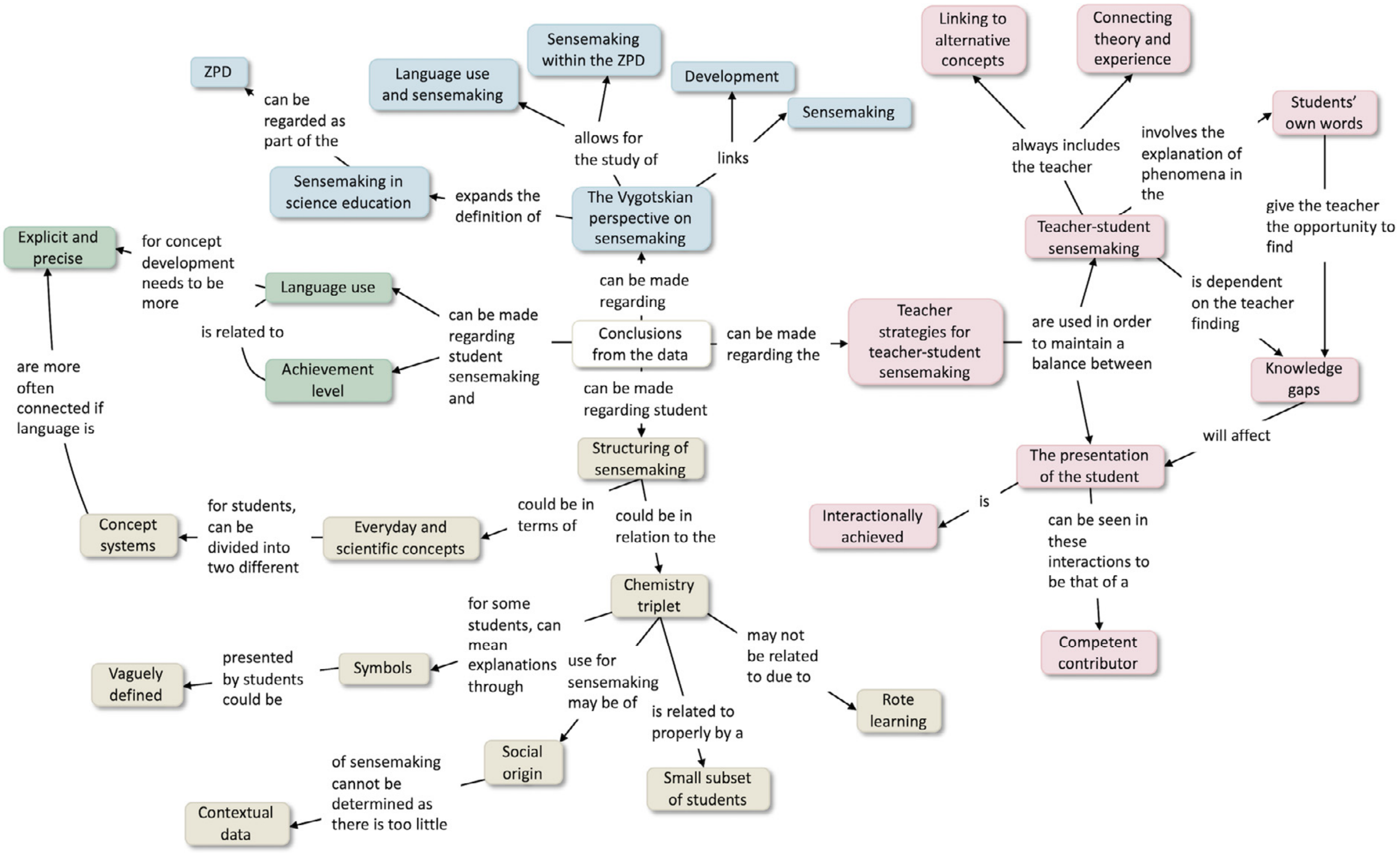


Figure 15. My main conclusions from the data, presented as a concept map.

7.7 Implications

7.7.1 Arguing for an alternative theoretical framework for studying chemistry teaching and learning

In this thesis, I have combined theories about thinking in chemistry (Johnstone, 1991; Taber, 2013) with theories about sensemaking (Odden & Russ, 2019a; Weick, 1995) and redefined them from a Vygotskian perspective. In this way, the connection between language use, sensemaking and chemistry learning was framed theoretically and could be investigated through analysis of empirical data. Defining sensemaking in chemistry from a Vygotskian perspective provides a theoretical framework that includes language use, conceptual learning and development, social interaction, as well as motivational aspects for learning. In this way, a research gap was filled in terms of the provision of a novel theoretical framework that can be utilised to study language use and concept development as part of sensemaking in chemistry teaching and learning. This framework can be utilised for the purpose of studying chemistry teaching and learning from a holistic perspective, and allows for the integration of research from different areas within science education. Vygotsky believed his research approach could be particularly beneficial for the study of context-based formation of conceptual meanings in relation to development of psychological functions and structured thought (Daniels, 2008; Vygotsky, 1934/1987).

The main theoretical frameworks utilised for studying learning in chemistry are individualist and constructivist, which includes the theories about the chemistry triplet (Cooper & Stowe, 2018; Johnstone, 2006; Taber, 2013). Because of the triplet's epistemological origins (which does not include a view of thinking as being interiorised as part of social learning), I propose that there is an unspoken assumption with regard to the triplet model for chemistry learning that students implicitly understand and utilise the three triplet knowledge domains, but have difficulties switching between them. In his summary of his foundational research on chemistry learning and the triplet, Johnstone (2006) highlighted the importance of the teacher explicitly guiding students between triplet conceptual levels, or meaning spaces, during classroom teaching. Taber (2013), developing the triplet concept further for chemistry researchers, stressed the importance of utilising both the symbolic domain and redescriptive shifts between scientific terminology and everyday language as a resource in shifting between levels. However, there has so far been no questioning of whether the students actually grasp these levels as entities that the teachers move between. Based on the facts that (1) several students in this study were not able to connect to the triplet scaffold in any meaningful way, and (2) many of the students could also not sort their concepts according to the chemistry triplet model (this was actually the hardest task for them during the practice concept mapping session, where concepts were often discussed with regard to their nature and just sorting the five concepts took about 15 minutes), the results of this study questions this assumption. It could, of course, be argued that defining chemical equilibrium was so difficult for the students that it would be unreasonable to expect them to connect to the triplet scaffold as well. However, the connection between poor definition of conceptual meaning in relation to the triplet and shapes indicating rote learning in the concept maps paints a slightly different picture. Instead, the results of the thesis point to a connection between deep learning and structured sensemaking following the cultural norms of chemistry. It could be reasonably suggested, based on the data, that students who focus on memorising and rote learning do not develop an understanding for the knowledge domains of chemistry represented by the chemistry triplet. Continuing this argument, it can also be argued that an understanding of the knowledge domains of the triplet can be, but is not necessarily, developed through schooling.

Sensemaking in science education is a well-defined concept (Odden & Russ, 2019a). However, much like the triplet model, it is based on a cognitivist individualist model for how students learn science (Odden, 2021a). Therefore, this model does not prescribe to students acting with mediational means, nor to the importance of the collective aspects of concept formation and development, despite there being convincing evidence supporting the latter (Mercer, 2013). In this thesis, I have reinterpreted sensemaking from a Vygotskian perspective in order to open up for the study of social and collaborative aspects of sensemaking. The results show that the experienced teachers in the present study teach chemical equilibrium through co-construction of meaning with students at all achievement levels. The results also show that all of students who participated fully in the present study, and especially those with poorly developed scientific language, needed the teacher's help for sensemaking and formation of conceptual meaning through collaborative sensemaking. Hence, the results of the study argue against a cognitivist and individualist view of sensemaking as part of science learning, which would potentially leave many students left behind in terms of enacted chemistry classroom learning.

The framework developed in this thesis can be useful, not only for looking at the connection between language use, social interaction and meaning formation (which was the focus of this thesis), but also for looking at the connection between context, sensemaking and development of structured thinking. Considering the many instances of unstructured thinking shown in the student concept maps collected for this thesis, that would be an interesting focus for further research that could open up for alternative understandings of teaching and learning in chemistry.

7.7.2 Suggestions for further research about chemistry teaching and learning: The role of language, emotions, social interactions, and context

The results of this thesis provide a plausible explanation for the connection between perceived chemistry language ability and chemistry self-concept at upper secondary level (Rüschenpöhler & Markic, 2020); namely, that having access to the mediational means of chemistry helps students make sense of chemical phenomena and connect concepts (albeit not as fully as in collaboration with the teacher). This would naturally lead to students having a more positive perception of their abilities in chemistry as a subject, especially with the teacher supporting their self-presentation as part of the dialogic interaction. Another interesting focus for further research would be to look at students' chemistry language development over time in relation to their chemistry self-concept, emotional experience and classroom interactions. This would be especially interesting if native speakers were to be compared to students who speak a different language from the school language at home.

In connecting language and social interaction to sensemaking about chemical equilibrium, I believe that the results of the present study have contributed to a more nuanced understanding of student learning in chemistry. Although I have mostly studied student learning of chemical equilibrium (the pilot study was on acid-base reactions, but the main study focused on chemical equilibrium as a learning topic), the position of this subtopic as a keystone in understanding chemical reactions indicates that it is reasonable to suggest that the way the students learn chemical equilibrium could also apply to other subtopics in chemistry and student populations in similar contexts. For instance, relating to the chemistry triplet or not in a concept map could be regarded as a generalisable skill, and student approaches to learning (deep or surface) can be related to larger overall context such as exam pressures and the subject's relevance to student everyday life (Marton & Säljö, 2005). Also, the important role of language in connecting theory and experience is well established (Odden & Russ, 2019a). However, the results from the present study will need to be confirmed by further research on different chemistry subtopics and different student populations. Such research could provide deeper insights into the complexities of chemistry teaching and learning.

7.7.3 Didactical implications

As this is a qualitative study, I cannot argue that the results of the present study are largely generalisable to chemistry learning. However, I have argued (in Chapter 5.1.2) that, due to the diverse sample, the similar learning progression in Sweden to other Western countries, and the consistency of the results with previously reported international research on learning in chemistry, the transferability of the results of the thesis to other schools operating within similar contexts is plausible. I would therefore like to point out some implications for teaching that can be deduced from this thesis project that could be useful for teachers teaching similar student populations in similar contexts.

This thesis has contributed to a greater understanding of how students make sense of chemistry, what is required for sensemaking, and how they can be helped. One important aspect to consider is whether students are able to use the essential psychological tools – that is, language – to form the essential concept relations in the concept system being taught. As has been seen in this study, students using less explicit and precise language had more difficulty connecting theory and experience and deciding which psychological tools to use to mediate their understanding. Hence, students using more vague scientific language would likely require more classroom support in bridging theory and experience in their own words during practical work, and in choosing which concepts to use in order to do so.

Another important implication from this thesis is to consider chemistry students' approaches to learning in relation to their learning context. As the results of this thesis show, many of the students exhibited indicators of rote learning in their concept maps. There was also a relationship between language use and achievement, and the results showed that students could sometimes be both verbose and adopt a rote-learning approach. There could be several reasons for rote learning, such as pressure to perform, lack of personal interest (Marton & Säljö, 2005), or disengagement due to a poor academic self-concept developed from previous experiences of failure (Bong & Skaalvik, 2002). According to the present study, participation in learning in the ZPD appears to be dependent on language use; therefore, such disengagement could potentially develop from failure to engage in learning in the ZPD due to less developed scientific language. Such students could benefit from language-supporting practices such as explaining concepts in words that are known to the students (Gieske et al., 2022), group discussions in mixed groups allowing learners to describe and explain phenomena at the same time as they share words and expressions with each other (Jakobsson & Kouns, 2023), using concept maps to organise student thought before writing assignments (Isabelle, 2015), and, using knowledge integration maps similar to the ones utilised in this study for student group or pair discussion and teacher formative feedback based on shape (Paper II; Kinchin, 2020; Schwendimann & Linn, 2016). Incidentally, discussing concept maps in terms of how known and new concepts are related to each other is a classroom exercise that would promote deep learning approaches for students of all language levels (Marton & Säljö, 2005). Consideration should also be given to how learning is assessed, as short-answer questions are poor indicators of student learning compared to concept maps (Zele et al., 2004) and problems based on calculations can be performed well by novice learners adopting mechanistic approaches (Anderson & Schönborn, 2008). As I have shown, concept-mapping can be reasonably taught in one lesson, and asking the students to provide a pencil-drawn concept map with just a few key concepts as part of a test could be feasible, especially as a recurring test item. If such an item is aimed at triplet knowledge domains, it could also promote long term learning of the nature of chemistry (Thomas, 2017).

A third implication from this study concerns the planning of teaching. This thesis not only demonstrates how to help students make sense of chemistry phenomena but also shows that chemistry students with poorly developed conceptual meanings have a hard time making sense of observations during practical work. Therefore, it is recommended that practical work is planned as late as possible during the teaching of a subtopic of chemistry, and that teachers act consciously to mediate sensemaking with the students in their classrooms. This conscious act of mediation would include (1) eliciting student explanations of phenomena in their own words, (2) offering alternative concepts and connecting theory and experience, and (3) presenting students as competent in the interaction. Examples of practice can be found in Paper IV.

7.8 Final words

Many years ago, I asked myself why students cannot make sense of what they are doing in the chemistry laboratory. Based on the research presented in this thesis, I think that the answer to this question has two aspects.

The first aspect has to do with how we learn. As has been shown in this thesis, chemistry sensemaking must first occur between teacher and student before any chemistry learning can take place. What sense students make on their own varies tremendously and, in most cases, does not reach the sensemaking being aimed for. This is why the teacher needs to be there to guide the dialogue and to show the ways of the cultural practice of chemistry.

The second aspect has to do with words and word meanings. If the word meanings are not established for the student, the laboratory becomes a place of unresolved, foggy concepts. Also, as Weick (1995) pointed out, when under pressure arising from the shock of encountering complexity or confusion, people resort to noticing the familiar instead of the new, leading to loss of overall meaning. In these cases, it may be easier to memorise words and phrases to get by, but how does this affect the student's emotional experience of learning and their achievement over time?

I believe that my research has shown the importance of both the teacher, and of language use, in chemistry sensemaking. It is my hope that the thesis can be a support for chemistry teachers in their role as carriers of the cultural practice of chemistry, gift-givers of sensemaking and language, and sources of student academic confidence in the chemistry subject.

8 SVENSK SAMMANFATTNING

> *"Jag tänkte att samtalet* gjorde *att jag förstod det … alltså … typ allt. Så när jag stod och pratade och diskuterade fram och tillbaka med min labbpartner och sen med läraren, så lärde jag mig ju vad det var, för att när jag bara gjorde det först, så förstod jag inte riktigt exakt hur det fungerar. Så när jag fick prata med dom så förstod jag att jaha, det är självklart att det blir så."*
>
> Högpresterande elev efter kemilaboration, svensk gymnasieskola
> (citat från fokusgruppsintervju, opublicerade data)

8.1 Inledning

Den här avhandlingen är en kemididaktisk studie om begripliggörande av kemi i gymnasieskolan. I avhandlingen analyseras hur elevers språkanvändning och tidigare kunskaper påverkar deras lärande i kemiämnet, och hur lärare stöttar elever på olika nivåer i lärandet. Genom studien försöker jag förstå hur elever använder sitt språk för att tolka fenomen när de lär sig kemi, och hur lärare kan hjälpa elever att nå ett begripliggörande som kan främja deras lärande långsiktigt. Elevers svårigheter att förstå kemi genom att sammankoppla upplevda fenomen till kemins teoretiska modeller och kemins symbolspråk, är väldokumenterat inom den kemididaktiska forskningen. Begripliggörandet står som huvudfokus i avhandlingen, både som kärnan i begreppsutveckling baserat på Vygotskijs teorier om lärande, och även som grunden för utvecklandet av expertis i kemiämnet. Forskningsfrågorna fokuserar på hur elevers språkanvändning är kopplad till deras begripliggörande av kemi, och hur lärare agerar för att göra kemi begripligt i klassrummet.

I min avhandling kombinerar jag teorier om tänkande i kemi (Johnstone, 1991; Taber, 2013) med teorier om begripliggörande (Odden, 2021b; Weick, 1995) och omformulerar dem inom ramen för Vygotskijs teorier runt tänkande och språk. Detta gör det möjligt för mig att beskriva och analysera kopplingen mellan språk, begripliggörande och lärande i kemi. I avhandlingen definierar jag begripliggörande med hjälp av kemins språk som en central del i lärar-elevdialogen som utgör grunden för lärande inom zonen för framtida utveckling, proximala utvecklingszonen (på engelska kallad zone of proximal development, ZPD). Därmed fyller jag en forskningslucka gällande teoretiska ramverk för studier av språkanvändning, lärande och begreppsutveckling inom kemins didaktik. Avhandlingen innehåller också flera fallstudier runt hur elever i gymnasieskolan begripliggör kemi, dvs. hur de använder sitt språk för att mediera kopplingen mellan kemins teori, symboler och kemiska fenomen, samt hur deras lärare arbetar för att hjälpa dem genom meningsutforskande dialoger. Denna forskning bidrar till kunskapsläget genom att förklara varför språket är en så viktig del i kemilärandet, samt genom att visa praktiskt hur lärare kan stötta elever med varierande språkförmågor i klassrummet.

8.2 Teori

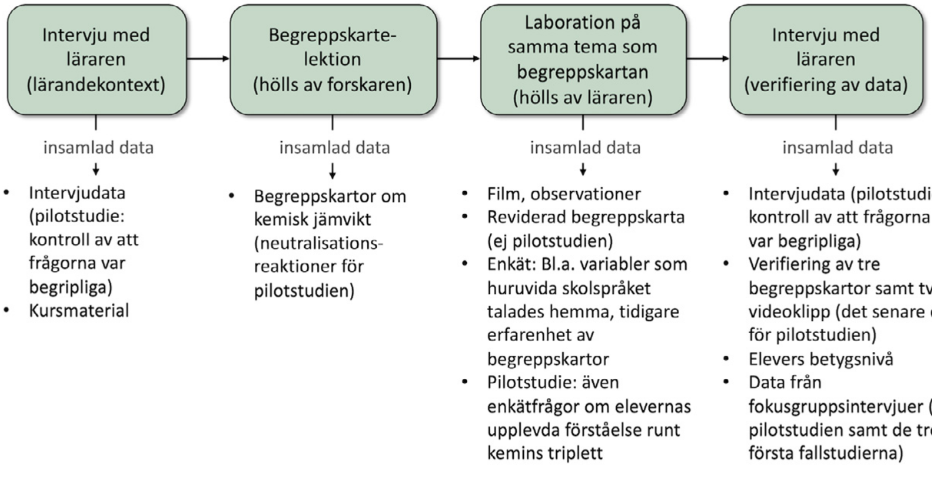
Vygotskijs lärandeteori i *Tänkande och språk* (Vygotsky, 1934/1987) står som grund i avhandlingen, i och med att den använts för att koppla samman teorier om begripliggörande, tänkande i kemi och lärande. Från Vygotskijs lärandeteori används nyckelbegrepp som *psykologiska verktyg* (ord som medierande resurser för tänkandet), *vardagsbegrepp*, *vetenskapliga begrepp* sam den *proximala utvecklingszonen*. I teorin beskrivs hur meningsutforskande dialoger med hjälp av psykologiska verktyg (såsom ord och symboler) mellan elev och lärare leder till elevens utveckling genom att denne lär sig den kulturella praktiken av att mediera meningsbildning med hjälp av ord. Denna språkpraktik kan sedan formas om till att bli en del av elevens medvetna tänkande (den *interioriseras*). I meningsbildning ingår att relatera vardagsbegrepp och vetenskapliga begrepp till varandra, där även etablerade vetenskapliga begrepp för eleven och nya vetenskapliga begrepp för eleven relateras i ett bergreppssystem. Hur och vilka begrepp som relateras är beroende av elevens personliga och emotionella upplevelse av situationen (*perezhivanie*).

Teorier om begripliggörande inom både naturvetenskapligt lärande (Odden & Russ, 2019a) och sociologi (Weick, 1995) har beaktats för att definiera och förklara olika aspekter av begripliggörande i analysen. Begripliggörande har definierats som den process som sker när upplevelse och teori relateras i en förklaring med egna ord som ett svar på att en kunskapslucka har upptäckts (Odden & Russ, 2019a). Kunskapsluckan kan ge upphov till ett hot mot självbilden, och begripliggörandet är delvis beroende av kontextuella ledtrådar (Weick, 1995). Teorier om s.k. *tankenivåer* (eller kunskapsdomäner) inom kemin som indelade i upplevelsebaserade, symboliska och teoretiska/förklarande (kemins ”triplett”; Johnstone, 1991; Taber, 2013) har även inkorporerats för att relatera forskningen till forskning inom kemins didaktik och definiera begripliggörande från ett kemididaktiskt perspektiv (se Figur 16). Detta innebär att kemins olika begrepp kan, beroende på kontexten de används i, ses som upplevelsebaserade, symboliska och teoretiska/förklarande, samt att relaterandet av dessa emellan kan definieras som begripliggörande av kemi.

Figur 16. Kunskapsdomäner, som när de sammanlänkas blir involverade i kemins begripliggörande. Baserat på kemididaktiska modeller om tankenivåer i kemi (Johnstone, 1991; Taber, 2013), samt begripliggörande inom naturvetenskapligt lärande (Odden & Russ, 2019b).

8.3 Metodologisk ansats och metod

Forskningen hade en kvalitativ ansats och planerades som en jämförande fallstudie med ett djupare fokus på kortvariga (1–4 minuters) klassrumsinteraktioner i fem olika klasser med varierande prestationsnivå, typ av skola (kommunal skola eller friskola) och omgivning (storstad, småstad eller universitetsstad). Materialet som samlades in var elevproducerade begreppskartor om neutralisationsreaktioner (11 stycken, för pilotstudien, som utfördes på ytterligare en skola i en medelstor stad) och kemisk jämvikt (88 stycken, för huvudstudien), intervjuer med lärare, samt observationer och videoinspelningar av laborationer, antingen på temat neutralisationsreaktioner (för pilotstudien) eller jämviktsförskjutning (för huvudstudien; se Figur 17).



Figur 17. Överblick över studiens utförande.

Begreppskarteteknik lärdes ut under en lektion baserat på en väletablerad forskningsmetod (Ruiz-Primo et al., 2001). Sedan introducerades eleverna till kemins triplett som ett sätt att sortera begrepp som upplevelsebaserade, symboliska eller förklarande, och under de sista 20–30 minuterna fick alla elever konstruera sina begreppskartor där de även uppmanades att sortera begreppen (fem givna plus eventuella egna) enligt kemins triplett (som var utritad högst upp på alla begreppskartor; se Figur 18). Under nästa lektion, som var laborativ, filmades eleverna och läraren och lärar-elevsamtalen spelades in. Efter laborationens slut fick eleverna redigera sina begreppskartor enligt sin nya förståelse och fylla i en enkät. I enkäten uppgav de bland annat om de talade ett annat språk än skolspråket hemma och hur stor erfarenhet de hade sedan tidigare av att göra begreppskartor (de allra flesta hade ingen erfarenhet alls). Läraren intervjuades före och efter studien för att ge information om kontexten och verifiera ifall begreppskartorna och samtalen var autentiska.

Figur 18 Hänvisning till kemins triplett som fanns högst upp på varje begreppskarta. Denna typ av ”början” för en begreppskarta kan hjälpa elever med lite erfarenhet att komma igång med sin konstruktion. I denna typ av begreppskarta skrivs begrepp (definierat som *saker* eller *händelser*; Novak, 2002) i rutor som sammanlänkas med pilar med sammanlänkande text på. Under studien fick eleverna skriva sina begrepp på färgade lappar och rita pilar mellan dem med blyertspenna. Texten till pilarna skrevs på en lapp med annan färg och sattes sedan ovanpå pilen. På så sätt var det lätt att redigera kartan.

Analysen av begreppskartorna gjordes med stöd i tidigare forskning och från ett etnografiskt perspektiv, där begreppskartorna räknades som kulturella produkter producerade inom en viss undervisningskontext där det krävs att den som analyserar är insatt i den kultur som omger elever och lärare (Altheide & Schneider, 2013). Jag använde även min egen bakgrund som kemist och kemilärare för att tolka lärarnas och elevernas utsagor. Videoinspelningarna analyserades med hjälp av samtalsanalys, vilket innebar att analysen av lärar-elevsamtalen hade en induktiv, etnografisk ansats (Heritage, 1984).

Det ramverk som användes som stöd i kodningen var Vygotskijs lärandeteori, forskning om kemins tankenivåer, samt forskning om bedömning av språkanvändning i begreppskartor. Begreppet begripliggörande (Odden & Russ, 2019a; Weick, 1995) tillkom induktivt i analysen som det begrepp som bäst kunde beskriva materialet och fungera som ett ramverk runt studien i sin helhet, om det definierades inom ramen för språk och lärande.

Med avseende på min bedömning av språkanvändningen i begreppskartorna, så använde jag forskning om hur man kan jämföra elevers språk i begreppskartor (Yin et al., 2005) samt även forskning om hur vetenskapligt språk kan definieras och läras ut i klassrum med elever som talar ett annat språk än skolspråket hemma (O. Lee et al., 2019). Ett välutvecklat vetenskapligt språk kan från dessa perspektiv definieras som ett språk som är utförligt och precist. Elever som använder ett utförligt och precist språk använder relevanta begrepp samt ämnesspecifika symboler för att ge en välartikulerad förklaring av ett samband eller ett fenomen (ibid.).

8.4 Resultat från de olika delstudierna

8.4.1 Delstudie I

Under denna pilotstudie undersöktes hur elva elever relaterade till kemins triplett under en begreppskartelektion som lades innan en laboration om neutralisationsreaktioner (se metod ovan). Eleverna fick sedan fylla i en enkät om sina upplevelser av övningen och laborationen.

I begreppskartorna sågs en varierad förståelse för kemins triplett, vilken kan ses som en modell för begripliggörande i kemi enligt kulturell tradition. Vissa elever länkade till tripletten med meningsfull text på sina pilar och gjorde den till en del av begreppskartan, andra ritade bara pilar (trots att resten av kartan innehöll pilar med text på), medan en tredje grupp kopierade fraser från ett exempel som hade givits ut. Svårighet att relatera till kemins triplett noterades även bland resten av begreppskartorna tillhörande forskningsprojektet, där ett samband fanns mellan a) elevernas förmåga att länka till tripletten högst upp, och, b) elevernas förmåga att sortera begreppen som upplevelsebaserade, symboliska eller förklarande (ej publicerade data). I enkäten sade fyra av elva elever att de fann idén om kemins triplett svår att förstå.

I dessa kartor sågs även varierande sätt hos eleverna att definiera symbolisk mening. Detta betydde att t.ex. symboler kunde beskrivas som tillhörande empiriska data, eller att partiklar definierades som symboler. De elever som hade svårt att definiera symbolisk mening i sina begreppskartor upplevde begreppskarteövningen som speciellt användbar.

En slutsats som kan dras för denna studies resultat är att begreppskartor baserade på kemins triplett verkar stödja begripliggörande för elever, speciellt de som visade på en begränsad förståelse för begripliggörande enligt kemins kulturella praktik. För mer läsning, se Hamnell-Pamment (2019).

8.4.2 Delstudie II

I denna delstudie undersöktes begreppsutveckling med användning av Vygotskijs teorier om språk och lärande. Fokus för analysen var hur elevernas språkanvändning relaterade till hur de kopplade samman det vardagliga begreppet ”färgförändring” med begreppssystemet för kemisk jämvikt i sina begreppskartor. En integrering av detta vardagsbegrepp i det vetenskapliga begreppssystemet då begreppskartan konstruerades tolkades som lärande och begripliggörande av kemi i den proximala utvecklingszonen. Här definierades alltså konstruktion av begreppskartor som ett slags kollaborativt lärande, eftersom eleverna gavs en ”början” och begrepp att jobba med.

I delstudien beskrivs olika sätt som eleverna kopplade samman vardagsbegreppet ”färgförändring” med det vetenskapliga begreppssystemet för kemisk jämvikt. Vissa elever integrerade det vardagliga begreppet i begreppssystemet, andra konstruerade ett separat begreppssystem för empiriska data i sin karta (inklusive färgförändring) som de inte kopplade till teorin, en tredje grupp lade vardagsbegreppet helt för sig vid sidan om det vetenskapliga begreppssystemet, och en sista grupp kunde inte konstruera ett begreppssystem för kemisk jämvikt och inte heller koppla till vardagsbegreppet ”färgförändring”.

När sammankopplingen mellan vardagsbegreppet och begreppssystemet jämfördes med elevernas språkanvändning, så kunde elever med mer explicit och precist språk oftare koppla ihop sin förståelse av kemisk jämvikt med vardagsbegreppet ”färgförändring”. Elever som talade ett annat språk än skolspråket hemma kopplade också mer sällan ihop sin förståelse av kemisk jämvikt med vardagsbegreppet ”färgförändring”, jämfört med elever som talade skolspråket hemma.

En slutsats drogs från resultaten att elevers språkanvändning påverkade deras möjlighet att delta i lärande och begripliggörande i den proximala utvecklingszonen. För mer läsning, se Hamnell-Pamment (2023a).

8.4.3 Delstudie III

I denna delstudie undersöktes hur eleverna sammankopplade och organiserade kemins kunskapsdomäner enligt kemins triplett i sina begreppskartor. På detta sätt relaterades elevernas begreppskartor till en modell för vad man anser vara kemisk expertis, eller ett begripliggörande enligt kemins kulturella tradition (Johnstone, 1991; Kozma & Russell, 2005; Taber, 2013). Sambandet mellan detta begripliggörande och elevernas vetenskapliga språkanvändning samt prestationer i ämnet enligt tidigare ämnesbetyg kunde sedan undersökas.

Med utgångspunkt i analysen drogs slutsatsen att begreppskartorna kunde delas in i fyra nivåer av begripliggörande enligt kemins kulturella praktik:

1. Begreppskartor där kunskapsdomänerna var tydligt definierade, språket tydligt och många korslänkar mellan begrepp fanns.
2. Begreppskartor där en viss förståelse för tripletten visades genom kopplingarna i kartan, men där kunskapsdomänerna var delvis ostrukturerade. Istället sågs strängar av parallella narrativ i kartorna med färre korslänkar mellan begreppen.
3. Begreppskartor där symboler användes som observationsbegrepp eller förklaringar. Dessa kartor hade också strängar av parallella narrativ och mer ostrukturerade kunskapsdomäner.
4. Begreppskartor som saknade strukturerade kunskapsdomäner. Dessa kartor hade mestadels vagt språk, men det fanns även kartor med precis och explicit språk. Länkarna mellan begreppen tenderade att vara associativa, dvs. saknade en övergripande struktur.

Resultaten visade på ett samband mellan elevers prestationsnivå och deras vetenskapliga språk, där elever med högre betyg oftare hade ett precist och explicit språk och valde mer relevanta begrepp till sina begreppskartor. Elevernas prestationsnivå var dock inte relaterad till hur de strukturerade upp kunskapsdomäner i sina begreppskartor. Istället var det variation mellan skolklasser, där vissa elevgrupper strukturerade sina kartor i högre grad än andra. Till exempel noterade jag en stor andel av begreppskartor av nivå 4 i två klasser: en väldigt lågpresterande klass, och en väldigt högpresterande klass där de flesta använde ett utförligt och precist språk. Alltså kunde vissa elever med ett mycket välutvecklat vetenskapligt språk erhålla ett högt betyg utan att använda sig kemins kulturella praktik i sina begripliggörande av fenomen.

I begreppskartorna illustrerades brist på begripliggörande också med att kartor med sämre struktur hade flera strängar av narrativ (tanketrådar som inte sammanförts med andra tankar), eller narrativ som radade upp olika associationer runt ett visst begrepp utan övergripande struktur. Dessa typer av strukturer i begreppskartor indikerar utantillinlärning och ytinlärning hos eleverna (Kinchin, 2020; Säljö, 1975). Djupare lärande, vilket kan utrönas från ett utvecklat språk och många korslänkar i en begreppskarta (Kinchin, 2020), sågs bara i kartor av nivå 1. Elevers brist på begripliggörande enligt kemins kulturella praktik sammanföll alltså med vissa tecken på ytinlärningsstrategier.

Slutsatsen som drogs från denna studies resultat var att ett välutvecklat vetenskapligt språk i kemi inte nödvändigtvis betyder att begripliggörande enligt kemins kulturella tradition kan medieras. Det konstaterades även att det är möjligt att bedömning av elevers förmågor i kemi inte alltid inkluderar denna aspekt av begripliggörande, trots att begripliggörande av kemi inkluderas i båda av de undersökta skolsystemens läroplaner. För mer läsning, se Hamnell-Pamment (2023b).

8.4.4 Delstudie IV

I denna delstudie undersökte jag hur erfarna lärare går till väga när de leder elever till begripliggörande av kemisk jämvikt i lärar-elevdialoger, vilket jag med utgångspunkt i det teoretiska ramverket har definierat som begreppsbildning i den proximala utvecklingszonen.

Alla dialoger som innehöll begripliggörande hade samma övergripande struktur, vilken innebar att konversationen först initierades av antingen lärare eller elev, eleven uttryckte sitt begripliggörande med sina egna ord alternativt bad om hjälp, läraren ledde en begripliggörandedialog med eleven alternativt gav en förklaring, och konversationen avslutades.

Tre huvudhandlingar från lärarna utgjorde delar av begripliggörandet i alla dialoger:

- länka upplevelser med teori, till exempel fråga vad eleven tror händer med koncentrationen i lösningen när färgen förändras;
- länka till alternativa teoretiska begrepp och därmed öppna för nya sätt att tänka för eleven, till exempel genom att be eleven fundera runt vad som händer med reaktionshastigheterna i reaktionen; och
- hantera spänningar i konversationen som uppkom när elevens kunskapsluckor blottades och tystnad uppstod.

Det noterades även att reaktionsformeln för de jämviktssystem som användes verkade kunna mediera kopplingen mellan upplevelser och teori för eleverna som en del i lärar-elevinteraktionen, och därmed hjälpa beggripliggörandet.

Handlingar som lärarna använde för att hantera spänningar i konversationen var handlingar som upprätthöll elevens presentation som kompetent i interaktionen, och därmed neutraliserade hotet mot elevens jaguppfattning (Goffman, 1955; Weick, 1995). Exempelvis kunde lärarna

- använda sig av inkluderande pronomen (”vi”) för att bekräfta elevens samhörighet i den vetenskapliga gemenskapen;
- påpeka svårigheten i en uppgift, antingen genom ett direkt påpekande eller ett skämt;
- bekräfta en respons som giltig från ett annat perspektiv;
- stödja elevens begripliggörande genom ledtrådar bestående av gester eller omformuleringar av elevens yttranden; eller,
- föra bort uppmärksamheten från eleven genom att ta över konversationen, t.ex. genom att förklara ett moment eller föra in ett nytt begrepp in dialogen (det senare innebar alltså en kombination av lärarens länkande till alternativa begrepp och hantering av spänningar).

Delstudiens slutsats var att när studier görs om begripliggörande i kemi bör elevers emotionella upplevelser tas i beaktning. Exemplen på hur erfarna lärare hjälper elever att göra kemi begripligt kan användas som diskussionsmaterial för att stödja kemilärares professionella utveckling. För mer läsning, se avhandlingens manuskript (Paper IV).

8.5 Diskussion och slutsats

8.5.1 Begripliggörande som centralt i språkanvändning, tänkande och begreppsutveckling

I denna avhandling har modeller för begripliggörande omdefinierats teoretiskt med hjälp av Vygotskijs teorier om tänkande och språk, och relaterats till kemididaktisk forskning. Genom att använda detta ramverk har begripliggörande i kemi kunnat definieras som en del i begreppsbildning, dialogisk interaktion, kulturellt lärande samt situerat lärande, allt medierat med hjälp av elevers och lärares språk. Ramverket har öppnat upp för studier som rör sambandet mellan språk, elev-lärarinteraktion och begreppsutveckling i kemi, och det är min förhoppning att denna omdefiniering av begripliggörande kan vara användbar för forskningsfältet inom kemins didaktik.

8.5.2 Elevernas meningsfulla lärande och begripliggörande av kemi i studien

I avhandlingen definierar jag lärande i kemi enligt kemins kulturella praktik som ett lärande som medför utveckling av ett strukturerat tankesätt. Detta tankesätt inbegriper ett organiserande av, och ett sammanlänkande mellan, kemins olika kunskapsdomäner (kemins triplett). Tankesättet utvecklas genom begripliggörande inom proximala uttvecklingszonen, där kemins kunskapsdomäner används och definieras i samarbete med lärare (eller en mer kompetent kamrat) för att lösa problem.

Många elever i studien saknade indikationer på att de klarade av att göra kemi begripligt på ett meningsfullt, integrerat sätt, eftersom de verkade lära sig kemi delvis med hjälp av utantillärande av vissa fraser, och/eller inte kunde sammanlänka viktiga begrepp då de konstruerade sina begreppskartor. Svårigheter att sammanlänka viktiga begrepp har även setts i begreppskartor gjorda av blivande kemilärare (Kibar et al., 2013), och sättet att lära sig kemi är alltså inte unikt för eleverna i denna studie. Begreppskartorna i denna studie illustrerade att de flesta eleverna hade svårt att relatera till kemins triplett på ett meningsfullt sätt. Detta kunde jag se genom att flera elever inte interagerade med begreppskartornas ”början”, inte strukturerade sina kartor, och inte heller kunde uttrycka symbolisk mening. Det senare indikerar att eleverna hade svårt att mediera mening med hjälp av kemins symboler, ett problem i kemiundervisningen som även bekräftats av andra (Liu & Taber, 2016). Resultaten från avhandlingen bekräftar tidigare forskning, som visar på att elevers förståelse för kemins natur och vad som innebär begripliggörande av kemi kan variera (Thomas, 2017). Min forskning visar även på att meningsfullt lärande i kemi (påvisat genom förmåga till strukturerat begripliggörande) inte behöver vara relaterat till vare sig betygsnivå eller ett välutvecklat ämnesspråk i kemi. Däremot var ämnesspråket i kemi hos eleverna som deltog i denna forskningsstudie starkt relaterat till prestation, vilket ifrågasätter huruvida det sätt som kemi bedöms i svenska skolor verkligen innebär att elevers förmåga att använda modeller och kemins språk för att tolka fenomen utvärderas fullt ut.

Som noterats i delstudie II, så kunde elever använda sitt språk för begripliggörande i begreppsutveckling genom att sammanlänka vardagsbegrepp med vetenskapliga begrepp. Dock var det vetenskapliga begreppssystemet som användes i denna begreppsutveckling ofta helt eller delvis ostrukturerat och kunde innehålla delar som indikerade utantillärande eller associativt tänkande. Speciellt utantillärande gör det svårt att utveckla begreppssystemet vidare (Kinchin, 2020) och därmed öppna upp för ett strukturerat tänkande som kan involveras i meningsfullt lärande. Alltså innebar sättet som vissa av eleverna i studien lärde sig kemi på ett problem för framtida lärande inom ämnet.

8.5.3 Språkets roll för begripliggörande av kemi

Elevers bemästrande av kemins språk verkar, baserat på denna studie, ha stor inverkan på deras betyg, och även på deras möjligheter att delta i lärande i den proximala utvecklingszonen. Det vetenskapliga språket verkar alltså vara nödvändigt för begripliggörande i kemi, vilket är rimligt om man ser språk som en medierande resurs för tänkandet (Vygotsky, 1934/1987). Språksvaga elever (inklusive de som talade ett annat språk hemma), verkade finna det svårare att definiera kemisk jämvikt jämfört med språkstarka elever, och även att länka sin kemiska teoretiska kunskap till vardagsbegreppet ”färgförändring”. Anledningen att elever med ett välutvecklat vetenskapligt språk kunde delta i undervisningen verkade bero på att de till en hög grad kunde spontant använda sig av redan etablerade begrepp för att definiera kemisk jämvikt. Observationen att reaktionsformeln kunde användas för att sammanföra upplevelser (uttryckta med vardagsbegrepp) och teorier (uttryckta med vetenskapliga begrepp) pekar också på vikten av ämnesspråket i kemi för begreppsutveckling. Resultaten indikerar alltså att utvecklingen av strukturerad, begreppslig mening och språkanvändning i kemi är ömsesidigt beroende av varandra.

I studien sågs olika typer av användning av kemins symboler: som representationer, som matematiska förklaringsmodeller eller som medierare av mening. Förklaringar baserade på matematiska modeller kan leda till att den kemiska teorin kopplas bort (Zhao & Schuchardt, 2021), vilket även var vad som sågs här. De olika sätten att använda symboler skulle kunna ses som olika mognadsnivåer för de symboliska begreppen, men detta skulle behöva undersökas i en annan forskningsstudie.

Att elever som bättre behärskade kemins språk också bedömdes ligga på en högre prestationsnivå är i linje med litteratur som visar att elever som känner att de förstår kemins språk också har större tilltro till sina framtida prestationer och är uthålligare med sina studier (Rüschenpöhler & Markic, 2020). Elevers upplevda kompetens påverkar även deras klassrumsengagemang (Bong & Skaalvik, 2002; Raufelder et al., 2015) och deras prestation på sikt (Jansen et al., 2014; Wu et al., 2021). I Sverige innebär övergången till gymnasieskolan ett stort hopp i språkets komplexitet för kemiämnet (Ribeck, 2015), vilket gör det desto viktigare att språkstöd ges i kemiämnet för språksvaga elever i den svenska skolan. Exempel på språkstöd ges i avsnitt 8.5.6.

Baserat på resultaten presenterade i denna avhandling föreslår jag att anledningen till att språket påverkar kemielevers upplevda kompetens är att språket medierar begripliggörandet genom att teori lättare kan kopplas till fenomen, vilket kan leda till både en känsla av förståelse för eleven och en känsla av tillhörighet i kemiklassrummet. Dock behöver inte denna koppling mellan teori och fenomen vara fullständig eller ske enligt kemins kulturella praktik, vilket understryker lärarens viktiga roll i klassrummet att förmedla och vara en modell för vad kemins kulturella praktik innebär.

8.5.4 Begripliggörande i den proximala utvecklingszonen

Lärarna som studerades i delstudie IV arbetade genomgående för att presentera eleverna som kompetenta. Elevers akademiska självbild i kemi är också relaterad till deras framtida prestationer (Wu et al., 2021). Att hantera spänning i interaktioner mellan elever och lärare som en viktig del i begripliggörandet kan kopplas till Vygotskijs begrepp *perezhivanie*, dvs. att elevers lärande och utveckling beror på hur de ser på, tolkar och relaterar till en viss händelse (Vygotsky, 1934/2020). Samtidigt drivs elevens utveckling i relation till lärarens modellering och den kollaborativa interaktionen (ibid.)

Baserat på avhandlingens resultat kan slutsatsen dras att de flesta elever som studerades behövde stöd i sitt begripliggörande om kemisk jämvikt. Det kan noteras att runt hälften (41/88) av eleverna var mycket högpresterande utifrån lärarnas bedömning, men att även dessa i de flesta fall behövde stöd i sitt begripliggörande under laborationen. Detta är i linje med studier som visar på att behovet av lärarstöd för att koppla samman observationer med teori under laborativt lärande i gymnasieskolan (Gericke et al., 2022) och lärsvårigheter specifika för kemiområdet (Talanquer, 2008; Treagust et al., 2003).

Begripliggörande som en kulturell praktik enligt kemins triplett har tidigare kopplats till klassrummets normer för begripliggörande (Becker et al., 2013). Dock verkar det i denna avhandling som om många av eleverna lärde sig delar av kemistoffet med hjälp av utantillärning vilket ledde till svårigheter att koppla begrepp, och/eller hade svårt att delta i lärande i den proximala utvecklingszonen på den nivå som krävdes i undervisningen (vilket leder till omstrukturering av tänkandet över tid; Vygotsky, 1934/1987).

Jag föreslår, baserat på forskningen i denna avhandling, att det kemiska språkets natur och hur det används i begripliggörande kan göra det svårt för elever att se skillnad mellan olika typer av användning av symboler i interaktionen med läraren. Detta eftersom symboler i lärar-elevsamtal användes både som ledtrådar för begripliggörande och som medierande resurs för tänkande i samtal, medan vissa av eleverna i sina begreppskartor kunde använda symboler som förklaringar i sig själva. Det kan hända att symbolers användning i kemiundervisningen behöver tydliggöras av lärare med hjälp av metakommunikation.

8.5.5 Vidare forskning

Inom kemididaktisk forskning finns exempel på implicita antaganden att elever 'har' kunskapsdomäner som de behöver lära sig att navigera i kemiklassrummet (Johnstone, 1991; Taber, 2013). Resultaten från denna studie ifrågasätter dessa antaganden. Istället föreslås att organiserat tänkande inom triplettens kunskapsdomäner, sedda som en del av kemisters kulturella praktik, kan utvecklas (eller inte) genom undervisning i kemiämnet. Kopplingen mellan kontext, begripliggörande och utvecklingen av strukturerat tänkande vore ett intressant fokus för vidare forskning. Här är kopplingen mellan djupinlärning och utvecklingen av organiserat begripliggörande enligt kemiämnets kulturella praktik speciellt intressant att beforska.

Resultaten från avhandlingen kan också användas som argument emot en kognitivistisk, individualistisk syn på lärande, eftersom olika elever, speciellt de med svagare språk, uppenbarligen behövde lärarens hjälp för att utvecklas genom meningsbildning i samverkan. Språkförmågans centrala roll för lärande i kemi kan ses i sambandet mellan elevers akademiska självbild och deras vetenskapliga språkförmåga (Rüschenpöhler & Markic, 2020), men även i resultaten från delstudie IV, där elevers deltagande i kollaborativt lärande innebar att läraren kunde stötta elevens presentation som kompetent i interaktionen. Elevers utveckling av kemins språk över tid i relation till deras akademiska självbild, emotionella upplevelse och deltagande i klassrumsinteraktioner vore även det ett intressant fokus för vidare forskning, speciellt om en jämförelse kunde göras mellan elever som läser kemi på sitt förstaspråk och elever som läser kemi på ett annat språk än sitt förstaspråk.

8.5.6 Stöd för lärande i kemi

Med avseende på konkreta stöd för lärande i kemiklassrummet kan jag, baserat på resultaten i denna avhandling, rekommendera att elever med svagare vetenskapligt språk ges mer stöd i klassrummet att koppla samman teori och fenomen med sina egna ord, och även med att välja lämpliga teoretiska begrepp när de gör detta.

En annan aspekt att beakta är elevernas lärstrategier i relation till lärandekontexten. Utantillärande kan orsakas av prestationsångest, brist på intresse (Marton & Säljö, 2005), eller att eleven har utvecklat en likgiltighet för ämnet baserat på tidigare upplevelser av att misslyckas (Bong & Skaalvik, 2002). Sådan likgiltighet skulle kunna utvecklas om en elev inte kunnat delta i lärande och begripliggörande på grund av begränsad språkförmåga. Elever med svag språkförmåga skulle kunna stöttas med hjälp av t.ex. att nya begrepp förklaras med hjälp av ord de förstår (Gieske et al., 2022), att gruppdiskussioner förs där elever får beskriva och förklara fenomen samtidigt som de delar ord och uttryck med varandra (Jakobsson & Kouns, 2023), att begreppskartor används för att organisera tankarna före skrivuppgifter (Isabelle, 2015), samt att elevkonstruerade, begreppsintegrerande begreppskartor av samma typ som använts i denna studie används i grupp- eller pardiskussioner och ges formativ återkoppling från lärare (Kinchin, 2020; Schwendimann & Linn, 2016). Intressant i sammanhanget är att diskussioner om hur begrepp i begreppskartor är relaterade till varandra är en övning som har karaktären av djupinlärning (Marton & Säljö, 2005). För ett exempel på hur kunskapsintegrerande begreppskartor kan användas i samband med språkstödjande undervisning, se Vestergård och Pamment (2020/2022).

Baserat på avhandlingens resultat föreslås att lärare funderar runt hur bedömning görs i kemiämnet. Kortsvarsfrågor ger ett dåligt underlag för bedömning av lärande (Zele et al., 2004) och problem som kan lösas enbart med hjälp av uträkningar kan leda till att elever med begränsad kunskap utvecklar mekaniska problemlösningsstrategier (Anderson & Schönborn, 2008). Som visats i denna studie kan begreppskartekonstruktion läras ut till en adekvat nivå på en lektion, och att rita en begreppskarta baserat på några få begrepp kan rimligtvis utgöra en del av ett väldisponerat prov. På så sätt skulle elevers integrering av begrepp kunna bedömas. En sådan provdel skulle kunna vara speciellt användbar om den upprepades och relaterades till kemins kunskapsdomäner, eftersom detta skulle kunna leda till att elever utvecklar en förståelse för tänkande inom kemi över tid (Thomas, 2017).

En sista implikation för lärande rör lärares planering av kemilaborationer. Baserat på resultaten i denna avhandling bör kemilaborationer planeras sent i en ämnesdel, och kemilärare bör medvetet verka för att skapa begripliggörande dialoger i klassrummet. Detta kan göras genom att 1. eleven uppmuntras att förklara fenomen med sina egna ord, och 2. läraren ger förslag på alternativa begrepp och hjälper eleven att sammankoppla upplevelse och teori, samtidigt som 3. eleverna presenteras som kompetenta i interaktionen med avseende på deras bidrag till begripliggörandet. Exempel på erfarna lärares begripliggörande dialoger med elever ges i delstudie IV (Hamnell-Pamment, manuskript).

8.5.7 Slutord

För många år sedan, när jag började undervisa i kemi, frågade jag mig själv varför så få elever och studenter på universitetet finner vad de gör i kemilaboratoriet begripligt. Baserat på vad jag funnit i min avhandling, tror jag svaret på denna fråga kan delas in i två delar.

En del av svaret har att göra med hur vi lär oss. Kemin måste först göras begriplig mellan elev och lärare för att ett kemilärande ska kunna ske. Här behövs läraren, både som en guide för eleverna och som en bärare och överförare av kemins kulturella praktik.

Den andra delen av svaret har att göra med ord och ords mening. Om meningen bakom orden inte är etablerad för eleven, blir laboratoriet en plats för icke förklarade, luddiga begrepp. När människor möter förvirring, eller komplexitet, tenderar de att bara se det familjära, och förlorar då kontakten med den övergripande meningen (Weick, 1995). Kanske blir det lättare då, att lära sig fraser utantill, men hur påverkar detta elevens emotionella upplevelse av lärandet, och även deras prestationer över tid?

Det är min uppfattning att min forskning har visat på vikten av både lärarens arbete och språkanvändningen vid kemins begripliggörande. Jag hoppas att avhandlingen kan bli ett stöd för kemilärare i deras roll som bärare av kemins kulturella praktik, givare av begriplighet och språk, och källor till elevers akademiska självkänsla i kemiämnet.

APPENDIX

Appendix A. Semi-structured interview questions for teacher interviews

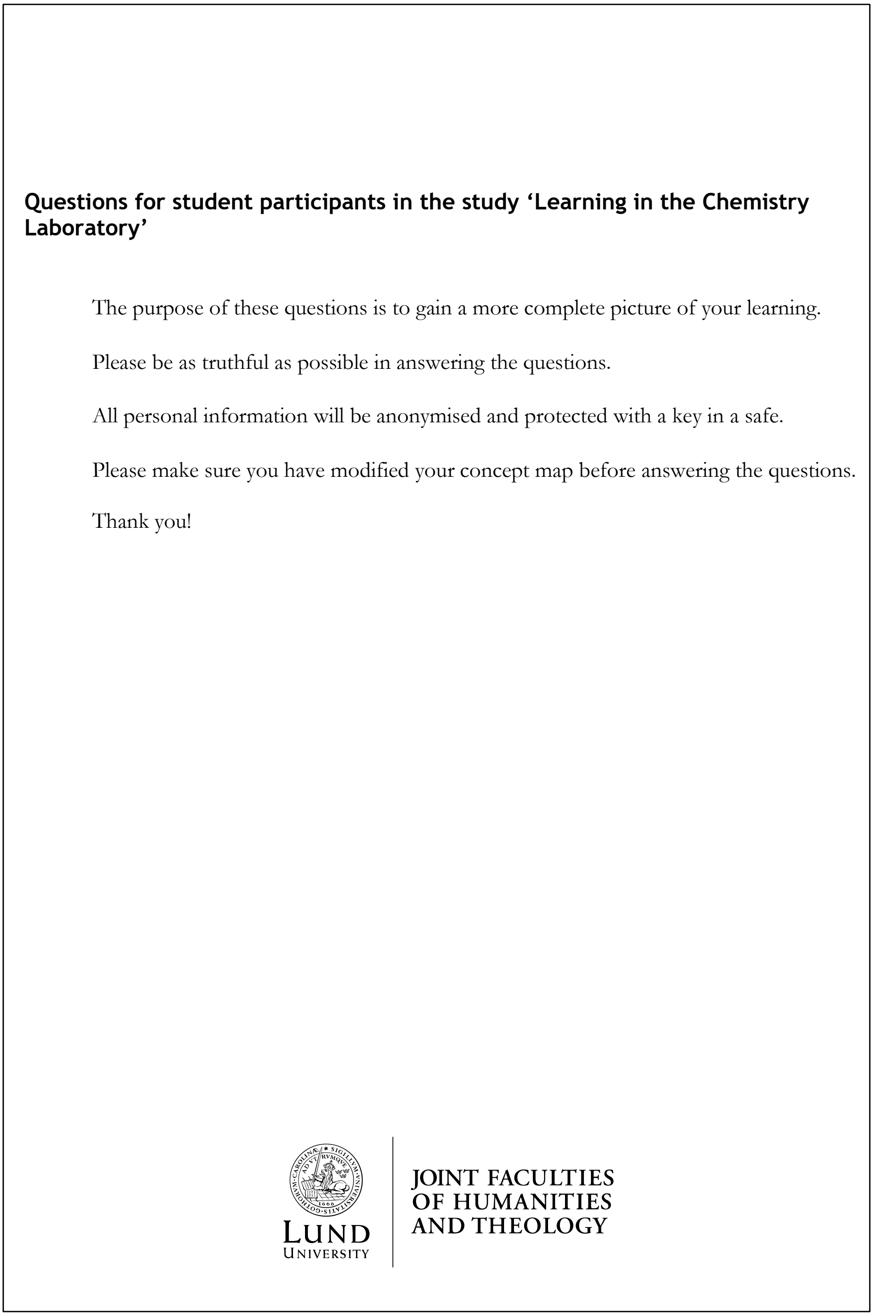
Interview 1 (pre-lab interview)

1. Can you tell me about how this lab fits into your lesson plan for the current chemistry topic being taught?
2. How much do you think your planning of the labs are affected by the lab sheets you have available?
3. What do you aim for the students to do during this lab?
4. If we consider student engagement: how engaged do think this group of students is when it comes to labwork in chemistry?
5. As a final topic, I would like to look at labwork from a more general perspective. What should in your opinion be achieved by labwork in chemistry in upper secondary school?
    - What makes you decide to use lab activities?
    - What, in your opinion, are students' roles in the lab?
    - Would you compare the way scientists work with the way students learn in science?
6. Is there anything you would like to add that you feel is important for me to know before this lab?

Interview 2 (discussion of video clips and three concept maps; general questions)

1. Would you say this was a typical lab introduction from you?
2. How typical would you say this is of how you and the students talk during the lab?
3. How, in your opinion, did the students' understanding of chemical equilibrium change during this lab?
4. What factors do you think were important for the change in understanding?
    - Do you think the use of concept maps had any effect on the lesson?
5. Do you think these concept maps show an accurate representation of what these students know?
6. How do you feel about the type of school you are working at?
7. What do you feel is the most important thing in teaching in general?
8. Have you worked as a teacher for more than five years?
9. Have you worked at this school for more than five years?
    - Do you have a position of increased responsibility at the school? What position?

Appendix B. Survey questions



Questions for student participants in the study 'Learning in the Chemistry Laboratory'

The purpose of these questions is to gain a more complete picture of your learning.

Please be as truthful as possible in answering the questions.

All personal information will be anonymised and protected with a key in a safe.

Please make sure you have modified your concept map before answering the questions.

Thank you!

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Question 1

Please answer the following questions (please note that there are no right or wrong answers):

(a) How do you think your understanding of chemical equilibrium has changed during this lab?

Please use two to three sentences, be as specific as you can, use chemical terminology when describing the theory, and answer in first person (for instance: "Before the lab, I thought… / Now I understand that…").

(b) Was there a particular part of the laboratory exercise that contributed to the change in your understanding of chemical equilibrium that you have described above?

For example:

handling the equipment
seeing something during the experiment
speaking to other students or the teacher
taking notes
drawing the concept map
etc.

Please use one to two sentences and answer in first person ("I feel that…").

(c) What do you think was the goal of today's laboratory exercise?

Please use one to two sentences and answer in first person ("I believe that…")

Question 2

In this question, you will use your knowledge of chemical equilibrium to predict an event in a test tube during a practical.

Observe the following reversible reaction, which appears orange-red in equilibrium:

$$2\ \mathrm{CrO_4^{2-}(aq, yellow)} + 2\ \mathrm{H_3O^+(aq)} \rightleftharpoons \mathrm{Cr_2O_7^{2-}(aq, red)} + 3\ \mathrm{H_2O(l)}$$

(a) What happens to the colour of the solution when water is added to the test tube?

(b) Explain your answer by drawing a picture that you believe could represent the distribution of the molecules in the test tube before and after the addition of water.

Please use symbolic representations for the molecules in your drawing, such as H_2O. As an aid, symbols representing chromate and dichromate ions are shown underneath. Also, please add name and symbols of any other molecules that you use.

Before the addition of water After the addition of water

Name	Dichromate ion	Chromate ion
Symbol	$\mathrm{Cr_2O_7^{2-}}$	$\mathrm{CrO_4^{2-}}$

Please continue by filling in your personal information on the final page.

Personal information

Name: ____

Please tick the box by the appropriate answer:

Gender: ☐ Male ☐ Female ☐ I cannot/do not wish to identify as male or female

Do you speak another language than the school language at home?

☐ Yes (most of the time or all the time) ☐ Partially ☐ No (not at all or just a little)

How often have you constructed concept maps before this study?

☐ Never ☐ Sometimes ☐ Often

When you constructed your concept map, did you consciously make the *shape* special or particular in any way (different from the instruction)?

☐ No, the shape just emerged ☐ Partially ☐ Yes

If you answered 'Partially' or 'Yes' above, please describe what you were thinking when you chose a shape:

____

Please check that you have answered all the questions before handing in your answers and your modified concept map.

Thank you very much for your participation!

Appendix C. Added question to pilot study student survey

Question 2

Please answer the following questions:

(a) How helpful did you consider yesterday's class on how to make concept maps in chemistry?

☐ Not at all ☐ Very little ☐ A little ☐ Quite a lot ☐ A great deal

(b) Is there some part of making concept maps you have not understood? You can choose more than one option.

☐ What concepts are
☐ How to make a proposition
☐ What linking words are
☐ What a focus question is
☐ How to use examples in concept maps
☐ How to differentiate between observations, symbols and particulate explanations
☐ Other (please state): ____

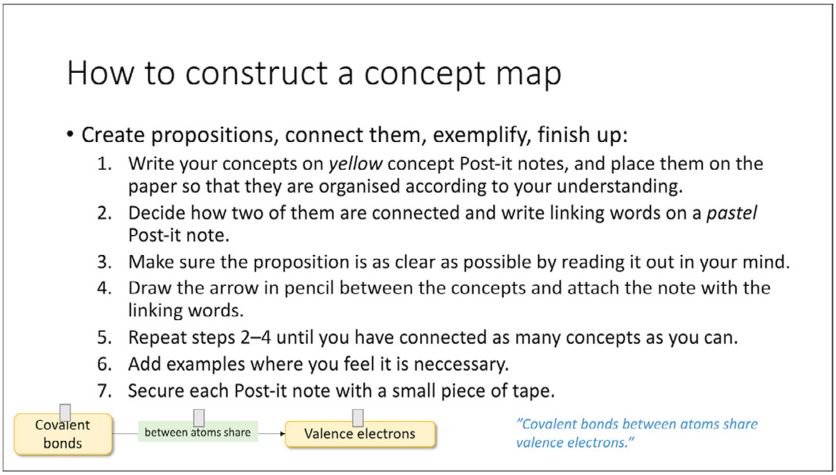
(c) Do you have any suggestions for improving the instruction on how to make concept maps?

(d) Did you feel that participating in this study was valuable to you in any way?

☐ Not at all ☐ Very little ☐ A little ☐ Quite a lot ☐ A great deal

Please continue by filling in your personal information on the final page.

Appendix D. Instructions for concept mapping and concept mapping worksheets[14]



How to construct a concept map

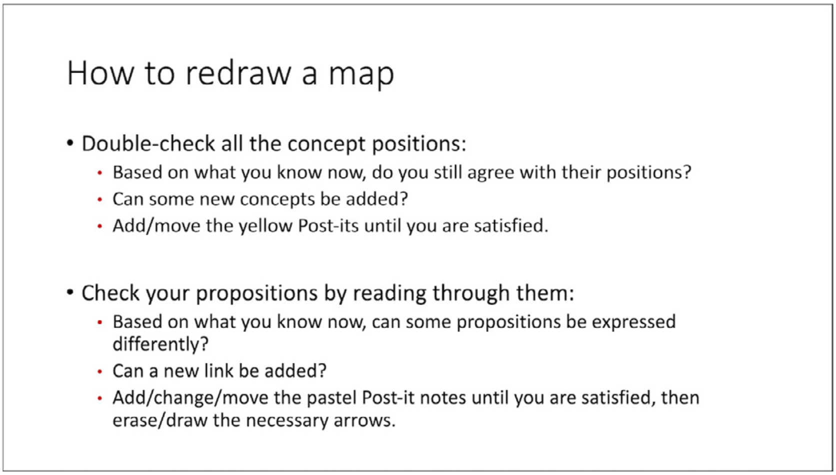
- Create propositions, connect them, exemplify, finish up:
  1. Write your concepts on *yellow* concept Post-it notes, and place them on the paper so that they are organised according to your understanding.
  2. Decide how two of them are connected and write linking words on a *pastel* Post-it note.
  3. Make sure the proposition is as clear as possible by reading it out in your mind.
  4. Draw the arrow in pencil between the concepts and attach the note with the linking words.
  5. Repeat steps 2–4 until you have connected as many concepts as you can.
  6. Add examples where you feel it is neccessary.
  7. Secure each Post-it note with a small piece of tape.

Covalent bonds

between atoms share

Valence electrons

"Covalent bonds between atoms share valence electrons."



How to redraw a map

- Double-check all the concept positions:
  - Based on what you know now, do you still agree with their positions?
  - Can some new concepts be added?
  - Add/move the yellow Post-its until you are satisfied.

- Check your propositions by reading through them:
  - Based on what you know now, can some propositions be expressed differently?
  - Can a new link be added?
  - Add/change/move the pastel Post-it notes until you are satisfied, then erase/draw the necessary arrows.

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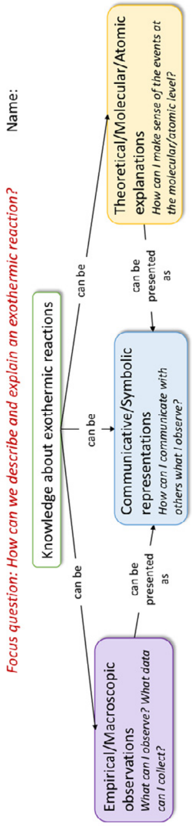
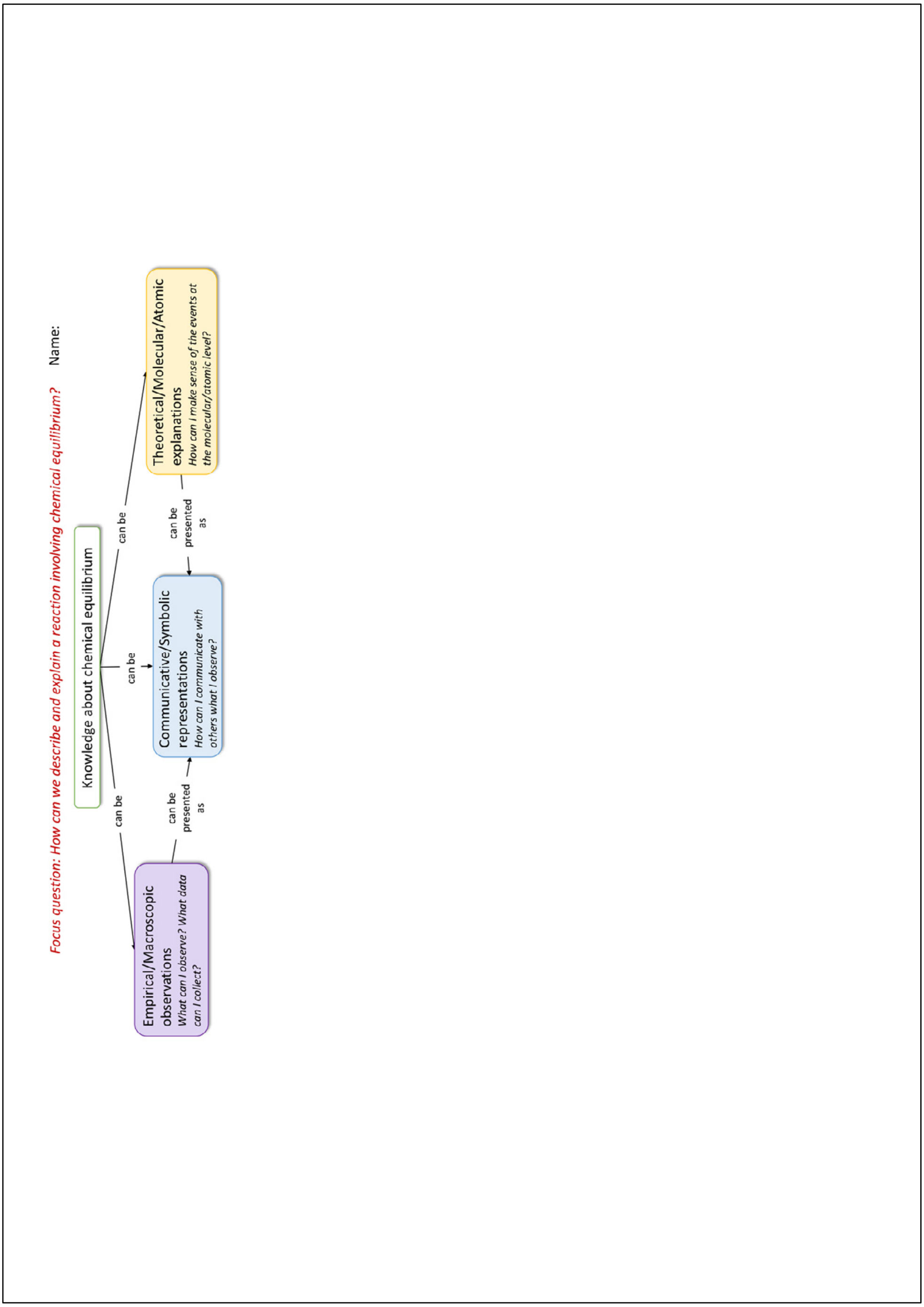
[14] A2 or A3 size is recommended for the worksheets. These worksheets are adapted for the International Baccalaureate Diploma curriculum. 5x4 cm sticky notes were used.



Given concepts: Heat, $\Delta H < 0$, Chemical bonds, Specific heat capacity, Temperature. Add at least two concepts of your own.



Given concepts: Colour change, Concentration, K_c, $\rightleftharpoons$, Reversible. Add at least two concepts of your own. The concept map skeleton is also shown in Figure 13 on page 109.

REFERENCES

Abrahams, I., & Millar, R. (2008). Does practical work really work? A study of the effectiveness of practical work as a teaching and learning method in school science. *International Journal of Science Education*, *30*(17), 1945–1969. https://doi.org/10.1080/09500690701749305

Adams, A., Jessup, W., Criswell, B. A., Weaver-High, C., & Rushton, G. T. (2015). Using inquiry to break the language barrier in chemistry classrooms. *Journal of Chemical Education*, *92*(12), 2062–2066. https://doi.org/10.1021/ed500837p

Aguiar, J. G., & Correia, P. R. M. (2016). Using concept maps as instructional materials to foster the understanding of the atomic model and matter-energy interaction. *Chemistry Education Research and Practice*, *17*, 756–765. https://doi.org/10.1039/C6RP00069J

Aguilar-Tamayo, M. F., & Aguilar-García, M. F. (2008). Novak and Vygotsky and the representation of the scientific concept. *Concept mapping: Connecting educators. Proceedings of the Third International Conference on Concept Mapping, Tallin, Estonia & Helsinki, Finland.*

Åkerblom, A., Součková, D., & Pramling, N. (2019). Preschool children's conceptions of water, molecule, and chemistry before and after participating in a playfully dramatized early childhood education activity. *Cultural Studies of Science Education*, *14*(4), 879–895. https://doi.org/10.1007/s11422-018-9894-9

Alderson-Day, B., & Fernyhough, C. (2015). Inner speech: Development, cognitive functions, phenonemology, and neurobiology. *Psychological Bulletin*, *141*(5), 931–965. https://doi.org/10.1037/bul0000021

Alexander, P. A. (2007). Bridging cognition and socioculturalism within conceptual change research: Unnecessary foray or unachievable feat? *Educational Psychologist*, *42*(1), 67–73. https://doi.org/10.1080/00461520709336919

Altheide, D. L., & Schneider, C. J. (2013). Qualitative media analysis. In *Qualitative media analysis*. SAGE Publications. https://doi.org/10.4135/9781452270043

Anderson, T. R., & Schönborn, K. J. (2008). Bridging the educational research-teaching practice gap. Conceptual understanding, part 1: The multifaceted nature of expert knowledge. *Biochemistry and Molecular Biology Education*, *36*(4), 309–315. https://doi.org/10.1002/bmb.20209

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

Andersson, B. (1990b). Pupils conceptions of matter and its transformations (age 12-16). In P. L. Lijnse, P. Licht, W. de Vos, & A. J. Waarlo (Eds.), *Relating macroscopic phenomena to microscopic particles: A central problem in secondary science education* (pp. 12–35). CD-Beta Press.

Arievitch, I. M., & Haenen, J. P. P. (2005). Connecting sociocultural theory and educational practice: Galperin's approach. *Educational Psychologist*, *40*(3), 155–165. https://doi.org/10.1207/s15326985ep4003_2

Askling, B. (2006). *Utbildningsvetenskap – Ett vetenskapsområde tar form (Vetenskapsrådet rapportserie 16:2006)*. https://www.vr.se/analys/rapporter/vara-rapporter/2006-11-01-utbildningsvetenskap---ett-vetenskapsomrade-tar-form.html

Ausubel, D. P., Novak, J. D., & Hanesian, H. (1978). *Educational psychology: A cognitive view* (R. & W. Holt, Ed.).

Bain, K., Rodriguez, J. M. G., Moon, A., & Towns, M. H. (2018). The characterization of cognitive processes involved in chemical kinetics using a blended processing framework. *Chemistry Education Research and Practice*, *19*(2), 617–628. https://doi.org/10.1039/c7rp00230k

Bain, K., Rodriguez, J. M. G., & Towns, M. H. (2019). Chemistry and mathematics: Research and frameworks to explore student reasoning. *Journal of Chemical Education*, *96*(10), 2086–2096. https://doi.org/10.1021/acs.jchemed.9b00523

Bakhtin, M. M. (1981). *The dialogic imagination: Four essays by M. M. Bakhtin* (C. Emerson & M. Holquist, Trans.) (M. Holquist, Ed.). University of Texas Press. (Original work published 1975)

Bandura, A. (1989). Regulation of cognitive processes through perceived self-efficacy. *Developmental Psychology*, *25*(5), 729–735. http://dx.doi.org/10.1037/0012-1649.25.5.729

Barke, H.-D. (2015). Learners ideas, misconceptions, and challenge. In J. García-Martínez & E. Serrano-Torregrosa (Eds.), *Chemistry education: Best practices, opportunities and trends.* (pp. 395–420). Wiley-VCH Verlag GmbH & Co. KGaA. https://doi.org/10.1002/9783527679300

Barke, H.-D., Hazari, A., & Yitbarek, S. (2010). *Misconceptions in chemistry: Addressing perceptions in chemical education*. Springer.

Becker, N., Rasmussen, C., Sweeney, G., Wawro, M., Towns, M., & Cole, R. (2013). Reasoning using particulate nature of matter: An example of a sociochemical norm in a university-level physical chemistry class. *Chemistry Education Research and Practice*, *14*(1), 81–94. https://doi.org/10.1039/c2rp20085f

Becker, N., Stanford, C., Towns, M. H., & Cole, R. (2015). Translating across macroscopic, submicroscopic, and symbolic levels: The role of instructor facilitation in an inquiry-oriented physical chemistry class. *Chem. Educ. Res. Pract.*, *16*(4), 769–785. https://doi.org/10.1039/C5RP00064E

Becker, N., & Towns, M. (2012). Students' understanding of mathematical expressions in physical chemistry contexts: An analysis using Sherin's symbolic forms. *Chemistry Education Research and Practice*, *13*(3), 209–220. https://doi.org/10.1039/c2rp00003b

Beghetto, R. A. (2009). Correlates of intellectual risk taking in elementary school science. *Journal of Research in Science Teaching*, *46*(2), 210–223. https://doi.org/10.1002/tea.20270

Benedict-Chambers, A., Kademian, S. M., Davis, E. A., & Palincsar, A. S. (2017). Guiding students towards sensemaking: Teacher questions focused on integrating scientific practices with science content. *International Journal of Science Education*, *39*(15), 1977–2001. https://doi.org/10.1080/09500693.2017.1366674

Ben-Zvi, R., Eylon, B., & Silberstein, J. (1988). Theories, principles and laws. *Education in Chemistry*, *25*, 89–92.

Besterfield-Sacre, M., Gerchak, J., Lyons, M., Shuman, L. J., & Wolfe, H. (2004). Scoring concept maps: An integrated rubric for assessing engineering education. *Journal of Engineering Education*, *93*(2), 105–115. https://doi.org/https://doi.org/10.1002/j.2168-9830.2004.tb00795.x

Biggs, J., Kember, D., & Leung, D. Y. P. (2001). The revised two-factor study process questionnaire: R-SPQ-2F. *British Journal of Educational Psychology*, *71*, 133–149. https://doi.org/https://doi.org/10.1348/000709901158433

Biggs, J., & Tang, C. (2007). *Teaching for quality learning at university*. Open University Press.

Bills, L. (2000). Politeness in teacher-student dialogue in mathematics: A socio-linguistic analysis. *For the Learning of Mathematics*, *20*(2), 40–47.

Blikstad-Balas, M. (2017). Key challenges of using video when investigating social practices in education: contextualization, magnification, and representation. *International Journal of Research and Method in Education*, *40*(5), 511–523. https://doi.org/10.1080/1743727X.2016.1181162

Blown, E. J., & Bryce, T. G. K. (2017). Switching between everyday and scientific language. *Research in Science Education*, *47*(3), 621–653. https://doi.org/10.1007/s11165-016-9520-3

Bong, M., & Skaalvik, E. M. (2002). Academic self-concept and self-efficacy: How different are they really? In *Educational Psychology Review* (Vol. 18, Issue 1).

Borén, H., Boström, A., Börner, M., Larsson, M., & Lillieborg, S. (2012). *Kemiboken 2*.

Boujaoude, S., & Attieh, M. (2008). The effect of using concept maps as study tools on achievement in chemistry. *Eurasia Journal of Mathematics, Science, and Technology Education*, *4*(3), 233–246. https://doi.org/10.1046/j.1365-294X.2001.01359.x

Bretz, S. L. (2008). Qualitative research designs in chemistry education research. In D. M. Bunce & R. S. Cole (Eds.), *Nuts and Bolts of Chemical Education Research* (pp. 79–99). American Chemical Society.

Bretz, S. L. (2019). Evidence for the importance of laboratory courses [Editorial]. *Journal of Chemical Education*, *96*(2), 193–195. https://doi.org/10.1021/acs.jchemed.8b00874

Broman, K., Bernholt, S., & Parchmann, I. (2018). Using model-based scaffolds to support students solving context-based chemistry problems. *International Journal of Science Education*, *40*(10), 1176–1197. https://doi.org/10.1080/09500693.2018.1470350

Broman, K., & Parchmann, I. (2014). Students' application of chemical concepts when solving chemistry problems in different contexts. *Chemistry Education Research and Practice*, *15*(4). https://doi.org/10.1039/c4rp00051j

Brown, B. A., Donovan, B., & Wild, A. (2019). Language and cognitive interference: How using complex scientific language limits cognitive performance. *Science Education*, *103*(4), 750–769. https://doi.org/10.1002/sce.21509

Brown, B. A., & Spang, E. (2008). Double talk: Synthesizing everyday and science language in the classroom. *Science Education*, *92*(4), 708–732. https://doi.org/10.1002/sce.20251

Burrows, A., Holman, J., Parsons, A., Pilling, G., & Price, G. (2013). *Chemistry3*. Oxford University Press.

Burrows, N. L., & Mooring, S. R. (2015). Using concept mapping to uncover students' knowledge structures of chemical bonding concepts. *Chem. Educ. Res. Pract.*, *16*(1), 53–66. https://doi.org/10.1039/C4RP00180J

Cañas, A. J., Novak, J. D., & Reiska, P. (2012). Freedom vs. restriction of content and structure during concept mapping - possibilities and limitations for construction and assessment. *Concept maps: theory, methodology, technology. Proceedings of the Fifth International Conference on Concept Mapping*, *2*(1), 247–257. http://cmc.ihmc.us/cmc2012papers/cmc2012-p192.pdf

Cañas, A. J., Novak, J. D., & Reiska, P. (2015). How good is my concept map? Am I a good Cmapper? *Knowledge Management & E-Learning*, *7*(71), 6–19. http://www.kmel-journal.org/ojs/index.php/online-publication/article/viewFile/407/244

Cannady, M. A., Vincent-Ruz, P., Chung, J. M., & Schunn, C. D. (2019). Scientific sense-making supports science content learning across disciplines and instructional contexts. *Contemporary Educational Psychology*, *59*, 1–15. https://doi.org/10.1016/j.cedpsych.2019.101802

Carlsen, W. S. (2007). Language and science learning. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 57–74). Routledge.

Chaiklin, S. (2003). The zone of proximal development in Vygotsky's analysis of learning and instruction. In A. Kozulin, B. Gindis, V. S. Ageyev, & S. M. Miller (Eds.), *Vygotsky's educational theory in cultural context* (pp. 39–64). Cambridge University Press.

Chen, Y. C., Park, S., & Hand, B. (2016). Examining the use of talk and writing for students' development of scientific conceptual knowledge through constructing and critiquing arguments. *Cognition and Instruction*, *34*(2), 100–147. https://doi.org/10.1080/07370008.2016.1145120

Cheung, D. (2007). The adverse effects of Le Châtelier's principle on teacher understanding of chemical equilibrium. *Journal of Chemical Education*, *86*(4), 514–518.

Chevron, M.-P. (2014). A metacognitive tool: Theoretical and operational analysis of skills exercised in structured concept maps. *Perspectives in Science*, *2*, 46–54. https://doi.org/10.1016/j.pisc.2014.07.001

Childs, P. E., & Sheehan, M. (2009). What's difficult about chemistry? An Irish perspective. *Chemistry Education Research and Practice*, *10*(3), 204. https://doi.org/10.1039/b914499b

Chin, C. (2006). Classroom interaction in science: Teacher questioning and feedback to students' responses. *International Journal of Science Education*, *28*(11), 1315–1346. https://doi.org/10.1080/09500690600621100

Chiu, M., Chou, C., & Liu, C. (2002). Dynamic processes of conceptual change : Analysis of constructing mental models of chemical equilibrium. *Journal of Research in Science Teaching*, *39*(8), 688–712. https://doi.org/10.1002/tea.10041

Cipra, C., & Müller-Hilke, B. (2019). Testing anxiety in undergraduate medical students and its correlation with different learning approaches. *PLoS ONE*, *14*(3). https://doi.org/10.1371/journal.pone.0210130

Clarà, M. (2017). How instruction influences conceptual development: Vygotsky's theory revisited. *Educational Psychologist*, *52*(1), 50–62. https://doi.org/10.1080/00461520.2016.1221765

Cohen, L., Manion, L., & Morrison, K. (2018). *Research methods in education* (8th ed.). Routledge.

Cooper, G., Thomas, D. P., Prain, V., & Fraser, S. (2022). Associations between Australian students' literacy achievement in early secondary school and senior secondary participation in science: Accessing cultural and science capital. *International Journal of Science Education*, *44*(10), 1549–1564. https://doi.org/10.1080/09500693.2022.2086317

Cooper, M. M., & Stowe, R. L. (2018). Chemistry education research—From personal empiricism to evidence, theory, and informed practice. *Chemical Reviews*, *118*(12), 6053–6087. https://doi.org/10.1021/acs.chemrev.8b00020

Cowan, K. (2014). Multimodal transcription of video: Examining interaction in Early Years classrooms. *Classroom Discourse*, *5*(1), 6–21. https://doi.org/10.1080/19463014.2013.859846

Criswell, B. A. (2012). Reducing the degrees of freedom in chemistry classroom conversations. *Chemistry Education Research and Practice*, *13*(1), 17–29. https://doi.org/10.1039/C2RP00002D

Daniels, H. (2008). *Vygotsky and research*. Routledge.

Daubenmire, P. L. (2014). *Using multiple representations to resolve conflict in student conceptual understanding of chemistry* [Doctoral dissertation, UC Berkeley]. https://escholarship.org/uc/item/10c4h3dn

Davydov, V. V. (1995). The influence of L. S. Vygotsky on education theory, research, and practice (S. T. Kerr Transl.). *Educational Researcher*, *24*(3), 12–21. https://doi.org/10.3102/0013189X024003012

De Jong, O., & Taber, K. S. (2007). Teaching and learning the many faces of chemistry. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 631–652). Routledge.

de Ries, K. E., Schaap, H., van Loon, A. M. M. J. A. P., Kral, M. M. H., & Meijer, P. C. (2022). A literature review of open-ended concept maps as a research instrument to study knowledge and learning. *Quality and Quantity*, *56*(1), 73–107. https://doi.org/10.1007/s11135-021-01113-x

Deng, J. M., Rahmani, M., & Flynn, A. B. (2022). The role of language in students' justifications of chemical phenomena. *International Journal of Science Education*, *44*(13), 2131–2151. https://doi.org/10.1080/09500693.2022.2114299

Derbentseva, N., Safayeni, F., & Cañas, A. J. (2007). Concept maps: Experiments on dynamic thinking. *Journal of Research in Science Teaching*, *44*(3), 448–465. https://doi.org/10.1002/tea.20153

Derry, S. J., Pea, R. D., Barron, B., Engle, R. A., Erickson, F., Goldman, R., Hall, R., Koschmann, T., Lemke, J. L., Sherin, M. G., & Sherin, B. L. (2010). Conducting video research in the learning sciences: Guidance on selection, analysis, technology, and ethics. *Journal of the Learning Sciences*, *19*(1), 3–53. https://doi.org/10.1080/10508400903452884

D'Mello, S., & Graesser, A. (2012). Dynamics of affective states during complex learning. *Learning and Instruction*, *22*(2), 145–157. https://doi.org/10.1016/j.learninstruc.2011.10.001

D'Mello, S., Lehman, B., Pekrun, R., & Graesser, A. (2014). Confusion can be beneficial for learning. *Learning and Instruction*, *29*, 153–170. https://doi.org/10.1016/j.learninstruc.2012.05.003

Donnell, A. M. O., Dansereau, D. F., & Hall, R. H. (2002). Knowledge maps as scaffolds for cognitive processing. *Educational Psychology Review*, *14*(1), 71–86. https://doi.org/https://doi.org/10.1023/A:1013132527007

Drew, P. (2016). Contested evidence in courtroom cross-examination: The case of a trial for rape. *Law in Action: Ethnomethodological and Conversation Analytic Approaches to Law*, *January 1992*, 51–76.

Driel, J. H., & Gräber, W. (2002). The teaching and learning of chemical equilibrium. In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, & J. H. Van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 271–292). Kluwer Academic Publishers. https://doi.org/10.1007/0-306-47977-x_12

Dudas, C., Rundgren, C. J., & Lundegård, I. (2022). Exploratory considerations in chemistry education—Didactic modelling for complexity in students' discussions. *Science and Education*. https://doi.org/10.1007/s11191-021-00316-w

Duit, R., & Treagust, D. F. (1998). Learning in science – From behaviourism towards social constructivism and beyond. In *International Handbook of Science Education* (pp. 3–25).

Duit, R., & Treagust, D. F. (2012). How can conceptual change contribute to theory and practice in science education? In B. J. Fraser, K. G. Tobin, & C. J. McRobbie (Eds.), *Second International Handbook of Science Education* (pp. 107–118). Springer.

Engel de Abreu, P. M. J., Conway, A. R. A., & Gathercole, S. E. (2010). Working memory and fluid intelligence in young children. *Intelligence*, *38*(6), 552–561. https://doi.org/10.1016/j.intell.2010.07.003

Entwistle, N., & Nisbet, J. (2013). The nature and experience of academic understanding. *The Psychology of Education Review*, *37*(1), 5–14.

Erickson, F. (2006). Definition and analysis of data from videotape: Some research procedures and their rationales. In J. L. Green, G. Camilli, P. B. Elmore, A. Skukauskaité, & E. Grace (Eds.), *Handbook of Complimentary Methods in Education Research* (pp. 177–191). Lawrence Erlbaum Associates.

Eun, B. (2019). The zone of proximal development as an overarching concept: A framework for synthesizing Vygotsky's theories. *Educational Philosophy and Theory*, *51*(1), 18–30. https://doi.org/10.1080/00131857.2017.1421941

Fang, Z. (2005). Scientific literacy: A systemic functional linguistics perspective. *Science Education*, *89*(2), 335–347. https://doi.org/10.1002/sce.20050

Fang, Z. (2006). The language demands of science reading in middle school. *International Journal of Science Education*, *28*(5), 491–520. https://doi.org/10.1080/09500690500339092

Fazio, X., & Gallagher, T. L. (2019). Science and language integration in elementary classrooms: Instructional enactments and student learning outcomes. *Research in Science Education*, *49*(4), 959–976. https://doi.org/10.1007/s11165-019-9850-z

Fitzgerald, M. S., & Palincsar, A. S. (2019). Teaching practices that support student sensemaking across grades and disciplines: A conceptual review. *Review of Research in Education*, *43*(1), 227–248. https://doi.org/10.3102/0091732X18821115

Flyvbjerg, B. (2001). *Making social science matter.* Cambridge University Press.

Francisco, J. S., Nakhleh, M. B., Nurrenbern, S. C., & Miller, M. L. (2002). Assessing student understanding of general chemistry with concept mapping. *Journal of Chemical Education*, *79*(2), 248–257.

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, *111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111

Furberg, A., & Arnseth, H. C. (2009). Reconsidering conceptual change from a socio-cultural perspective: analyzing students' meaning making in genetics in collaborative learning activities. *Cultural Studies of Science Education*, *4*(1), 157–191. https://doi.org/10.1007/s11422-008-9161-6

Furtak, E. M., Seidel, T., Iverson, H., & Briggs, D. C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching : A meta-analysis. *Review of Educational Research*, *82*(3), 300–329.

Gabel, D. L., Samuel, K. V., & Hunn, D. (1987). Understanding the particulate nature of matter. *Journal of Chemical Education*, *64*(8), 695–697. https://doi.org/10.1021/ed064p695

Gale, N. K., Heath, G., Cameron, E., Rashid, S., & Redwood, S. (2013). Using the framework method for the analysis of qualitative data in multi-disciplinary health research. *BMC Medical Research Methodology*, *13*(1). https://doi.org/10.1186/1471-2288-13-117

Gee, J. P. (2004). Language in the science classroom: Academic social languages as the heart of school-based literacy. In W. E. Saul (Ed.), *Crossing borders in literacy and science instruction: Perspectives on theory and practice* (pp. 13–32).

Geertz, C. (1973). Thick description: Toward an interpretive theory of culture. In *The Interpretation of Cultures: Selected Essays* (pp. 3–30). Basic Books. https://doi.org/10.4135/9781412984591.n6

Gericke, N., Högström, P., & Wallin, J. (2022). A systematic review of research on laboratory work in secondary school. In *Studies in Science Education*. Routledge. https://doi.org/10.1080/03057267.2022.2090125

Ghirardi, M., Marchetti, F., Pettinari, C., Regis, A., & Roletto, E. (2015). Implementing an equilibrium law teaching sequence for secondary school students to learn chemical equilibrium. *Journal of Chemical Education*, *92*(6), 1008–1015. https://doi.org/10.1021/ed500658s

Gieske, R., Streller, S., & Bolte, C. (2022). Transferring language instruction into science education: evaluating a novel approach to language-and subject-integrated science teaching and learning. *Research in Subject-Matter Teaching and Learning*, *5*, 144–162. https://doi.org/10.23770/rt1860

Gilbert, J. K., & Treagust, D. F. (2009). Introduction: Macro, submicro and symbolic representations and the relationship between them: Key models in chemical education. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple representations in chemical education* (pp. 1–8). Springer Netherlands.

Goffman, E. (1955). On face-work: An analyisis of ritual elements in social interaction. *Psychiatry*, *18*(3), 213–31.

Goffman, E. (1974). *Frame analysis: An essay on the organization of experience*. Harvard University Press.

Good, R. G. (2005). Cautionary notes on assessment of understanding science concepts and nature of science. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Assessing science understanding. A human constructivist view* (pp. 343–374). Elsevier. https://doi.org/10.1016/B978-0-12-498365-6.X5000-8

Gredler, M. E. (2012). Understanding Vygotsky for the classroom: Is it too late? *Educational Psychology Review*, *24*(1), 113–131. https://doi.org/10.1007/s10648-011-9183-6

Green, G., & Rollnick, M. (2006). The role of structure of the discipline in improving student understanding: The case of organic chemistry. *Journal of Chemical Education*, *83*(9), 1376. https://doi.org/10.1021/ed083p1376

Greeno, J. G., & Engeström, Y. (2014). Learning in activity. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (2nd ed., pp. 128–147). Cambridge University Press.

Gunnarsson, G. (2008). *Den laborativa klassrumsverksamhetens interaktioner* [Doctoral dissertation, Linköping University]. https://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-14908

Gunstone, R. (1990). Reconstructing theory from practical experience. In B. Woolnough (Ed.), *Practical Science* (pp. 67–77). Open University Press.

Gunstone, R. F., & Champagne, A. B. (1990). Promoting conceptual change in the laboratory. In E. Hegarty-Hazel (Ed.), *The student laboratory and the science curriculum* (pp. 159–182). Routledge.

Gunstone, R. F., & White, R. T. (1981). Understanding of gravity. *Science Education*, *65*(3), 291–299.

Hamnell-Pamment, Y. (2023a). Scientific language use and sensemaking in concept maps: Interaction between concept systems, scientific concepts and everyday concepts. *Knowledge Management & E-Learning: An International Journal*, *15*, 448–467. https://doi.org/10.34105/j.kmel.2023.15.026

Hamnell-Pamment, Y. (2023b). The role of scientific language use and achievement level in student sensemaking. *International Journal of Science and Mathematics Education*. https://doi.org/10.1007/s10763-023-10405-7

Hamza, K. M., & Wickman, P.-O. (2008). Describing and analyzing learning in action: An empirical study of the importance of misconceptions in learning science. *Science Education*, *92*(1), 141–164. https://doi.org/10.1002/sce.20233

Hand, B., & Choi, A. (2010). Examining the impact of student use of multiple modal representations in constructing arguments in organic chemistry laboratory classes. *Research in Science Education*, *40*(1), 29–44. https://doi.org/10.1007/s11165-009-9155-8

Harle, M., & Towns, M. H. (2011). A review of spatial ability literature, its connection to chemistry, and implications for instruction. *Journal of Chemical Education*, *88*(3), 351–360. https://doi.org/10.1021/ed900003n

Henriksson, A. (2012). *Syntes kemi 2*. Gleerups Utbildning.

Heritage, J. (1984). *Garfinkel and ethnomethodology*. Polity Press.

Hernández, G. E., Criswell, B. A., Kirk, N. J., Sauder, D. G., & Rushton, G. T. (2014). Pushing for particulate level models of adiabatic and isothermal processes in upper-level chemistry courses: a qualitative study. *Chem. Educ. Res. Pract.*, *15*(3), 354–365. https://doi.org/10.1039/C4RP00008K

Hicks, D. (1996). Contextual inquiries: A discourse-oriented study of classroom learning. In *Discourse, Learning, and Schooling* (pp. 104–142). Cambridge University Press. https://doi.org/10.1017/CBO9780511720390.004

Hinton, M. E., & Nakhleh, M. B. (1999). Students' microscopic, macroscopic, and symbolic representations of chemical reactions. *The Chemical Educator*, *4*(5), 158–167. https://doi.org/10.1007/s00897990325a

Hipkiss, A. M. (2014). *Klassrummets semiotiska resurser: En språkdidaktisk studie av skolämnena hem- och konsumentkunskap, kemi och biologi (Studier i språk och litteratur fråm Umeå universitet 23) [The semiotic resources of the classroom: A language-didactic study of the school subjects home and consumer studies, chemistry and biology (Umeå Studies in the Educational Sciences 2)]* [Doctoral dissertation, Umeå University]. https://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-93671

Hirsch, E. D. (2003). Reading comprehension requires knowledge – of words and the world. *American Educator*, *27*(1), 10–13.

Hofstein, A. (2017). The role of laboratory in science teaching and learning. In K. S. Taber & B. Akpan (Eds.), *Science education – An international course companion* (pp. 357–368). Sense Publishers.

Hofstein, A., & Kind, P. M. (2012). Learning in and from science laboratories. In B. J. Fraser, K. G. Tobin, & C. J. McRobbie (Eds.), *Second international handbook of science education* (pp. 189–207). Springer.

Hofstein, A., & Lunetta, V. N. (2004). The laboratory in science education: Foundations for the twenty-first century. *Science Education*, *88*(1), 28–54. https://doi.org/10.1002/sce.10106

Howe, C., Hennessy, S., Mercer, N., Vrikki, M., & Wheatley, L. (2019). Teacher-student dialogue during classroom teaching: Does it really impact on student outcomes? *Journal of the Learning Sciences*, *28*(4–5), 462–512. https://doi.org/10.1080/10508406.2019.1573730

Huddle, P. A., & Pillay, A. E. (1996). An in-depth study of misconceptions in stoichiometry and chemical equilibrium at a South African university. *Journal of Research in Science Teaching*, *33*(1), 65–77. https://doi.org/10.1002/(SICI)1098-2736(199601)33:1<65::AID-TEA4>3.0.CO;2-N

Hughes, M., & Greenhough, P. (2004). Learning from homework: A case study. In L. Poulson & M. Wallace (Eds.), *Learning to read critically in teaching and learning* (pp. 85–109). SAGE Publications, Ltd. https://doi.org/10.4135/9780857024466

Hutchby, I., & Wooffitt, R. (2008). *Conversation Analysis* (2nd ed.). Polity Press.

Illeris, K. (2007). *How we learn. Learning and non-learning in school and beyond.* Routledge.

International Baccalaureate Organization. (2014). *Chemistry guide*. https://ibchem.com/root_pdf/Chemistry_guide_2016.pdf

International Baccalaureate Organization. (2017). *Diploma Programme grade descriptors*. https://www.ibo.org/contentassets/0b0b7a097ca2498ea50a9e41d9e1d1cf/dp-grade-descriptors-en.pdf

Isabelle, A. (2015). Concept mapping revisited: Nurturing children's writing skills in science. *Language and Literacy Spectrum*, *25*, 44–57.

Jaber, L. Z., & BouJaoude, S. (2012). A macro–micro–symbolic teaching to promote relational understanding of chemical reactions. *International Journal of Science Education*, *34*(7), 973–998. https://doi.org/10.1080/09500693.2011.569959

Jakobsson, A. (2012). Sociokulturella perspektiv på lärande och utveckling: Lärande som begreppsmässig precisering och koordinering [Sociocultural perspectives on learning and development: Learning as conceptual clarification and coordination]. *Pedagogisk Forskning i Sverige*, *17*(3–4), 152–170.

Jakobsson, A., & Kouns, M. (2023). Subject-language perspectives on multilingual students learning in science. *European Journal of Science and Mathematics Education*, *11*(2), 197–214. https://doi.org/10.30935/scimath/12568

Jansen, M., Schroeders, U., & Lüdtke, O. (2014). Academic self-concept in science: Multidimensionality, relations to achievement measures, and gender differences. *Learning and Individual Differences*, *30*, 11–21. https://doi.org/10.1016/j.lindif.2013.12.003

Jin, H., & Yoong Wong, K. (2010). Training on concept mapping skills in geometry. *Journal of Mathematics Education*, *3*(1), 104–119.

Johnstone, A. H. (1982). Macro and microchemistry. *Chemistry in Britain*, *18*(6), 409–410.

Johnstone, A. H. (1991). Why is science difficult? Things are seldom what they seem. *Journal of Computer Assisted Learning*, *7*(2), 75–83. https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemical Education*, *70*(9), 701. https://doi.org/10.1021/ed070p701

Johnstone, A. H. (2006). Chemical education research in Glasgow in perspective. *Chemistry Education Research and Practice*, *7*(2), 49–63. https://doi.org/10.1002/(SICI)1098-237X(199704)81:2<193::AID-SCE5>3.0.CO;2-A

Kalyuga, S., Ayres, P., Chandler, P., & Sweller, J. (2003). The expertise reversal effect. *Educational Psychologist*, *38*(1), 23–31. https://doi.org/10.1207/S15326985EP3801_4

Kamberelis, G., & Wehunt, M. D. (2012). Hybrid discourse practice and science learning. *Cultural Studies of Science Education*, *7*(3), 505–534. https://doi.org/10.1007/s11422-012-9395-1

Kansanen, P., Hansén, S.-E., Sjöberg, J., & Kroksmark, T. (2011). Vad är allmändidaktik? In S.-E. Hansén & L. Forsman (Eds.), *Allmändidaktik – vetenskap för lärare* (pp. 29–50). Studentlitteratur.

Kapon, S. (2017). Unpacking sensemaking. *Science Education*, *101*(1), 165–198. https://doi.org/10.1002/sce.21248

Kibar, Z. B., Yaman, F., & Ayas, A. (2013). Assessing prospective chemistry teachers' understanding of gases through qualitative and quantitative analyses of their concept maps. *Chemistry Education Research and Practice*, *14*, 542–554. https://doi.org/10.1039/c3rp00052d

Kinchin, I. M. (2014). Concept mapping as a learning tool in higher education: A critical analysis of recent reviews. *Journal of Continuing Higher Education*, *62*(1), 39–49. https://doi.org/10.1080/07377363.2014.872011

Kinchin, I. M. (2020). A 'species identification' approach to concept mapping in the classroom. *Journal of Biological Education*, *54*(1), 108–114. https://doi.org/10.1080/00219266.2018.1546763

Kinchin, I. M., Möllits, A., & Reiska, P. (2019). Uncovering types of knowledge in concept maps. *Education Sciences*, *9*(2). https://doi.org/10.3390/educsci9020131

Kind, P. M., Kind, V., Hofstein, A., & Wilson, J. (2011). Peer argumentation in the school science laboratory – Exploring effects of task features. *International Journal of Science Education*, *33*(18), 2527–2558. https://doi.org/10.1080/09500693.2010.550952

Kind, V. (2004). *Beyond appearances: Students' misconceptions about basic chemical ideas. A report prepared for the Royal Society of Chemistry*. Royal Society of Chemistry. http://www.rsc.org/images/Misconceptions_update_tcm18-188603.pdf

Kousa, P., & Aksela, M. (2019). The needs for successful chemistry teaching in diverse classes: Teachers' beliefs and practices. *Lumat*, *7*(1), 79–100. https://doi.org/10.31129/LUMAT.7.1.390

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching*, *34*(9), 949–968. https://doi.org/10.1002/(SICI)1098-2736(199711)34:9<949::AID-TEA7>3.0.CO;2-U

Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *Journal of the Learning Sciences*, *9*(2), 105–143. https://doi.org/10.1207/s15327809jls0902_1

Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In J. K. Gilbert (Ed.), *Visualization in Science Education* (pp. 121–145). Springer. https://doi.org/10.1007/1-4020-3613-2_8

Kozulin, A. (1998). *Psychological tools: A sociocultural approach*. Harvard University Press.

Kozulin, A. (2003). Psychological tools and mediated learning. In A. Kozulin, B. Gindis, V. S. Ageyev, & S. M. Miller (Eds.), *Vygotsky's educational theory in cultural context* (pp. 15–38). Cambridge University Press.

Lantolf, J. P. (2003). Intrapersonal communication and internalization in the second language classroom. In A. Kozulin, B. Gindis, V. S. Ageyev, & S. M. Miller (Eds.), *Vygotsky's educational theory in cultural context* (pp. 349–370). Cambridge University Press.

Lantolf, J. P., & Swain, M. (2019). On the emotion–cognition dialectic: A sociocultural response to Prior. *Modern Language Journal*, *103*(2), 528–530. https://doi.org/10.1111/modl.12574

Lee, E. N., & Orgill, M. K. (2022). Toward equitable assessment of English language learners in general chemistry: Identifying supportive features in assessment items. *Journal of Chemical Education*, *99*(1), 35–48. https://doi.org/10.1021/acs.jchemed.1c00370

Lee, O., Grapin, S., & Haas, A. (2018). Talk in the science classroom. In A. L. Bailey, C. A. Maher, & L. C. Wilkinson (Eds.), *Language, literacy and learning in the STEM disciplines: How language counts for english learners* (pp. 35–52). Routledge.

Lee, O., Llosa, L., Grapin, S., Haas, A., & Goggins, M. (2019). Science and language integration with English learners: A conceptual framework guiding instructional materials development. *Science Education*, *103*(2), 317–337. https://doi.org/10.1002/sce.21498

Lee, O., Quinn, H., & Valdés, G. (2013). Science and language for English language learners in relation to Next Generation Science Standards and with implications for Common Core State Standards for English language arts and mathematics. *Educational Researcher*, *42*(4), 223–233. https://doi.org/10.3102/0013189X13480524

Lemke, J. L. (1990). *Talking science: Language, learning and values*. Ablex Publishing Corporation.

Lemke, J. L. (1998). Multimedia literacy demands of the scientific curriculum. *Linguistics and Education*, *10*(3), 247–271. https://doi.org/10.1016/S0898-5898(99)00009-1

Lemke, J. L. (2005). Multiplying meaning: Visual and verbal semiotics in scientific text. In J. R. Martin & R. Veel (Eds.), *Reading science: Critical and functional perspectives on discourses of science* (pp. 87–113). Routledge. https://doi.org/10.4324/9780203982327-17

Leont'ev, A. N. (1981). The problem of activity in psychology. In J. V Wertsch (Ed.), *The concept of activity in Soviet psychology* (pp. 37–71). M. E. Sharpe. (Original work published 1974)

Leont'ev, A. N. (1997). On Vygotsky's creative development. In *The collected works of L. S. Vygotsky. Volume 3: Problems of general psychology* (pp. 9–32).

Lidar, M. (2010). *Erfarenhet och sociokulturella resurser. Analyser av elevers lärande i naturorienterande undervisning.* Uppsala University.

Lidar, M., Lundqvist, E., & Östman, L. (2006). Teaching and learning in the science classroom the interplay between teachers' epistemological moves and students' practical epistemology. *Science Education*, *90*(1), 148–163. https://doi.org/10.1002/sce.20092

Lijnse, P. (2010). Didactics of science: The forgotten dimension in science education. In K. Kortland & K. Klaasen (Eds.), *Designing theory-based teaching-learning sequences for science education: Proceedings of the symposium in honour of Piet Lijnse at the time of his retirement as Professor of Physics Didactics at Utrecht University* (pp. 125–142). CDBeta Press.

Linell, P. (2001). *Approaching dialogue: Talk, interaction and contexts in dialogical perspectives.* John Benjamins Publishing Company.

Liu, Y., & Taber, K. S. (2016). Analysing symbolic expressions in secondary school chemistry: Their functions and implications for pedagogy. *Chemistry Education Research and Practice, 17*(3), 439–451. https://doi.org/10.1039/c6rp00013d

Lopez, E. J., Shavelson, R. J., Nandagopal, K., Szu, E., & Penn, J. (2014). Factors contributing to problem-solving performance in first-semester organic chemistry. *Journal of Chemical Education*, *91*(7), 976–981. https://doi.org/10.1021/ed400696c

Lopez, E., Kim, J., Nandagopal, K., Cardin, N., Shavelson, R. J., & Penn, J. H. (2011). Validating the use of concept-mapping as a diagnostic assessment tool in organic chemistry: Implications for teaching. *Chemistry Education Research and Practice*, *12*(2), 133–141. https://doi.org/10.1039/C1RP90018H

Lunetta, V. N., Hofstein, A., & Clough, M. P. (2007). Learning and teaching in the school science laboratory: An analysis of research, theory and practice. In S. Abell & N. Lederman (Eds.), *Handbook of research on science education* (pp. 393–441). Lawrence Erlbaum Associates.

Macbeth, D. (2003). Hugh Mehan's learning lessons reconsidered: On the differences between the naturalistic and critical analysis of classroom discourse. *American Educational Research Journal*, *40*(1), 239–280. https://doi.org/10.3102/00028312040001239

Machado, C. T., & Carvalho, A. A. (2020). Concept mapping: Benefits and challenges in higher education. *Journal of Continuing Higher Education*, *68*(1), 38–53. https://doi.org/10.1080/07377363.2020.1712579

Markic, S., & Childs, P. E. (2016). Language and the teaching and learning of chemistry. *Chemistry Education Research and Practice*, *17*(3), 434–438. https://doi.org/10.1039/c6rp90006b

Markow, P. G., & Lonning, R. A. (1998). Usefulness of concept maps in college chemistry laboratories: Students' perceptions and effects on achievement. *Journal of Research in Science Teaching*, *35*(9), 1015–1029. https://doi.org/10.1002/(SICI)1098-2736(199811)35:9<1015::AID-TEA4>3.0.CO;2-G

Martin, B. L., Mintzes, J. J., & Clavijo, I. E. (2000). Restructuring knowledge in biology: Cognitive processes and metacognitive reflections. *International Journal of Science Education*, *22*(3), 303–323. https://doi.org/10.1080/095006900289895

Marton, F., & Säljö, R. (2005). Approaches to learning explaining differences in outcome. In F. Marton, D. Hounsell, & N. Entwhistle (Eds.), *The experience of learning: Implications for teaching and studying in higher education* (3rd (Internet), pp. 106–125). University of Edinburg, Centre for Teaching, Learning and Assessment.

Matusov, E. (2020). Pattern-recognition, intersubjectivity, and dialogic meaning-making in education. *Dialogic Pedagogy*, *8*, E1–E23. https://doi.org/10.5195/DPJ.2020.314

McClure, J. R., Sonak, B., & Suen, H. K. (1999). Concept map assessment of classroom learning: Reliability, validity, and logistical practicality. *Journal of Research in Science Teaching*, *36*(4), 475–492. https://doi.org/10.1002/(SICI)1098-2736(199904)36:4<475::AID-TEA5>3.0.CO;2-O

McDonnell, L., Barker, M. K., & Wieman, C. (2016). Concepts first, jargon second improves student articulation of understanding: Jargon and student articulation of understanding. *Biochemistry and Molecular Biology Education*, *44*(1), 12–19. https://doi.org/10.1002/bmb.20922

Mercer, N. (1995). *The guided construction of knowledge: Talk amongst teachers and learners*. Frankfurt Lodge.

Mercer, N. (2008). Changing our minds: A commentary on 'Conceptual change: a discussion of theoretical, methodological and practical challenges for science education.' *Cultural Studies of Science Education*, *3*(2), 351–362. https://doi.org/10.1007/s11422-008-9099-8

Mercer, N. (2013). The social brain, language, and goal-directed collective thinking: A social conception of cognition and its implications for understanding how we think, teach, and learn. *Educational Psychologist*, *48*(3), 148–168. https://doi.org/10.1080/00461520.2013.804394

Mercer, N., Dawes, L., Wegerif, R., & Sams, C. (2004). Reasoning as a scientist: Ways of helping children to use language to learn science. *British Educational Research Journal*, *30*(3), 359–377. https://doi.org/10.1080/01411920410001689689

Mercer, N., & Littleton, K. (2007). *Dialogue and the development of children's thinking*. Routledge.

Miles, M. B., Huberman, A. M., & Saldaña, J. (2014). *Qualitative analysis: A methods sourcebook* (3rd ed.). SAGE Publications.

Miller, R. (2011). *Vygotsky in perspective*. Cambridge University Press.

Mohan, B. (2001). The second language as a medium for learning. In B. Mohan, C. Leung, & C. Davison (Eds.), *English as a second language in the mainstream: Teaching, learning and identity* (pp. 107–126). Pearson Education.

Mortimer, E. F., & Scott, P. H. (2003). *Meaning making in secondary science classrooms*. Open University Press.

Mortimer, E. F., & Wertsch, J. v. (2003). The architecture and dynamics of intersubjectivity in science classrooms. *Mind, Culture, and Activity*, *10*(3), 230–244. https://doi.org/10.1207/s15327884mca1003_5

Murphy, B., Horner, G., Tarcy, D., & Bylikin, S. (2014). *Oxford IB Diploma Programme: Chemistry course companion*. Oxford University Press.

National Research Council. (2006). *America's lab report: Investigations in high school science*. National Academies Press.

Nesbit, J. C., & Adesope, O. O. (2006). Learning with concept and knowledge maps: A meta-analysis. *Review of Educational Research*, *76*(3), 413–448.

Newman, B. M., & Newman, P. R. (2020). Cognitive developmental theories. In *Theories of adolescent development* (pp. 183–211). Academic Press.

Ngo, T., Unsworth, L., & Herrington, M. (2022). Teacher orchestration of language and gesture in explaining science concepts in images. *Research in Science Education*, *52*(3), 1013–1030. https://doi.org/10.1007/s11165-021-10011-z

Novak, J. D. (2002). Meaningful learning: The essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of learners. *Science Education*, *86*(4), 548–571. https://doi.org/10.1002/sce.10032

Novak, J. D., & Cañas, A. J. (2008). *The theory underlying concept maps and how to construct them (Technical Report IHMC CmapTools 2006-01 Rev 01-2008).* https://cmap.ihmc.us/publications/researchpapers/TheoryUnderlyingConceptMaps.pdf

Novak, J. D., & Gowin, D. B. (1984). *Learning how to learn*. Cambridge University Press.

Novak, J. D., & Musonda, D. (1991). A twelve-year longitudinal study of science concept learning. *American Educational Research Journal*, *28*(1), 117–153.

Nygård Larsson, P., & Jakobsson, A. (2020). Meaning-making in science from the perspective of students' hybrid language use. *International Journal of Science and Mathematics Education*, *18*(5), 811–830. https://doi.org/10.1007/s10763-019-09994-z

Odden, T. O. B. (2021a). How conceptual blends support sensemaking: A case study from introductory physics. *Science Education*, *105*(5), 989–1012. https://doi.org/10.1002/sce.21674

Odden, T. O. B., & Russ, R. S. (2019a). Defining sensemaking: Bringing clarity to a fragmented theoretical construct. *Science Education*, *103*(1), 187–205. https://doi.org/10.1002/sce.21452

Odden, T. O. B., & Russ, R. S. (2019b). Vexing questions that sustain sensemaking. *International Journal of Science Education*, *41*(8), 1052–1070. https://doi.org/10.1080/09500693.2019.1589655

Olander, C., & Ingerman, Å. (2011). Towards an inter-language of talking science: Exploring students' argumentation in relation to authentic language. *Journal of Biological Education*, *45*(3), 158–164. https://doi.org/10.1080/00219266.2011.591414

Oliveira, A. W. (2010). Improving teacher questioning in science inquiry discussions through professional development. *Journal of Research in Science Teaching*, *47*(4), 422–453. https://doi.org/10.1002/tea.20345

O'Reilly, T., & McNamara, D. S. (2007). The impact of science knowledge, reading skill, and reading strategy knowledge on more traditional "high-stakes" measures of high school students' science achievement. *American Educational Research Journal*, *44*(1), 161–196. https://doi.org/10.3102/0002831206298171

Osborne, R., & Wittrock, M. (1985). The generative learning model and its implications for science education. *Studies in Science Education*, *12*, 59–87.

O'Toole, M. (1996). Science, schools, children and books: Exploring the classroom interface between science and language. *Studies in Science Education*, *28*(1), 113–144. https://doi.org/10.1080/03057269608560086

Parry, K. W. (2004). Constant comparison. In M. S. Lewis-Beck, A. Bryman, & T. Futing Liao (Eds.), *The SAGE encyclopedia of social science research methods*. SAGE Publications.

Patron, E., Wikman, S., Edfors, I., Johansson-Cederblad, B., & Linder, C. (2017). Teachers' reasoning: Classroom visual representational practices in the context of introductory chemical bonding. *Science Education*, *101*(6), 887–906. https://doi.org/10.1002/sce.21298

Pearsall, N. R., Skipper, J., & Mintzes, J. (1997). Knowledge restructuring in the life sciences: A longitudinal study of conceptual change in biology. *Science Education*, *81*(2), 193–215.

Pekdağ, B., & Azizoğlu, N. (2013). Semantic mistakes and didactic difficulties in teaching the "amount of substance" concept: A useful model. *Chemistry Education Research and Practice*, *14*(1), 117–129. https://doi.org/10.1039/C2RP20132A

Peräkylä, A. (2016). Conversation analysis. In *The Blackwell Encyclopedia of Sociology* (pp. 1–4). John Wiley & Sons, Ltd.

Persson, A. (2018). *Framing social interaction: Continuities and cracks in Goffman's frame analysis*. Routledge.

Pham, L., & Tytler, R. (2022). The semiotic function of a bridging representation to support students' meaning-making in solution chemistry. *Research in Science Education*, *52*(3), 853–869. https://doi.org/10.1007/s11165-021-10022-w

Piquette, J. S., & Heikkinen, H. W. (2005). Strategies reported used by instructors to address student alternate conceptions in chemical equilibrium. *Journal of Research in Science Teaching*, *42*(10), 1112–1134. https://doi.org/10.1002/tea.20091

Plass, J. L., & Kalyuga, S. (2019). Four ways of considering emotion in cognitive load theory. In *Educational Psychology Review* (Vol. 31, Issue 2, pp. 339–359). Springer New York LLC. https://doi.org/10.1007/s10648-019-09473-5

Postareff, L., Mattsson, M., Lindblom-Ylänne, S., & Hailikari, T. (2017). The complex relationship between emotions, approaches to learning, study success and study progress during the transition to university. *Higher Education*, *73*(3), 441–457. https://doi.org/10.1007/s10734-016-0096-7

Potvin, P., Nenciovici, L., Malenfant-Robichaud, G., Thibault, F., Sy, O., Mahhou, M. A., Bernard, A., Allaire-Duquette, G., Blanchette Sarrasin, J., Brault Foisy, L. M., Brouillette, N., St-Aubin, A. A., Charland, P., Masson, S., Riopel, M., Tsai, C. C., Bélanger, M., & Chastenay, P. (2020). Models of conceptual change in science learning: Establishing an exhaustive inventory based on support given by articles published in major journals. *Studies in Science Education*, *56*(2), 157–211. https://doi.org/10.1080/03057267.2020.1744796

Pozzer, L., & Roth, W.-M. (2020). A cultural-historical perspective on the multimodal development of concepts in science lectures. *Cultural Studies of Science Education*, *15*(1), 31–70. https://doi.org/10.1007/s11422-019-09910-5

Prain, V., & Tytler, R. (2022). Theorising learning in science through integrating multimodal representations. *Research in Science Education*, *52*(3), 805–817. https://doi.org/10.1007/s11165-021-10025-7

Quílez, J. (2012). First-year university chemistry textbooks' misrepresentation of Gibbs energy. *Journal of Chemical Education*, *89*(1), 87–93. https://doi.org/10.1021/ed100477x

Quinn, H., Lee, O., & Valdes, G. (2011). Language demands and opportunities in relation to next generation science standards for English language learners: What teachers need to know. In *Understanding language: language, literacy and learning in the content areas [The Understanding Language Initiative]* (Issue 1, pp. 1–12). Stanford University School of Education. ell.stanford.edu

Raufelder, D., Sahabandu, D., Martínez, G. S., & Escobar, V. (2015). The mediating role of social relationships in the association of adolescents' individual school self-concept and their school engagement, belonging and helplessness in school. *Educational Psychology*, *35*(2), 137–157. https://doi.org/10.1080/01443410.2013.849327

Rector, M. A., Nehm, R. H., & Pearl, D. (2013). Learning the language of evolution: Lexical ambiguity and word meaning in student explanations. *Research in Science Education*, *43*(3), 1107–1133. https://doi.org/10.1007/s11165-012-9296-z

Redish, E. F., & Kuo, E. (2015). Language of physics, language of math: Disciplinary culture and dynamic epistemology. *Science and Education*, *24*(5–6), 561–590. https://doi.org/10.1007/s11191-015-9749-7

Rees, S., Kind, V., & Newton, D. (2021). The development of chemical language usage by "non-traditional" students: the interlanguage analogy. *Research in Science Education*, *51*(2), 419–438. https://doi.org/10.1007/s11165-018-9801-0

Regis, A., Albertazzi, P. G., & Roletto, E. (1996). Concept maps in chemistry education. *Journal of Chemical Education*, *73*(11), 1084–1088. https://doi.org/10.1021/ed073p1084

Reiser, B. J., Michaels, S., Moon, J., Bell, T., Dyer, E., Edwards, K. D., McGill, T. A. W., Novak, M., & Park, A. (2017). Scaling up three-dimensional science learning through teacher-led study groups across a state. *Journal of Teacher Education*, *68*(3), 280–298. https://doi.org/10.1177/0022487117699598

Rhodes, S. M., Booth, J. N., Palmer, L. E., Blythe, R. A., Delibegovic, M., & Wheate, N. J. (2016). Executive functions predict conceptual learning of science. *British Journal of Developmental Psychology*, *34*(2), 261–275. https://doi.org/10.1111/bjdp.12129

Ribeck, J. (2015). *Steg för steg (Data linguistica 28) [Step by step (Publication No. 28)]* [Doctoral thesis]. University of Gothenburg.

Rincke, K. (2011). It's rather like learning a language: Development of talk and conceptual understanding in mechanics lessons. *International Journal of Science Education*, *33*(2), 229–258. https://doi.org/10.1080/09500691003615343

Ritchie, J., Spencer, L., & O'Connor, W. (2014). Carrying out qualitative analysis. In J. Ritchie, J. Lewis, C. Nicholls McNaughton, & R. Ormston (Eds.), *Qualitative research practice: A guide for social science students and researchers* (pp. 217–262). SAGE Publications.

Rivard, L. P. (2004). Are language-based activities in science effective for all students, including low achievers? *Science Education*, *88*(3), 420–442. https://doi.org/10.1002/sce.10114

Rogoff, B. (1990). *Apprenticeship in thinking: Cognitive development in social context*. Oxford University Press.

Roth, W.-M., & Lawless, D. (2002). Science, culture, and the emergence of language. *Science Education*, *86*(3), 368–385. https://doi.org/10.1002/sce.10008

Roth, W.-M., McRobbie, C. J., Lucas, K. B., & Boutonné, S. (1997). The local production of order in traditional laboratories: A phenomenological analysis. *Learning and Instruction*, *7*(2), 107–136.

Rowlands, S. (2000). Turning Vygotsky on his head: Vygotsky's "scientifically based method" and the socioculturalist's "social other." *Science and Education*, *9*, 537–575. https://doi.org/https://doi.org/10.1023/A:1008748901374

Ruiz-Primo, M. A., Schultz, S. E., Li, M., & Shavelson, R. J. (2001). Comparison of the reliability and validity of scores from two concept-mapping techniques. *Journal of Research in Science Teaching*, *38*(2), 260–278. https://doi.org/10.1002/1098-2736(200102)38:2<260::AID-TEA1005>3.0.CO;2-F

Ruiz-Primo, M. A., Schultz, S. E., & Shavelson, R. J. (1997). *Concept map-based assessment in science: Two exploratory studies (CSE Technical Report 436)*. https://cresst.org/wp-content/uploads/TECH436.pdf

Ruiz-Primo, M. A., & Shavelson, R. J. (1996). Problems and issues in the use of concept maps in science assessment. *Journal of Research in Science Teaching*, *33*(6), 569–600. https://doi.org/10.1002/(SICI)1098-2736(199608)33:6<569::AID-TEA1>3.0.CO;2-M

Ruiz-Primo, M. A., Shavelson, R. J., Li, M., & Schultz, S. E. (2001). On the validity of cognitive interpretations of scores from alternative concept-mapping techniques. *Educational Assessment*, *7*(2), 99–141. https://doi.org/https://doi.org/10.1207/S15326977EA0702_2

Rüschenpöhler, L., & Markic, S. (2020). Secondary school students' chemistry self-concepts: Gender and culture, and the impact of chemistry self-concept on learning behaviour. *Chemistry Education Research and Practice*, *21*(1), 209–219. https://doi.org/10.1039/c9rp00120d

Russ, R. S., & Berland, L. K. (2019). Invented science: A framework for discussing a persistent problem of practice. *Journal of the Learning Sciences*, *28*(3), 279–301. https://doi.org/10.1080/10508406.2018.1517354

Russ, R. S., & Odden, T. O. B. (2017). Intertwining evidence- and model-based reasoning in physics sensemaking: An example from electrostatics. *Physical Review Physics Education Research*, *13*(2). https://doi.org/10.1103/PhysRevPhysEducRes.13.020105

Ryoo, K. (2015). Teaching science through the language of students in technology-enhanced instruction. *Journal of Science Education and Technology*, *24*(1), 29–42. https://doi.org/10.1007/s10956-014-9518-4

Safayeni, F., Derbentseva, N., & Cañas, A. J. (2005). A theoretical note on concepts and the need for Cyclic Concept Maps. *Journal of Research in Science Teaching*, *42*(7), 741–766. https://doi.org/10.1002/tea.20074

Schwendimann, B. A., & Linn, M. C. (2016). Comparing two forms of concept map critique activities to facilitate knowledge integration processes in evolution education. *Journal of Research in Science Teaching*, *53*(1), 70–94. https://doi.org/10.1002/tea.21244

Säljö, R. (2010). *Lärande och kulturella redskap: Om lärprocesser och det kollektiva minnet [Learning and cultural tools: on learning processes and collective memory]* (2nd ed.). Norstedt.

Sawyer, R. K. (2002). Unresolved tensions in sociocultural theory: Analogies with contemporary sociological debates. *Culture and Psychology*, *8*(3), 283–305. https://doi.org/10.1177/1354067X02008003838

Schegloff, E. A. (2007). *Sequence organization in interaction – A primer in conversation analysis* (Vol. 1). Cambridge University Press.

Schneider, M., & Preckel, F. (2017). Variables associated with achievement in higher education: A systematic review of meta-analyses. *Psychological Bulletin*, *143*(6), 656–600. https://doi.org/10.1037/bul0000098.supp

Schönborn, K. J., & Anderson, T. R. (2008). Bridging the educational research-teaching practice gap - Conceptual understanding, part 2: Assessing and developing student knowledge. *Biochemistry and Molecular Biology Education*, *36*(5), 372–379. https://doi.org/10.1002/bmb.20230

Schoultz, J., Säljö, R., & Wyndhamn, J. (2001). Heavenly talk: Discourse, artifacts, and children's understanding of elementary astronomy. *Human Development*, *44*(2), 103–118.

Schuchardt, A. M., & Schunn, C. D. (2016). Modeling scientific processes with mathematics equations enhances student qualitative conceptual understanding and quantitative problem solving. *Science Education*, *100*(2), 290–320. https://doi.org/10.1002/sce.21198

Schwendimann, B. A. (2011). *Mapping biological ideas: Concept maps as knowledge integration tools for evolution education* [Doctoral thesis, University of California, Berkleley]. https://pqdtopen.proquest.com/doc/928947890.html?FMT=ABS

Schwendimann, B. A., & Linn, M. C. (2016). Comparing two forms of concept map critique activities to facilitate knowledge integration processes in evolution education. *Journal of Research in Science Teaching, 53*(1), 70–94. https://doi.org/10.1002/tea.21244

Seah, L. H. (2016). Elementary teachers' perception of language issues in science classrooms. *International Journal of Science and Mathematics Education*, *14*(6), 1059–1078. https://doi.org/10.1007/s10763-015-9648-z

Seah, L. H., Clarke, D. J., & Hart, C. E. (2011). Understanding students' language use about expansion through analyzing their lexicogrammatical resources. *Science Education*, *95*(5), 852–876. https://doi.org/10.1002/sce.20448

Seah, L. H., & Silver, R. E. (2020). Attending to science language demands in multilingual classrooms: A case study. *International Journal of Science Education*, *42*(14), 2453–2471. https://doi.org/10.1080/09500693.2018.1504177

Serder, M., & Jakobsson, A. (2016). Language games and meaning as used in student encounters with scientific literacy test items. *Science Education*, *100*(2), 321–343. https://doi.org/10.1002/sce.21199

Séré, M.-G. (2002). Towards renewed research questions from the outcomes of the European project Labwork in Science Education. *Science Education*, *86*(5), 624–644. https://doi.org/10.1002/sce.10040

Shavelson, R. J., & Ruiz-primo, M. A. (2005). On the psychometrics of assessing science understanding. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Assessing Science Understanding. A Human Constructivist View* (pp. 303–341). Academic Press. https://doi.org/10.1016/B978-012498365-6/50015-9

Sherin, B. (2006). Common sense clarified: The role of intuitive knowledge in physics problem solving. *Journal of Research in Science Teaching*, *43*(6), 535–555. https://doi.org/10.1002/tea.20136

Shipstead, Z., Harrison, T. L., & Engle, R. W. (2016). Working memory capacity and fluid intelligence: Maintenance and disengagement. *Perspectives on Psychological Science*, *11*(6), 771–799. https://doi.org/10.1177/1745691616650647

da Silva, J. R. R. T. (2021). Memory, imagination, and meaning-making in learning scientific concepts: A case study about the concept of substance in chemistry. *Human Arenas*, *4*(4), 577–598. https://doi.org/10.1007/s42087-020-00134-6

Sinapuelas, M. L. S., & Stacy, A. M. (2015). The relationship between student success in introductory university chemistry and approaches to learning outside of the classroom. *Journal of Research in Science Teaching*, *52*(6), 790–815. https://doi.org/10.1002/tea.21215

Skolverket. (1994). *GyVux 1994:14. Naturvetenskapsprogrammet. Programmål, kursplaner, betygskriterier och kommentarer [GyVux 1994:14. Swedish Natural Science Programme. Program aims, course curricula, grading criteria, and comments].*

Skolverket. (2000). *Gy2000. NV 2000:14. Naturvetenskapsprogrammet. Programmål, kursplaner, betygskriterier och kommentarer [Gy2000. NV 2000:14. Swedish Natural Science Programme. Program aims, course curricula, grading criteria, and comments].*

Skolverket. (2011). *Läroplan, examensmål och gymnasiegemensamma ämnen för gymnasieskola 2011 [Curricula, examination aims and common subjects for Swedish upper secondary school 2011].*

Skolverket. (2022). *Kemi [Chemistry at Swedish upper secondary school]*. Skolverket. https://www.skolverket.se/undervisning/gymnasieskolan/laroplan-program-och-amnen-i-gymnasieskolan/gymnasieprogrammen/amne?url=-996270488%2Fsyllabuscw%2Fjsp%2Fsubject.htm%3FsubjectCode%3DKEM%26version%3D2%26tos%3Dgy&sv.url=12.5dfee44715d35a5cdfa92a3

Smagorinsky, P. (2018). Deconflating the ZPD and instructional scaffolding: Retranslating and reconceiving the zone of proximal development as the zone of next development. *Learning, Culture and Social Interaction*, *16*(October 2017), 70–75. https://doi.org/10.1016/j.lcsi.2017.10.009

Smart, J. B., & Marshall, J. C. (2013). Interactions between classroom discourse, teacher questioning, and student cognitive engagement in middle school science. *Journal of Science Teacher Education*, *24*(2), 249–267. https://doi.org/10.1007/s10972-012-9297-9

Sonesson, A., Tullberg, A., Rydén, L., Ellervik, U., Svahn, O., Jörnland, L., & Rosén, B. (2013). *Gymnasiekemi 2 [Swedish upper secondary school chemistry 2]*. Liber.

Soysal, Y., & Yilmaz-Tuzun, O. (2021). Relationships between teacher discursive moves and middle school students' cognitive contributions to science concepts. *Research in Science Education*, *51*, 325–367. https://doi.org/10.1007/s11165-019-09881-1

Srinivasan, M., McElvany, M., Shay, J. M., Shavelson, R. J., & West, D. C. (2008). Measuring knowledge structure: reliability of concept mapping assessment in medical education. *Academic Medicine*, *83*(12), 1196–1203. https://doi.org/10.1097/ACM.0b013e31818c6e84

Staarman, J. K., & Mercer, N. (2012). The guided construction of knowledge talk amongst teachers and students. In K. Littleton, C. Wood, & J. K. Staarman (Eds.), *International handbook of psychology in education* (pp. 75–104). Emerald Group Publishing Ltd.

Stein, M. K., Engle, R. A., Smith, M. S., & Hughes, E. K. (2008). Orchestrating productive mathematical discussions: Five practices for helping teachers move beyond show and tell. *Mathematical Thinking and Learning*, *10*(4), 313–340. https://doi.org/10.1080/10986060802229675

Stieff, M., Ryu, M., & Yip, J. C. (2013). Speaking across levels – Generating and addressing levels confusion in discourse. *Chemistry Education Research and Practice*, *14*(4), 376–389. https://doi.org/10.1039/C3RP20158A

Taber, K. S. (2010). Straw men and false dichotomies: Overcoming philosophical confusion in chemical education. *Journal of Chemical Education*, *87*(5), 552–558. https://doi.org/10.1021/ed8001623

Taber, K. S. (2013). Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemistry Education Research and Practice*, *14*(2), 156–168. https://doi.org/10.1039/C3RP00012E

Taber, K. S. (2015). The role of conceptual integration in understanding and learning chemistry. In J. García-Martínez & E. Serrano-Torregrosa (Eds.), *Chemistry education: Best practices, opportunities and trends* (pp. 375–394). Wiley-VCH.

Taber, K. S. (2017). Teaching and learning chemistry. In K. S. Taber & B. Akpan (Eds.), *Science education: An international course companion* (pp. 325–341). Sense Publishers.

Taber, K. S. (2019). Progressing chemistry education research as a disciplinary field. *Disciplinary and Interdisciplinary Science Education Research*, *1*(1). https://doi.org/10.1186/s43031-019-0011-z

Talanquer, V. (2008). Students' predictions about the sensory properties of chemical compounds: Additive versus emergent frameworks. *Science Education*, *92*(1), 96–114. https://doi.org/10.1002/sce.20235

Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry "triplet." *International Journal of Science Education*, *33*(2), 179–195. https://doi.org/10.1080/09500690903386435

Talanquer, V. (2015). Threshold concepts in chemistry: The critical role of implicit schemas. *Journal of Chemical Education*, *92*(1), 3–9. https://doi.org/10.1021/ed500679k

The Swedish Research Council. (2011). *God forskningssed (Vetenskapsrådets rapportserie 2011:1). [Good research conduct. Report series of the Swedish Research Council 2011:1]*

Thomas, G. P. (2017). 'Triangulation:' an expression for stimulating metacognitive reflection regarding the use of 'triplet' representations for chemistry learning. *Chemistry Education Research and Practice*, *18*(4), 533–548. https://doi.org/10.1039/C6RP00227G

Towns, M. H., Cole, R. S., Moon, A. C., & Stanford, C. (2019). Argumentation in physical chemistry. In S. Erduran (Ed.), *Advances in chemistry education* (pp. 247–274). The Royal Society of Chemistry. https://doi.org/10.1039/9781788012645-00247

Towns, M. H., & Kraft, A. (2011). Review and synthesis of research in Chemical Education from 2000-2010. *Journal of Science Education and Technology*, 1–38.

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, *25*(11), 1353–1368. https://doi.org/10.1080/0950069032000070306

Treagust, D. F., & Duit, R. (2008). Conceptual change: A discussion of theoretical, methodological and practical challenges for science education. *Cultural Studies of Science Education*, *3*(2), 297–328. https://doi.org/10.1007/s11422-008-9090-4

Valsiner, J. (1998). Dualisms displaced: From crusades to analytic distinctions. *Human Development*, *41*, 350–354.

van der Veer, R., & Valsiner, J. (1993). *Understanding Vygotsky: A quest for synthesis*. Wiley-Blackwell.

van der Veer, R., & Valsiner, J. (1994). *The Vygotsky reader*.

van der Veer, R., & Yasnitsky, A. (2011). Vygotsky in English: What still needs to be done. *Integrative Psychological and Behavioral Science*, *45*(4), 475–493. https://doi.org/10.1007/s12124-011-9172-9

Van Laere, E., Aesaert, K., & van Braak, J. (2014). The role of students' home language in science achievement: A multilevel approach. *International Journal of Science Education*, *36*(16), 2772–2794. https://doi.org/10.1080/09500693.2014.936327

Vestergård, J., & Pamment, Y. (2022). *Att fördjupa ämnes- och språkkunskaperna (ämnesspecifik text: Kemi) [To deepen subject knowledge and language skills at secondary school. Subject-specific text: Chemistry)*. Skolverket. https://larportalen.skolverket.se/api/resource/P03WCPLAR166277

Vilhunen, E., Chiu, M. H., Salmela-Aro, K., Lavonen, J., & Juuti, K. (2022). Epistemic emotions and observations are intertwined in scientific sensemaking: A study among upper secondary physics students. *International Journal of Science and Mathematics Education*. https://doi.org/10.1007/s10763-022-10310-5

Vladušić, R., Bucat, R., & Ožić, M. (2016). Understanding of words and symbols by chemistry university students in Croatia. *Chemistry Education Research and Practice*, *17*(3), 474–488. https://doi.org/10.1039/c6rp00037a

Vygotsky, L. S. (1962). *Thought and Language*. https://doi.org/10.1037/11193-006 (Original work published 1934)

Vygotsky, L. S. (1978). *Mind in society*. Harvard University Press. (Original work published 1934)

Vygotsky, L. S. (1981). The instrumental method in psychology. In J. V Wertsch (Ed.), *The concept of activity in Soviet psychology* (pp. 134–143). M. E. Sharpe. (Original work published 1930)

Vygotsky, L. S. (1986). Thought and language (A. Kozulin, trans.). In *Thought and Language*. Cambridge University Press. https://doi.org/10.4324/9781315524139 (Original work published 1934)

Vygotsky, L. S. (1987). Thinking and speech. (N. Minick, Trans.). In R. W. Rieber & A. S. Carton (Eds.), *The collected works of L. S. Vygotsky. Volume 1: Problems of general psychology*. Plenum Press. (Original work published 1934)

Vygotsky, L. S. (2020). The problem of the environment in pedology. In *L.S. Vygotsky's pedological works. Volume 1. Foundations of pedology* (pp. 65–84). Springer Nature Singapore. (Original work published 1934)

Vygotsky, L. S. (1994). The development of thinking and concept formation in adolescence. In R. van der Veer & J. Valsiner (Eds.), *The Vygotsky reader* (pp. 185–265). Basil Blackwell Ltd. (Original work published 1931)

Vygotsky, L. S., & Luria, A. (1930/1994). Tool and symbol in child development. In R. van der Veer & J. Valsiner (Eds.), *The Vygotsky Reader* (pp. 99–174). Blackwell Publishers. (Original work published 1930)

Walker, J. M. T., & King, P. H. (2003). Concept mapping as a form of student assessment and instruction in the domain of bioengineering. *Journal of Engineering Education*, *19*(3), 167–179. https://doi.org/10.1002/j.2168-9830.2003.tb00755.x

Warfa, A. R. M., Roehrig, G. H., Schneider, J. L., & Nyachwaya, J. (2014). Role of teacher-initiated discourses in students' development of representational fluency in chemistry: A case study. *Journal of Chemical Education*, *91*(6), 784–792. https://doi.org/10.1021/ed4005547

Weick, K. E. (1995). *Sensemaking in organizations*. SAGE Publications.

Wells, G. (2008). Learning to use scientific concepts. *Cultural Studies of Science Education*, *3*(2), 329–350. https://doi.org/10.1007/s11422-008-9100-6

Wenger, E. (2009). A social theory of learning. In *Contemporary theories of learning: Learning theorists...in their own words* (pp. 209–218). Routledge.

Wertsch, J. V. (1991). *Voices of the mind: A sociocultural approach to mediated action*. Harvard University Press.

Wertsch, J. V. (1998). *Mind as action*. Oxford University Press.

Wertsch, J. V. (2008). From social interaction to higher psychological processes. *Human Development (0018716X)*, *51*(1), 66–79.

Wertsch, J. v, Tulviste, P., & Hagstrom, F. (1993). *A sociocultural approach to agency* (E. A. Forman, N. Minick, & C. A. Stone, Eds.; pp. 337–356). Oxford University Press.

Widing, L., Nilsson, P., & Granklint Enochson, P. (2023). A social semiotic lens to capture meaning-making of polymeric concepts during modelling in chemistry education. *Chemistry Education Research and Practice*. https://doi.org/10.1039/d2rp00211f

Wittrock, M. C. (2010). Learning as a generative process. *Educational Psychologist*, *45*(1), 40–45. https://doi.org/10.1080/00461520903433554

Wu, H., Guo, Y., Yang, Y., Zhao, L., & Guo, C. (2021). A meta-analysis of the longitudinal relationship between academic self-concept and academic achievement. *Educational Psychology Review*, *33*(4), 1749–1778. https://doi.org/10.1007/s10648-021-09600-1

Yaman, F. (2020). Pre-service science teachers' development and use of multiple levels of representation and written arguments in general chemistry laboratory courses. *Research in Science Education*, *50*(6), 2331–2362. https://doi.org/10.1007/s11165-018-9781-0

Yan, F., & Talanquer, V. (2015). Students' ideas about how and why chemical reactions happen: Mapping the conceptual landscape. *International Journal of Science Education*, *37*(18), 3066–3092. https://doi.org/10.1080/09500693.2015.1121414

Yang Hansen, K., & Gustafsson, J. E. (2016). Causes of educational segregation in Sweden – School choice or residential segregation. *Educational Research and Evaluation*, *22*(1–2), 23–44. https://doi.org/10.1080/13803611.2016.1178589

Yeo, J., & Gilbert, J. K. (2022). Producing scientific explanations in physics – A multimodal account. *Research in Science Education*, *52*(3), 819–852. https://doi.org/10.1007/s11165-021-10039-1

Yin, Y., Vanides, J., Ruiz-Primo, M. A., Ayala, C. C., & Shavelson, R. J. (2005). Comparison of two concept mapping techniques: Implications for scoring, interpretation, and use. *Journal of Research in Science Teaching*, *42*(2), 166–184. https://doi.org/https://doi.org/10.1002/tea.20049

Yuan, K., Steedle, J., Shavelson, R., Alonzo, A., & Oppezzo, M. (2006). Working memory, fluid intelligence, and science learning. *Educational Research Review*, *1*(2), 83–98. https://doi.org/10.1016/j.edurev.2006.08.005

Zele, E. Van, Lenaerts, J., & Wieme, W. (2004). Improving the usefulness of concept maps as a research tool for science education. *International Journal of Science Education*, *26*(9), 1043–1064. https://doi.org/10.1080/1468181032000158336

Zhao, F. F., & Schuchardt, A. (2021). Development of the Sci-math Sensemaking Framework: Categorizing sensemaking of mathematical equations in science. In *International Journal of STEM Education* (Vol. 8, Issue 1). https://doi.org/10.1186/s40594-020-00264-x

Zinchenko, V. P. (2004). The psychological theory of activity: “Remembrances of the future.” *Journal of Russian & East European Psychology*, *42*(2), 30–68. https://doi.org/10.1080/10610405.2004.11059215

Zittoun, T., & Brinkmann, S. (2012). Learning as meaning making. In N. M. Seel (Ed.), *Encyclopedia of the sciences of learning* (pp. 1809–1811). Springer US. https://doi.org/10.1007/978-1-4419-1428-6_1851