Supporting Learning and Teaching of Chemistry in the Undergraduate Classroom

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Abstract
There is agreement in research about the need to find better ways of teaching chemistry to enhance students’ understanding. This thesis aims to contribute to the understanding of how we better support teaching and learning of undergraduate chemistry to make it meaningful and intelligible for students from the outset. The thesis is concerned with examining the interactions between student, specific content and teacher in the undergraduate chemistry classroom; that is, the processes making up the three relations of the didactic triangle. The data consists of observations of students and tutors during problem-solving activities in an introductory chemistry course and interviews with graduate students.

Systematic analyses of the different interactions between the student, the chemistry content, and the tutor are made using the analytical tool of practical epistemology analysis. The main findings of the thesis include detailed insights into how undergraduate chemistry students deal with newly encountered content together with didactic models and concrete suggestions for improved teaching and for supporting continuity and progression in the undergraduate chemistry classroom. Specifically, I show how students deal with the chemistry content through a complex interaction of knowledge, experiences, and purposes on different levels invoked by both students and tutors as they interact with each other. Whether these interactions have a positive or negative effect on students’ learning depends on the nature of knowledge, experiences and purposes that were invoked. Moreover, the tutor sometimes invoked other purposes than the ones related to the task at hand for connecting the activity to the subject matter in general. These purposes were not always made continuous with the activity which resulting in confusion among students. The results from these analyses were used for producing hypotheses and models that could support continuity and progression during the activity. The suggested models aim to make the content more manageable and meaningful to students, enabling connections to other experiences and purposes, and helping teachers and tutors to analyze and reflect on their teaching. Moreover, a purpose- and activity-based progression is suggested that gives attention to purposes in chemistry education other than providing explanations of chemical phenomena. The aim of this ‘progression in action’ is to engage students in activities were they can see the meaning of chemical concepts and ideas through their use to accomplish different chemical tasks. A general conclusion is that detailed knowledge about the processes of teaching and learning is important for providing adequate support to both undergraduate students and university teachers in the chemistry classroom.

Keywords: undergraduate chemistry education, learning and teaching processes, didactic triangle, chemical bonding, tutor-student interaction, practical epistemology analysis, continuity, progression, purposes.

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To Tom, Laura and Marvin
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List of Papers

**Paper 1**  

**Paper 2**  

**Paper 3**  
A. Manneh, I., Hamza M. K., Rundgren, C-J., & Eriksson, L. The role of anthropomorphisms in students’ reasoning about chemical structure and bonding. *Accepted in Asia-Pacific Forum on Science Learning and Teaching.*

**Paper 4**  
A. Manneh, I., Hamza M. K., Rundgren, C-J., & Eriksson, L. Progression in action for developing chemical knowledge. *Manuscript.*
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1 Introduction

The general statement *chemistry is difficult* is pointed out quite often in chemistry education research (e.g. Nakhleh 1992; Gabel 1999; Johnstone, 2010). The major concern of this research has been that as students fail to grasp the basic concepts and ideas in chemistry, this may have a negative influence on their interest in chemistry and, thus, on their willingness to engage in chemistry as citizens as well as to consider careers as chemists. However, many students who actually choose to study chemistry at university also find their studies unintelligible and meaningless, especially in the early stages of their undergraduate studies. This is reflected in the high risk of early dropout characteristic of undergraduate chemistry programs in several countries (Cooper & Pearson, 2012; Hailikari & Nevgi, 2010; Lewis & Lewis, 2007) which, in turn, results in the chemistry field losing individuals who can contribute to the development of the discipline. Of course, chemistry studies at university level are difficult in the sense that the subject is complex and based on advanced theories and intense research. At the same time, there is consensus that it should be possible to find ways of better supporting students’ first steps into the chemistry discipline. A central question for the field of chemistry education, therefore, is to develop our knowledge of how to enhance teaching so as to better support students’ learning of chemistry and make their undergraduate studies more intelligible and meaningful.

A major and well-known challenge with learning chemistry is that, as Kozma and Russel (1997) put it, “understanding chemistry relies on making sense of the invisible and untouchable. Much of what is chemistry exists at a molecular level and is not accessible to direct perception” (p. 949). This fact becomes particularly critical where the subject matter of chemical structure and bonding is concerned. Students have to learn about atomic structure, with electrons being arranged in orbitals, having spins, and forming different sorts of hybrid orbitals without actually seeing any of this. Thus, the understanding of this subject matter is developed through various models and students are expected to interpret a range of different symbolic representations of chemical bonds (Taber & Coll, 2002). At the same time, this topic is a fundamental explanatory framework in chemistry and lack of grasping the key concepts and ideas may influence the learning of other topics in chemistry (Levy Nahum, et al. 2013). From my own experience of studying chemistry I remember this topic, in particular, to be highly abstract and hard to learn. This perception became
even more evident when I read chemistry education research and found a wide range of studies that demonstrate how students’ difficulties with this topic persist even at tertiary level (e.g. Nakhleh, 1992; Nicoll, 2001; Sirhan, 2007; Taber, 2013). It is therefore suitable to examine this topic to explore how undergraduate chemistry studies could be made more intelligible to students.

Moreover, undergraduate chemistry typically has a weak connection to the common and regular chemistry practices and applications in which professional chemists engage in their daily work (e.g. Talanquer & Pollard, 2010). Chemistry at the undergraduate level has traditionally been taught as a series of concepts, procedures and algorithms (e.g. Bodner, 1992, Talanquer & Pollard, 2010). These concepts, procedures and algorithms are frequently emphasized by researchers and educators as basic and necessary for students to master before they can take part in more authentic chemical practices. As a result, undergraduate students are expected to use an abundance of new concepts that they encounter within a short period of time in order to provide scientifically appropriate explanations and engage in scientific discussions (Lemke, 1990; Wellington & Osborne, 2001) which has been shown to be challenging (e.g. Talanquer, 2010; Taber, 2013; Taber & Watts, 2000). As students struggle with these abstract and disconnected concepts and ideas, often with little relevance and meaning to them, they end up memorizing the content to simply make it through their studies. This general picture of undergraduate chemistry has been relatively unchanged for decades (Gillespie, 1991, 1997; Hawkes, 2005; Lloyd, 1992; Lloyd & Spencer, 1994).

The general view from research on undergraduate chemistry teaching and learning, then, is that students have difficulties learning chemical concepts and ideas about chemical bonding (as well as other topics in chemistry for that matter), and that the way chemistry is taught seems to make it even more unintelligible. However, there is significantly less research done on the teaching and learning processes behind these results. This made me raise a variety of questions concerning the relationship between the challenges of learning and the way of teaching, which were not actually addressed in the literature. How do students deal with the chemistry content they encounter in the classroom? How do the experiences and knowledge that students bring to classroom activities influence their learning of the content? How does the teachers’ teaching influence students’ learning? And, in particular, what is the relationship between how teachers teach and how students deal with certain content in the classroom? In short, I became interested in investigating the processes which make up the interactions between the student, the specific content and the teacher, since knowledge about these interactions seems vital for chemistry teachers to be aware of in order to make learning meaningful for their students.
In fact, the investigation of the relations between the student, the specific content, and the teacher is at the core of the discipline of didactics, with its central interest in studying teaching and learning processes inextricably connected to subject matter and specific context (Hudson, 2002). Particularly, the didactics approach aims to understand the learning and teaching situation as a whole, which involves the three main components – the student, the content, and the teacher. These three components and their relationships may be represented through the didactic triangle (Hudson, 2002). At the most basic level, the didactic triangle suggests a need to consider issues of how students deal with specific content, the teacher’s choice of content or methods, and the relationship between the teacher and the student in analyzing teaching and learning situations. This is not to say that every didactic study produces a fully comprehensive analysis of these three relationships, but rather to indicate that this complexity constitutes the ultimate interest of didactic research. This thesis aims to explore and analyze some of the complexity in undergraduate chemistry learning and teaching, and suggest how to make the basics taught early at undergraduate level more intelligible and meaningful to students.
2 Literature Review

Chemistry is a difficult subject to learn and teach. A wide range of research has addressed students’ difficulties with core chemical concepts and ideas while other research focuses on how teaching may be changed to facilitate students’ learning of chemistry. In this section, literature on students’ difficulties and literature on how to improve teaching of chemistry at the undergraduate level is reviewed. In addition, school science education research which focuses specifically on the learning and teaching processes in the classroom, and on how knowledge of these processes may help to reflect on and support improved teaching practices, has been considered.

Students’ Learning of Chemistry

A large body of research in chemistry education has investigated students’ ability to construct explanations and articulate their understanding of core chemical concepts and ideas (e.g. Coll & Treagust, 2003; Sirhan, 2007; Taber, 2002; Taber & Coll, 2002 and others). This focus reflects the importance in chemistry education, and science education in general, for students to develop the ability to construct explanations that make sense of scientific phenomena (Driver, Newton & Osborne, 2000; National research council, 1996; Taylor, 1996). Most research studies have been conducted through interviews in order to identify and demonstrate students’ often problematic understanding of chemical phenomena. Several studies have shown that students have difficulties in understanding chemical concepts and ideas about bonding (e.g. Coll & Treagust, 2003; Nicoll, 2001; Sirhan, 2007; Taber, 2013 and more). The major difficulties are primarily related to the abstract nature of matter. Students are expected to understand and explain chemical phenomena on three levels: the observable macroscopic level, the invisible microscopic level of atoms and molecules, and the symbolic or representational level (Johnstone, 1991). This “triplet” relationship, as it was called by Gilbert and Treagust (2009), makes the learning of many core concepts and ideas difficult to students (e.g. Gabel, 1999). It becomes even more difficult when the emphasis is on the symbolic level whereas most teaching and learning take place in chemistry at secondary school and beyond (Overton, Byers & Seery, 2009; Taber, 2009). In particular, chemical structure and bonding is one of the subjects that relies on developing understanding through various models and students need to interpret
many symbolic representations to explain chemical bonding (e.g. Taber & Coll, 2002).

Many studies have shown that students have difficulties in interpreting symbolic representations for explaining chemical phenomena (Chittleborough & Treagust, 2008; Davidowitz & Chittleborough, 2009; Kozma, 2003; Kozma & Russel, 1997; Nicoll, 2003; review study of Taskin & Bernholt, 2014). For example, interviews with students enrolled in an introductory chemistry course showed that they had difficulty understanding structural formulas. They could not relate different structural formulas to the same compound since the formulas were presented differently (Chittleborough & Treagust, 2008). In another study, Smith and Metz (1996) assessed students’ ability to translate between different representations. They found that many undergraduate students had difficulty in translating verbal to diagrammatic representations. Specifically, the students could define a strong acid as 100 % ionized but could not relate this verbal mode to the diagrammatic representation of a strong acid. Moreover, students show difficulties when using structural formulas for deriving information concerning the physical and chemical properties of compounds as well as their geometry (e.g. Cooper, Underwood, Hilley & Klymkowsky, 2012; Shane & Bodner, 2006). According to Marais and Jordaan (2000), dealing with symbols requires students to go through several cognitive steps in order to explain and solve a chemical problem. For instance, when solving a problem, students need to understand what different symbols in a given formula mean and identify the elements and the compound from a given formula. As a consequence, students may get caught up in the symbols and fail to link them to make sense of the underlying phenomena.

In view of the focus on the symbolic level for making sense of chemical phenomena, studies have shown that students have difficulties understanding the structure and behavior of the atom (e.g. Nicoll, 2001; Stefani & Tsaparlis, 2009; Taber, 2002; Tsaparlis, 1997). For example, Nicoll (2001) revealed through interviews that students had difficulties explaining atomic structure. The students invoked a solar system analogy in which they assigned the electrons to fixed orbits and/or compared them to the motion of planets. They also provided incorrect explanations of periodic trends such as the electronegativity trend and atomic size trend. Stefani and Tsaparlis (2009), in an interview study of second-year university students, further showed that students talk about atomic orbitals as definite regions in space and about electron clouds as exact representations of microscopic entities. Other challenges include distinguishing between atomic and molecular orbitals, and confounding the concepts of orbital, shell and subshell (Nakiboglu, 2003; Taber, 2002). Having learned first to describe the atom in terms of shells – which is concrete and definite – makes it difficult for students to describe it in terms of orbitals,
which is a ‘probability’ and not easy to visualize. Then, the difficulty differentiating between key aspects of different atomic models makes it even more challenging for students to use them to explain chemical phenomena. In particular, each model aims to explain certain aspects of the atom. Thus, the simple Bohr model explains atomic spectra, while an accurate description of how electrons are distributed in space around the nucleus requires the more advanced model of quantum mechanics.

The many abstract concepts and new terms that students encounter, especially early at undergraduate level, may be puzzling in themselves but even more difficult to integrate into scientifically and chemically appropriate explanations. One consequence of this is that students memorize chemical definitions and use chemical terms without understanding, mostly as a way to pass exams (e.g. Sözbilir, 2004). Also, students often resort to more concrete and familiar ways of providing explanations, such as analogical and anthropomorphic explanations. To provide anthropomorphic explanation means to ascribe human traits and motivation to inanimate objects, concepts and phenomena. Students, at all levels of education, frequently use anthropomorphisms to make sense of the microscopic level (Coll & Treagust, 2001; Taber & Watts, 1996; Talanquer, 2007, 2013). For example, in a study of Coll and Treagust (2001), secondary school, undergraduate, and postgraduate students used anthropomorphic expressions such as “want to give an electron”, “happy”, and “share” to articulate their understandings of bonding. The students also used analogical models such as the ‘sea of electrons’ to describe the bonding in metallic substances. Moreover, in a study of Talanquer (2013), college students actually preferred using teleological or anthropomorphic expressions when explaining chemical reactivity. But, according to these researchers, the use of such expressions does not necessarily mean that students hold anthropomorphic beliefs concerning bonding and structure. Rather, they may be used to aid students’ explanations. Despite that, the use or overuse of such expressions has been a concern since students sometimes seem to be satisfied with these kinds of explanations, thereby seeing no need to engage in more complex chemical reasoning (Taber & Watts, 1996; Talanquer, 2013).

Students at the undergraduate level often need to learn to use a range of rules and procedures to provide explanations of chemical phenomena. Procedures for balancing chemical equations, drawing Lewis structures, building electron configurations, and assigning names to compounds are only a fraction of those used to understand and explain chemistry at undergraduate level. Research has shown that students struggle to learn many rules and procedures and how to use them to explain chemical change in the structure, properties, and behavior of the atom. For example, students are shown to have difficulties writing balanced equations (e.g. Naah & Sanger, 2012; Yarroch, 1985), labelling atomic orbitals (Taber, 2002), and drawing Lewis structures (e.g. Ahmad & Omar,
1992; Cooper, Grove, Underwood, & Klymkowsky, 2010). Particularly, as these procedures include a sequence of steps with many details, students tend to follow them mechanically without understanding how they are supposed to be used and why. For example, the step-by-step procedure for drawing Lewis structures has been shown to be difficult for students, especially with increasing complexity of molecules and the many exceptions that students need to deal with (e.g. Ahmad & Omar, 1992; Cooper, et al., 2010; Miburo, 1998; Nassiff & Czerwinski, 2015). This results in students reverting to trial and error approaches despite the step by step procedure that guides the process of drawing these structures. Moreover, students have difficulties with knowing when to use certain rules. For example, students use the octet rule even when it is irrelevant or inadequate for explaining a phenomenon or solving a problem (Taber, 1995). To clarify, the octet rule is typically used as a “heuristic” to explain how elements generally gain or lose electrons to attain eight electrons in their valence shell to reach a noble gas configuration. But students also use it to explain reaction changes due to atoms “trying” to gain a full outer shell, which is not a valid explanation (Taber, 1995).

Indeed, these studies of students’ understanding of core chemical concepts and ideas have shown that students face a range of difficulties learning chemistry. A major approach for examining students’ understanding and addressing their difficulties has been through interviews. But, how students struggle with understanding chemistry in actual classroom situations has been significantly less explored. Particularly, little is known about the processes that occur in the classroom, which would help us to better understand how students try to make sense of chemistry, especially at university level.

Curriculum Development to Improve Teaching and Learning

Teaching chemistry is not an easy task, and researchers agree that we need to find better and more scientifically based ways of teaching chemistry in order to enhance students’ understanding (Bodner, 1992; Hawkes, 2005; Johnstone, 2010; Lloyd, 1992; Lloyd & Spencer, 1994). Several studies have suggested ways to improve teaching in undergraduate chemistry, mostly by reorganizing the content of part of or entire curricula. Particularly, researchers have designed curricula to make core chemical concepts and ideas more accessible and comprehensible to students and promote students’ interest in chemistry. Curriculum projects, for instance, Connected Chemistry (CC) (Stieff & Wilensky, 2003), the Chemistry XXI curriculum (Talanquer & Pollard, 2010), the Chemistry, Life, the Universe and Everything (CLUE) curriculum, and Chemistry in Context (CiC) (Schwartz et al., 1994) are among many initiatives to
improve chemistry education at the undergraduate level. These curricular developments aim to connect core concepts and ideas to the application and the practice of chemistry through authentic contexts. Other initiatives focus instead on changing the curricular sequence of activities, topics and courses within introductory chemistry and linking chemistry to other scientific subjects such as biology (e.g. DiBiase & Wagner, 2002; Garkov, 2006, Schwartz & Serie, 2001). Within these initiatives, the content is carefully (re)organized to support progressions around core concepts and ideas in chemistry and enhance meaningful learning. These curricular developments commonly include materials, methods, and activities specifically designed as teaching resources.

One example is a curriculum for connecting laboratory activities and lectures in a general chemistry course (DiBiase & Wagner, 2002). The curriculum and schedule were designed so that lectures were followed immediately by laboratory activities. In this way, observations and data from a laboratory activity were used in the subsequent lecture to enhance students’ understanding of chemical concepts and content. Another well-known curricular approach is context-based learning for making chemistry more meaningful to students by connecting chemical concepts to real-life issues (Belt, et al., 2002; Bulte, Westbroek, de Jong & Pilot, 2006; Grant et al., 2004; Parchmann, Broman, Busker & Rudnik, 2015; Sumter & Owens, 2011). This approach aims to engage students in practices related to the application of chemistry to add meaning and relevance to the chemistry content. For example, Belt, et al. (2002) developed case studies for teaching analytical chemistry. The contexts used were problem scenarios that the students likely encounter in everyday life. Relevant environmental, industrial, forensic, and pharmaceutical chemistry contexts were chosen for the application of analytical chemistry. Each case was designed to offer, at each stage of the problem, different activities that were flexible to be implemented in different learning situations. Another example is the modified approach to teaching general chemistry offered by Sumter and Owen (2011). The redesigned course serves as a template for context-based interdisciplinary teaching that suggests three main educational modules to be implemented in the following order: the fundamentals of general chemistry, medical approaches to inflammation, and neuroscience as a connector of chemistry, biology, and psychology.

Thus, these kinds of initiatives focus on organizing the content in new ways for enhancing students’ understanding of and interest in chemistry as well as offering instructional materials to help teachers accomplishing this. But how an offered curriculum design can be taught in the classroom is still the teachers’ task, and in particular, how to organize learning for specific students in specific contexts. Moreover, the effectiveness of such initiatives is commonly examined by assessing students’ understanding in terms of learning outcomes. But, how teachers actually teach the reorganized content and how students
interact with it in the classroom environment is not much known, especially
as any designed teaching material is necessarily shaped by the contingencies
of actual teaching in the classroom.

Teaching and Learning in Action

While research on chemistry education at university has focused primarily on
students’ understanding and curriculum development for enhancing students’
understanding, as shown above, there is another tradition in secondary science
education which focuses more on studying the learning and teaching process,
examining the different interactions between student, content and teacher in
the classroom (Hamza, 2013; Hamza & Wickman, 2009; Johansson & Wick-
man, 2011; Kelly & Crawford, 1997; Lidar, Lundqvist & Östman, 2006; Säljö
& Bergqvist, 1997; Wickman 2004; Ødegaard & Klette, 2012 and others).
These kinds of studies have analyzed students’ and teachers’ actions during
authentic classroom activities to understand the relations between teaching,
students’ learning process, and the content learned and taught in a specific
activity. I provide some examples from the Swedish tradition of learning and
teaching processes in the classroom. This, of course, with acknowledgment
that there is similar research in other countries (e.g. in Germany, France and
Switzerland) that is equally focused on processes and student-teacher-content
relations (e.g. Belova, Eilks & Feierabend, 2013; Ligozat, Lundqvist &
Amade-Escot, 2018; Sensevy, et al., 2008; Tiberghien, 2016).

Hamza and Wickman (2009) investigated secondary students’ learning pro-
cesses to examine students’ reasoning about an electrochemical cell during
laboratory work. The detailed analysis enabled studying how students’ rea-
soning developed in relation to the particulars and the contingencies of the
activity. They argued that these particulars and contingencies form part of a
scientific account of a natural phenomenon together with the general
knowledge of the subject matter studied. Lidar et al. (2006), analyzed second-
ary students’ learning during a chemistry practical in relation to a teacher’s
teaching. Their analysis showed that the teacher’s actions involved directing
students’ attention towards what is important to notice and what counts as rel-
evant knowledge in the specific situation. They concluded that learning sci-
ence involves being socialized into a specific discursive practice. Similarly,
Säljö and Bergqvist (1997) examined students’ and teachers’ communication
about the properties of light in a school physics laboratory. The detailed anal-
ysis of the interactions between the students, the content, and the teacher
showed that it was not clear to the students what they were expected to see
and explain about the behavior of light and why it was relevant. The study of
the processes enabled researchers to draw the conclusion that ‘seeing’ and un-
derstanding the behavior of light or any other phenomena is consistent with
the discourse of a particular practice which is not accessible to students unless they are provided with adequate support. Other studies focusing on learning and teaching processes in the science classroom have explored aesthetic experiences and their role in the science classroom (e.g. Jakobsson & Wickman, 2008; M anni, Ottander & Sporre, 2017), language and scientific literacy (e.g. Wickman & Ligozat, 2011), distractions in the school science classroom (Hamza, 2013), and how purposes may be used to promote students’ learning progression (e.g. Johansson & Wickman, 2011). The study of Johansson and Wickman (2011) analyzed students’ learning in relation to how the teacher teaches during a physics activity. By analyzing the learning and teaching processes two kinds of purposes were distinguished, namely purposes related to what students do at the moment and what they are supposed to learn in terms of scientific content. They found that the teacher successfully invoked proximate purposes but did not always succeed in relating these to the ultimate purpose of the lesson, which resulted in students failing to see how a proximate purpose was relevant to the ultimate purpose.

What is important here is that the exploration of the different interactions and detailed processes in the classroom provides valuable insights about students’ learning in relation to teaching in a specific context. As a result, these studies have generated specific didactic knowledge, in the form of hypotheses or models, which helps teachers to support students learning in action systematically. For instance, Wickman (2004) analyzed the practical epistemologies of university students during laboratory work in chemistry to understand the course students’ learning takes in interaction with certain sequences. In particular, this analysis showed how the sequence of encounters influences what students learn during laboratory work, suggesting hypotheses, for instance of the order of sequences to support students’ learning. Hamza and Wickman (2013) provided detailed analysis of how students’ learning progresses through an activity; specifically the relation between the particular and contingent aspects and how they interacted as students provided explanations related to an electrochemical cell. The study showed how to support students’ learning progression by not only focusing on students learning generalized conceptions and ideas, but also on the particular and contingent aspects of the school science activity students were engaged in and how they could be made continuous with each other. Specifically, they showed how these aspects were important for the progression of the students’ explanations of the real galvanic cell.

In sum, many studies have examined students’ (mis)understanding of chemistry, not least at university level. For university level, moreover, many studies have developed approaches to improve undergraduate chemistry teaching. However, students’ learning of chemistry content in the classroom and the relation to how teachers teach this content has been little explored in chemistry
at university level. This is particularly true when it comes to the different inter-
teractions between student, content and teacher during classroom activities.
On the other hand, this interest in processes and interactions has been the focus
of much science education research on primary and secondary school. In line
with this interest in the study of learning and teaching processes in the science
classroom, this thesis aims to investigate such interactions for better under-
standing learning and teaching processes in the undergraduate chemistry
classroom as well.
3 Aim and Research Questions

The objective of this thesis is to examine interactions between student, content and teacher in the undergraduate classroom and how that knowledge may be used to suggest ways for supporting teaching and learning in the classroom.

The overarching research question for this thesis is formulated as follows:

How may learning and teaching at the undergraduate level be supported in the classroom in order to make chemistry more intelligible and meaningful?

This research question was operationalized in the research aim and questions of each paper. Paper 1 examined the relationship between the student and the specific content of drawing Lewis structures with the aim of suggesting better ways of learning and teaching this content. The questions addressed were:

1. How do students employ the different steps of the formal procedure as they engage in drawing Lewis structures during problem-solving activities?

2. How do the different steps interact with each other and with other experiences that the students invoke as they engage in drawing Lewis structures?

Paper 2 examined the interaction between the student, the content, and the teacher. The specific content was determining oxidation states of atoms in molecules and the paper looked at how students dealt with this content with the help of a tutor. This paper addressed the following research questions:

3. What distinctions and purposes are invoked by the tutor for guiding the students to determine oxidation states of atoms in molecules?

4. How are the distinctions made by the tutor and the students related to the different purposes pursued during the activity?
5. In what ways do the distinctions and the related purposes invoked by the tutor enable or hinder students to determine oxidation states of atoms in molecules?

Paper 3 continued the examination of the interaction between the student and the content. Specifically, the focus was on the role of anthropomorphisms in students’ explanations of newly encountered concepts and ideas in chemical bonding. Based on the results in papers 1 and 2, this paper also aimed to find better ways of supporting students towards enhanced chemical understanding. The research question addressed was:

6. How may anthropomorphisms support first-year university students’ explanations of chemical structure and bonding during a problem-solving activity?

Paper 4, finally, developed into a theoretical discussion, supported by interviews with graduate students in chemistry, on how to make the learning and the teaching of chemistry more meaningful in the undergraduate classroom. It specifically addresses the question of which purposes students should be presented with during their undergraduate studies, and how the selection of different purposes may help teachers make chemistry content more meaningful.
4 Theoretical and Analytical Approach

In this thesis, the different interactions between the student, the content, and the teacher in the undergraduate chemistry classroom are examined. The different interactions between these three components that constitute the didactic triangle (Figure 1) are the core of the didactic approach (Hudson, 2002). Didactics considers the subject matter and its justification, together with the student and teacher, to be a central part of educational practices (Hudson, 2002). Traditionally, didactics has long been an important tool for planning, designing and analyzing teaching in schools in continental Europe. But research influenced by this tradition has also been conducted in other countries such as the US and UK (Hudson & Meyer, 2011).

The didactic triangle is a key tool for analyzing the complex relations between the student, the content, and the teacher in specific learning and teaching situations (Hudson, 2002). Specifically, it focuses on the different relationships between the student and the content, the student and the teacher, and the teacher and the content where didactic questions are addressed by asking what and how students learn, what teachers teach, how they teach, and why. This, in turn, helps bridging our knowledge about students’ learning of specific subject matter (chemistry) and how this knowledge can be useful for teaching. According to Wickman (2012), didactics as subject specific didactics, is both an academic discipline and a professional science for teachers, as it grew out of the need for teachers to give their teaching a systematic basis based on theory and empirical scrutiny, that is, beyond experiences gained from single lessons. Didactics, therefore, bridges theory and practice where an application of theoretically and practically established knowledge helps developing teaching practices. The crucial task of didactic research, then, is to describe what is going on in the classroom, and what teachers do and encounter in teaching activities that can serve as models of how teaching works (Wickman, 2014). These models, then, may become tools for teachers and researchers to analyze and design teaching practices.

Various models have been developed to support teaching practices. They vary from general models for analyzing learning and teaching in relation to any content, to models which analyze these processes in relation to specific content such as science or chemistry, and which focus on different relations in the didactic triangle. For example, the didactic analysis suggested by Klafki
(1958) is an early model for analyzing learning and teaching centered on the content. This model focuses on the relevance and accessibility of any content to the learner. The aim is to provide criteria that enable teachers to select relevant material for their students. This model may help teachers analyze any content in relation to the students. Other models focus more specifically on the learning and teaching of science, such as the model of curriculum emphases suggested by Roberts (1982). This model focuses on the analysis and selection of suitable science content for the learner in relation to a certain teaching purpose, such as learning the correct explanation or learning to conduct scientific inquiry. It goes beyond the selection of scientific facts, laws, and principles by focusing on the importance of the scientific knowledge for the learner by asking ‘why am I learning this?’ (Roberts, 1982). Another model suggested to support learning progressions in the science classroom is the model of organizing purposes (Johansson & Wickman, 2011). This model focuses on student-content-teacher and how teachers may support this interaction in the classroom. It distinguishes between two kinds of purposes – those that are directly connected to what students are supposed to do in the moment (proximate purposes) and those connected to what students are supposed to eventually learn from a teaching activity or the final goal (ultimate purposes). These purposes can be used by the teacher to organize and assess learning progressions in the classroom. Lastly, the model of the three levels of representations of the macroscopic, microscopic and symbolic (Johnstone, 1991) is an example of a model for supporting teachers in the choice and organization of chemistry content.

As the interest was not only to study the three relations in the didactic triangle in general terms, but to better understand the processes making up these different interactions as they take place in the classroom, a pragmatic approach was chosen. This approach provides a rationale for describing and analyzing the different interactions in the science classroom and has been particularly developed by researchers working within the didactics tradition (e.g. Johansson & Wickman, 2011; Wickman, 2004; Wickman & Östman, 2002). In particular, it provides a way to study the processes that take place in a classroom discourse where the different relations between the student, the content, and the teacher in the specific activity are examined in a systematic way, addressing didactic questions that include how teachers may choose and organize the content to be taught as well as their interactions with their students. This was particularly done through the use of practical epistemology analysis (PEA) developed by Wickman and Östman (2002). This tool was developed to serve the specific needs of didactics and of teachers (Wickman, 2012). It enables a detailed analysis of the learning and teaching process, providing descriptions of moment-by-moment changes seen in the actions of students and teachers/tutors during an activity. In that sense, it allows for analyzing students’ learning, not restricted to cognitive aspects, but actions situated in the specific
environment. This environment involves the interactions with peers, teachers/tutors, and previous experiences particular to individual students and perceived purposes. Thus, practical epistemology analysis not only aims to describe learning processes in the classroom, but also to help find ways of teaching to better support the processes of students’ learning of chemistry.

PEA amounts to a holistic view of learning including situational, continuous, and transformational aspects (Wickman, 2006). It relies upon Dewey’s principle of continuity of experience (Dewey, 1938/1997). Experience, according to Dewey, is continuously transformed by the transactions that occur between the individual and his or her surroundings. This occurs when present experiences are carried forward by being connected to previous experiences in a continuous process. In Dewey’s words

\[
\text{[\ldots] as an individual passes from one situation to another, his world, his environment, expands or contracts. [\ldots] What he has learned in the way of knowledge and skill in one situation becomes an instrument of understanding and dealing effectively with the situations which follow. The process goes on as long as life and learning continue (Dewey, 1938/1997, p.44).}
\]

As a result of making the elements of the present experience continuous with more familiar experiences, transformation or change of experience occurs. In that sense, every new experience adds to the individual’s repertoire of experiences for upcoming interactions with other individuals and situations. We know that when students engage in an activity they bring with them previous experiences gained from previous encounters with their surroundings (e.g. Hamza, 2013; Hamza & Wickman, 2009; Jakobson & Wickman, 2008). All these experiences play a central role in the learning process in the sense that they influence the way students approach the present learning situation. However, not all experiences contribute to meaningful learning in the educational context. The measure of educative significance and the quality of a certain experience depends on whether the different experiences are made continuous with each other in such ways that they can be used fruitfully in future experiences (Dewey, 1938/1997; Hamza, 2013; Wickman, 2006). The key question is, then, how different experiences are made continuous with the present activity, and how they influence the course of the activity (Wickman, 2004; 2006).

The situational (specific aspects of the present experience), continuous (previous knowledge and experiences), and transformational aspects (change of experience) are thus described and analyzed through practical epistemology analysis, PEA (Wickman, 2006). Particularly, PEA makes it possible to analyze how different aspects of an activity are made continuous with each other and how old meanings thereby change, gradually, as they interact with new
experiences. PEA includes four operational concepts for analyzing activities as a transformation of experience (Wickman, 2004; Wickman & Östman, 2002). *Encounter* refers to what students meet and interact with during an activity. Typical encounters are with written or oral instructions, problems, questions, text books, laboratory materials, peers, and teachers. As a result of encounters individuals notice *gaps*. In order to fill a gap individuals establish *relations* to what is already familiar to them which enables them to progress through the activity. These familiar experiences which are not questioned by the individuals are what *stand fast* in the activity. If a gap is not filled with relations it is said to *linger*, but gaps that are not filled in a certain encounter may be filled in upcoming encounters.

The central operational concepts in papers 1 to 3 are the gaps noticed during the activity and the relations established between different aspects of this activity. Specifically, in papers 1 and 3, as the focus was on student-content interaction, the operational concepts characterized were the gaps noticed and relations established by the students, whereas in paper 2, as the focus was on student-content-tutor interactions, the operational concepts characterized were the gaps noticed and relations established by both the students and the tutor. Moreover, the description of the relations, their composition, and the order in which they are established, constitutes an analysis of how continuity may or may not be established during the activity. This, in turn, provides insight into the ways students may or may not be able to connect new content to what is brought to the activity, including the students’ and tutor’s previous knowledge and experiences, as well as purposes.

It is important to point out that PEA is first applied in a first-person perspective which means that filling gaps with relations to what stand fast is towards the purposes which can be discerned through the actions of the participants. These purposes, in turn, are seen through the gaps that are noticed. This is a methodological measure taken to ensure that the researcher does not confuse his or her own research perspective and research purposes with those of the participants (Wickman, 2006). This also means that what stand fast in an encounter does not necessarily indicate the correct use of, for example, a word or a concept. From the researcher’s perspective, of course, not all relations established lead to better ways of dealing with the problems and of accomplishing the purpose of the educational context. Thus, when participants manage to establish continuity, which, from a third-person perspective leads in the “wrong” direction, PEA enables an analysis of what *else* students would have needed in terms of further gaps, relations or encounters and/or their arrangement in order to support their learning (cf. Hamza & Wickman, 2009; Wickman, 2004). Accordingly, PEA also enables an analysis of what is needed in the form of additional encounters, relations or gaps to establish continuity during the activity. In the end, this analysis, moreover, provides teachers with ways
of taking informed decisions for teaching in ways that support students’ learning of specific content which is the concern of the didactic approach.

Next, I illustrate how PEA was used to analyze the interaction between two elements of the didactic triangle, namely the student-content relation (Figure 1), addressing the didactic question of how students deal with specific chemistry content during an activity. The first part of the analysis provides a systematic description of how two students manage or fail to connect different experiences, and in the second part, suggesting what may be done by suggesting additional relations which may help students establish continuity between these experiences. During a problem-solving activity Emma and Julia tried to elucidate the newly encountered concept of electron affinity encountered in a previous lecture.

1  Emma: They need electron affin… it’s too much… electron affinity, that’s the ability to attract electrons.
2  Julia: Mm they… affinity, it’s like negativity.
3  Emma: Yeah.
4  Julia: I mean affinity means negativity… it’s the same thing, like alkaline… negative.

The main gap that Emma and Julia tried to fill was the meaning of electron affinity. In order to fill this gap, several successive relations were established, namely, “the ability to attract electrons”, “negativity”, and “alkaline”. These terms stood fast in the present context since they were not questioned by the students. From the students’ standpoint “negativity” and “negative” might refer to electronegativity, considering the very first relation (Turn 1). Alkaline, on the other hand, did not form part of the content of the present course. It is thus an example of how students may also resort to entirely irrelevant concepts as they strive to make a new concept continuous with their previous experiences. Possibly, since “alkaline” shares a common feature with “negative”, it was brought up here in relation to electron affinity and electronegativity.

From a third-person perspective, if we consider these relations about what counts as scientific knowledge, we might say that Emma and Julia misinterpreted the concept of electron affinity, since electron affinity, by definition, is the amount of energy released when an electron is added to a neutral atom. However, the way these students tried to make sense of the concept was by relating it to other familiar concepts, even if these might not have been suitable in that context. Apparently, the students here would have needed help to distinguish between the concepts which stood fast in the discussion. This may be done, for instance, by establishing further relations to how or for what purpose each of these concepts are used. This, in turn, may be accomplished by predicting what concepts are likely to be actualized, and suggest a reference in
the textbook as part of the assignment. Therefore, this analysis helps teachers/tutors or researchers better understand how ways of teaching may support students’ learning of certain content.

To sum up, PEA helped me accomplish the central aims of this study, namely, to produce detailed descriptions of the processes which comprise the interactions between the student, the chemistry content, and the teacher in the chemistry classroom; to analyze these descriptions in relation to the purpose of the activity; and to suggest hypotheses about how to support teaching and learning during the process.
5 Methods

The methods used to generate data for examining the interactions in the chemistry classroom were observations of undergraduate students’ discussions and interviews with graduate chemistry students. Observations for gathering detailed information about learning and teaching processes were used in papers 1 to 3. Interviews for gathering information about students’ experiences from studying at undergraduate level were used in paper 4. Next, I provide descriptions of the settings, data collection methods, and justification for these choices, followed by data analyses. Finally, ethical and methodological considerations are described.

Background

The focus in this thesis is the examination of the learning and teaching of chemistry that focuses on chemical structure and bonding. This subject matter is one of the core concepts in chemistry and is essential for learning other chemistry topics. Therefore, students start the study of bonding in their first year chemistry course at university. This made the introductory chemistry course suitable for data collection (data collection 1 and 2). Because this course provides students with the basic concepts and ideas of chemistry, it determines whether students proceed in their studies, especially when they find the chemistry unintelligible and meaningless. As a typical introductory course in chemistry it provided a broad introduction to physical, inorganic, organic, and biochemistry and consisted of four main modules: equilibrium, structural chemistry, reactivity, and biochemistry. According to the syllabus the main topics in the four modules of the course are:

1. **Equilibrium**: Basic chemical concepts, scientific models, chemical equilibria, and basic thermodynamics.
2. **Structural chemistry**: Introductory quantum mechanics, atomic structure, and periodic trends. Basic theories of chemical bonding and spectroscopy.
3. **Reactivity**: Strong and weak binding forces, chemical bonding and debonding linked to organic and bioorganic reactions, nomenclature, stereochemistry, and basic organic reaction mechanisms.

Each module consisted of three main activities, namely, lectures, laboratory activities, and problem-solving classes. These different activities were led by different teachers or teacher assistants. Moreover, laboratory activities were mandatory whereas lectures and problem-solving classes were not. Laboratory activities and problem-solving classes were usually led by teacher assistants who were graduate students. Lectures were typically scheduled three times a week and laboratory and problem-solving classes were scheduled once a week. This meant that laboratory activities and problem-solving classes were not always synchronized with relevant lectures. Yet content presented in lectures was usually practiced in laboratory activities and discussed actively by the students with the tutor in problem-solving classes. Problem-solving activities, thus, provided students with opportunities for active discussions which made these classes suitable for studying students’ reasoning about the basics in chemistry and, accordingly, for collecting data for this thesis.

Then, in order to gain more insight into undergraduate chemistry and especially how students deal with their studies, a sample of graduate students was interviewed (data collection 3). This perspective aims to add to and enrich our knowledge about how students deal with chemistry content at the undergraduate level. Graduate students were specifically interesting because, as students who had managed to get through their undergraduate studies and who could share their reflections on how they dealt with their studies, they could enhance the understanding of undergraduate chemistry.

Data Collection 1
I started with observing students in the second module of the introductory course, namely, structural chemistry. I chose this module since students encounter the topic of chemical structure and bonding in this module.

This first round of data collection was drawn from observations of students during problem-solving classes in the module of structural chemistry (paper 3). Before the collection of data I presented myself and the aim of my research to the students during the first lecture of the module. Thereafter, students who agreed to participate signed permission forms and handed them to me at the end of the lecture. As this is a first course for science majors, participating students were chemistry students as well as students from other science programs. A total time of 12 hours of audio recordings were generated from seven group discussions on three occasions. The subject area discussed during the
data collection were chemical structure and bonding with a focus on Bohr’s atom model, the quantum mechanical model of atomic and molecular orbitals, its applications on electron structure and periodic trends such as electronegativity trends, ionization energy trends, and electron affinity trends.

During data collection the students were discussing chemical problems provided in a handout as normal practice. In addition to the handout a book in general chemistry and a book of data were available. The book in general chemistry was called Chemical: Introducing inorganic, organic and physical chemistry. The Book of Data contains physics and chemistry data suitable for all A Level Physics and Chemistry students. As a nonparticipant, I did not interact with the students (Bryman, 2012) in order to capture the interaction as authentically as possible. Field notes were taken during these classes to support the audio recordings. I took field notes because video recording was inconvenient for some of the participating students.

A teacher assistant was also available during these problem-solving classes. He acted as a facilitator and provided support to the students by answering questions related to the problems to be solved and, if the students needed it, explaining any unclear content which had been presented in previous lectures. The teacher assistant was experienced and holds a doctorate in materials chemistry. Signed permission from the teacher assistant was also obtained before data collection commenced.

Data Collection 2

To gain further insight into the learning and teaching processes in the chemistry classroom, data was collected from observations of students during problem-solving classes in two modules of the course: the structural chemistry module and the reactivity module (papers 1 and 2). Eight sessions of student discussions generated a total time of 19 hours of audio and video recordings. The first contact with the participating students was after a lecture in the structural chemistry module. The ten participants were chemistry students and students from other science programs. Then, with the help of the lecturer, I communicated with the tutors attending these classes to acquire their permission as well.

During this data collection the students were discussing problems related to Lewis structures, resonance and hybridization. Additionally, some of the following basic concepts were involved: octet rule, formal charge, oxidation state, and electronegativity. In the reactivity module resonance and hybridization and the above mentioned concepts were also discussed in addition to nomenclature, stereochemistry and aromaticity of organic compounds.
In similar fashion to the process described in data collection 1, the students were solving problems provided in a handout with their general chemistry book and the Book of Data on hand. My role was a nonparticipant observer and I did not interact with the students or teacher assistants during these classes (Bryman, 2012). The same teacher assistant from the data collection 1 was present in this class. In the reactivity module, two teacher assistants were present during problem-solving classes, providing support by answering questions related to the problems in the handout and clarifying content introduced in previous lectures if needed. These two teacher assistants were organic chemistry doctoral students. Signed permissions were obtained from all teacher assistants before data collection started.

Data Collection 3

After studying in detail students’ reasoning about basic chemical concepts and ideas, I wanted to gain more insight into the learning and teaching of these basics from another perspective, particularly from the perspective of graduate students (paper 4). Graduate students were purposefully selected to participate because they might contribute valuable information about how they dealt with chemistry content during their own undergraduate studies. First, these students had successfully completed their undergraduate studies, so they could step back and reflect on their own learning experiences. Second, these students chose to continue studying advanced chemistry, so they could reflect on their undergraduate studies in relation to their current studies. Third, graduate students could provide reflections on their role as tutors in undergraduate chemistry courses. These experiences together had the potential to offer rich insights into undergraduate studies in chemistry.

Six graduate students agreed to take part in the study. Four of the students had studied undergraduate chemistry at different universities in Sweden and two students had completed their undergraduate studies abroad. Five of them were doctoral students and the sixth was just about to begin his doctoral studies. In their advanced studies the students were taking part in three main activities: taking courses, doing research, and tutoring undergraduates. Their role as tutors involved assisting during laboratory activities and problem-solving classes.

In-depth, qualitative interviews (Bryman, 2012) were conducted with the students. Each interview was between 55 minutes and 1 hour and 40 minutes long. The interviews followed a general structure where the students were asked to present themselves and their current studies. Then questions about their undergraduate studies were posed. The questions were broad and open-
ended to allow students to raise and discuss experiences they found interesting and relevant about their undergraduate studies. The main queries that guided the interviews were: How did you experience your undergraduate studies? What was easy, difficult or interesting during your studies at the undergraduate level? In what way? How do you experience the structure of the undergraduate chemistry education, namely, lectures, laboratory activities, and problem-solving classes? Follow-up questions were asked in order to gain clarity and further insight into what had been said during the interviews.

Data Processing and Analysis

The audio and video recordings from both observations (data collection 1 and 2) and interviews (data collection 3) were transcribed verbatim. The transcripts were then analyzed in relation to the aim and research questions of each paper. The analyses of all transcripts were conducted in the original language, Swedish.

The data analyzed in papers 1 and 2 came from data collection 2 and the data analyzed in paper 3 came from data collection 1. Before I describe the data analysis of each paper I will explain the reason for presenting the papers in this order. Initially, the approach to the first data collection was more explorative – the transcripts were read to get an overview and to characterize students’ ways of making sense of the chemistry content during the activity. Thereafter, the data processing and primary analysis took place in parallel with the analysis of the second data collection. But the final stage of the analysis which generated the research question posed in paper 3 was made later, influenced by the analyses and the results obtained in papers 1 and 2.

Paper 1 examined the relation between the student and the content with the focus on one of the basics in chemistry – drawing Lewis structures. When reading the transcripts, students’ difficulties with Lewis structures, both drawing them and using them for solving problems, were noticeable. Therefore, I became interested in examining in detail the process of drawing these structures (paper 1) and how students use them for solving problems (paper 2). In paper 1, the first step in the analysis was to identify the transcripts where students were engaged in drawing these structures. The transcripts were then complemented with student-generated diagrams of Lewis structures and other drawings produced during the process. These diagrams were reproduced from the video recordings and combined with the transcripts. The transcripts analyzed included 16 instances in which students exhaustively discussed some of molecules given in the handout. Five of these instances were then presented in paper 1. Paper 2 focused on how students deal with molecular structure for solving a chemical task in relation to how it is taught. Specifically, it examined
how students, with support and guidance from a tutor, learn to determine oxidation states of atoms in molecules by discerning relevant parts of these molecules. Thus, I identified and then analyzed sequences in the transcripts with discussions between students and tutor while the oxidation states of atoms in molecules were being determined. One extended sequence was presented in paper 2. This sequence included typical issues that were also partly seen in other sequences about different molecules.

In paper 3 I used transcripts from data collection 1 to examine how students deal with many basic concepts they encounter early at undergraduate level. While reading these transcripts, what particularly caught my attention was students’ use of anthropomorphisms when trying to clarify and explain unfamiliar chemical concepts and ideas. Thereafter, I identified sequences in the transcripts for further analysis where students used anthropomorphisms in explanations. In general, I identified anthropomorphic expressions throughout the transcripts but I found eight sequences in which anthropomorphisms appeared as part of more elaborate efforts to make sense of basic chemical concepts. These sequences were then chosen for closer examination of how students use these expressions when explaining chemical concepts and discussing chemical problems, and what additional gaps and/or relations they would have needed in order to improve their explanations.

Finally, in view of the results obtained in papers 1 to 3, paper 4 discussed how learning and teaching chemistry could be supported in the classroom. The concern was how students deal with the basics taught in undergraduate chemistry courses and what could be done to make these basics more intelligible and meaningful when they are first encountered. One salient feature which became evident that all students mentioned the lack of intelligible explanations for the phenomena they encountered during their undergraduate studies, together with a common experience of things coming together during courses at the advanced level. In this paper, sequences from the transcripts of interviews (data collection 3) were selected to support the line of argument discussed in the paper. In order to find relevant sequences I began with reading the transcripts and then separated the sections where students talked about their current advanced studies and the sections where they talked about their undergraduate studies. Thereafter, I chose sequences from the transcripts where students talked about their experiences during undergraduate study as my material for illustrating how students coped with their undergraduate studies.

Ethical Considerations

In qualitative research, ethical considerations are primarily centered on protecting the participants and ensuring integrity and quality of research. As my
descriptions of data collection, methods, and participant recruitment show, I followed the fundamental ethical considerations stipulated by the Swedish Research Council (2011). Particularly, the participating students and the tutors were fully informed about the purpose of this study, how it would be conducted, and that the research would be published in international journals and in a doctoral thesis. They were also informed that their participation was voluntarily and that they had the right to withdraw for any reason. They were guaranteed confidentiality and anonymity by the coding of transcripts with pseudonyms so that it would be impossible to identify students, through written or other forms of communication. I also ensured that access to the data from observations and interviews was restricted to the research group (me and my supervisors). Formal, written consent was obtained from both the students and the tutors. Finally, it is important to note that the purpose of this thesis was not to study individual students’ understanding of chemistry but to suggest ways to improve teaching and learning in the undergraduate chemistry classroom.

Methodological Considerations

To ensure quality of the study, validity and reliability need to be considered. In qualitative research these measures aim to increase the consistency, trustworthiness, and credibility of the results and decrease researcher bias (Bryman, 2012). Reliability traditionally refers to the ability to replicate the processes and the results of a study. Since this thesis aims to study the processes in the classroom that generated data from learning and teaching situations where each situation was special in relation to the specific experiences involved, repeating the study and obtaining similar results may not be possible. In qualitative research reliability is discussed more in terms of consistency in data collection and analyses which may be enhanced by describing, in a transparent way, the data collection and analytical procedures to show systematically how data is interpreted (Lewis & Ritchie, 2003). In order to enhance consistency throughout the analyses and to check data interpretation, the transcripts were examined and reexamined in group discussions with the coauthors. This, in turn, enhanced the transparency of interpretations and reduced researcher bias.

The data in this thesis (data collections 1 and 2) came from observations of two problem-solving classes with a limited number of students. Hence, generalizability in a traditional sense may not be possible. But a detailed understanding of the issues in a particular situation may form the basis for better understanding those issues in other similar settings (Morse, 1999). In that sense, it is reasonable to expect that some of the results may be applicable in other similar situations. Moreover, in data collection 3, six interviews were
conducted. This sample might be considered small, not achieving requisite data saturation to draw some general conclusions, but these interviews were not used as research results which strove to identify patterns of themes in students’ utterances. Rather, their aim was to provide in-depth understanding about undergraduate chemistry to support a theoretical discussion about how to support teaching and learning of chemistry in the classroom.
6 Summary of Papers

This section summarizes the four papers included in the thesis. Together they aim to contribute to our understanding of how to make chemistry more intelligible and meaningful in the undergraduate chemistry classroom. Each paper focuses on some issues related to the learning and teaching of the basics in chemistry and what can be done to support teaching practices. Paper 1 is about procedural learning and structural representations, paper 2 is about tutor-student interaction for dealing with structural representations, paper 3 is about how students deal with chemistry content by using anthropomorphisms, and paper 4 is about what purposes (other than explanations) undergraduate students may need to make chemistry intelligible and meaningful.

Paper 1: Developing an Approach for Teaching and Learning about Lewis Structures

Paper 1 examines how procedures in teaching certain content can be communicated to students in a more meaningful way. The procedure of drawing Lewis structures is analyzed using data from the structural chemistry module (data collection 2). Passages from the data where students were engaged in drawing Lewis structures were selected. How to produce Lewis structures is routinely introduced to students as a step-by-step procedure. However, numerous studies have shown that students struggle to draw Lewis structures according to these procedures (e.g. Ahmad & Omar, 1992; Miburo, 1998; Nicoll, 2003). To make the process of drawing Lewis structures more manageable for students, numerous studies have suggested different approaches (e.g. Nassiff & Czerwinski, 2015; Pardo, 1989; Purser, 2001) but students still struggle to draw these structures (e.g. Cooper, et al., 2010). Apparently, the procedure by itself is not enough and students require additional information to draw these structures effectively.

At first, a theoretical model for drawing Lewis structures was generated from the examination of the procedures presented in many general chemistry books. The analysis of these procedures showed that despite certain variation, for instance, the number of steps, the various procedures share three main elements.
These elements are: *constructing* the skeletal structure and distributing remaining electrons around atoms, *checking* the accuracy of the structure, and then, if the structure is inaccurate, making *modifications*. Thus, all procedures may be modeled through the elements of *construct*, *check* and *modify*, followed with iteration of *reconstruct* and *recheck* if needed (Figure 2). The model was initially developed to support a systematic analysis of how students dealt with the sequence of steps of the formal procedure and how other experiences were invoked in the process.

![Diagram](https://via.placeholder.com/150)

**Figure 2.** A model of the general procedure for drawing Lewis structures (Kaufmann et al., 2017)

The students typically went through the three basic elements of the model – they constructed, checked, and sometimes modified the structure. However, they did not always employ the steps of the formal procedure in the order in which they were introduced in the course. Neither were all steps always employed. Moreover, other experiences were invoked such as electronegativity values for different atoms and analogies to other familiar structures. In some cases the students constructed and checked the structure mostly in relation to the steps of the formal procedure. However, this was not enough for generating an accurate structure. For instance, when drawing the Lewis structure of NO₃⁻ (Figure 3), two students constructed the structure by drawing the skeletal structure and distributing the electron pairs on all atoms (steps of the formal procedure).

![Lewis Structure](https://via.placeholder.com/150)

**Figure 3.** Students’ drawings of Lewis structure of NO₃⁻.
This resulted in a structure with nitrogen in the center, double bonded to two oxygen atoms and one single bonded oxygen. Then, they checked the structure in relation to the octet rule only on the oxygen atoms, which the students apparently considered sufficient to confirm the accuracy of the structure. Therefore, no modification was made although it was needed since they had overlooked the five bonds on nitrogen. Students could have considered a modification if they had checked the octet rule on nitrogen and/or checked against other experiences concerning the number of bonds that nitrogen can form. In other cases, experiences such as analogies with other familiar structures were invoked to construct and/or check the generated structure. For instance, two students constructed the Lewis structure of CO$_3^{2-}$ through an analogy with the structure of NO$_3^-$ and then checked the accuracy of the structure against this analogy together with the procedural approach (the octet rule).

Iterations through reconstruction and recheck were also made. However, this iterative process was shown to be challenging for the students. They often reconstructed the structure by drawing another skeletal structure and rechecked its accuracy only against the octet rule. The reconstruction phase was commonly carried out by redistributing electron pairs (bonds/lone pairs) and rechecking both the octet rule and formal charge.

In sum, the students had difficulty employing the steps of the formal procedure and it was especially challenging for them to identify and appropriately apply other experiences and knowledge in relation to the procedure. This is not surprising considering the mere procedural approach to the task and that students are often expected to connect previously relevant information during the process. The model of construct, check, and modify may provide teachers with a more comprehensive approach to teaching students to draw Lewis structures that includes both the steps from the procedure and other relevant information. This in turn may help students to move from a merely procedural approach to an understanding of the logic and rationale behind the formal procedure.

**Paper 2: Tutor-student Interaction in Undergraduate Chemistry: A Case of Learning to Make Relevant Distinctions of Molecular Structures for Determining Oxidation States of Atoms**

The aim of paper 2 is to explore challenges and issues involved in supporting students’ learning when dealing with molecular structures for solving problems. Data from problem-solving activities where students solved problems with the tutor were analyzed (data collection 2). In the end, an example in which the students worked on determining the oxidation states of the atoms in
the molecule Fe(CN)$_6^{4-}$ with the help of the tutor, was chosen for inclusion in the paper. Thus, the study focused particularly on the challenge of how to make relevant distinctions of molecular structures for determining oxidation states of atoms. Studies have shown that the meaning and the assignment of oxidation states of atoms is not a simple task for students (Brandriet & Bretz, 2014; de Jong & Treagust, 2002; Garnett & Treagust, 1992). Applying the simple rules provided in textbooks is somewhat manageable for students, but the process becomes more difficult when dealing with more complex molecules such as metal complexes and organic compounds (e.g. Halkides, 2000; Jensen, 2011; Jurowski, Krzeczkowska, & Jurowska, 2015; Steinborn, 2004). For instance, when dealing with redox reactions involving organic molecules students struggled with assigning oxidation states to each carbon atom in the reaction (e.g. Halkides, 2000; Shibley, Amaral, & Aurentz, 2010). This occurred despite attempts to provide approaches for making the process of determining oxidation states more manageable for students (e.g. Calzaferri, 1999; Gupta et al., 2014; Steinborn, 2004).

During the activity, the tutor guided the students to make various distinctions which involved shifting focus between the different parts of the molecular structure for determining the oxidation states of the different atoms. Moreover, this ongoing shift, zooming in or zooming out of the molecule, was connected to a concomitant ongoing shift of purposes pursued by the tutor and the students.

An initial approach to the task involved invoking a general rule of electronegativity difference between the atoms within the molecule. Then the tutor guided the students towards certain distinctions by focusing on different parts of the molecule. However, the different distinctions that the tutor invoked actually depended on what purpose he pursued. Some of these purposes were directly related to the task whereas others were connected to general learning of the subject matter. For instance, on one occasion, a distinction was made by shifting the focus on the cyanide ion (CN$^-$) separately for the purpose of determining its overall charge. This purpose was a step towards the main purpose of the task. However, the tutor then shifted the purpose towards understanding why cyanide has a charge of -1. This purpose was not directly related to the task of determining oxidation states but a purpose pursued by the tutor for students to acquire an understanding of the negative charge of cyanide. In this case, he succeeded in getting the students on board, likely because the purpose was clearly communicated to the students.

Other distinctions made by the tutor were more challenging for students since their purpose was not as clearly communicated. For instance, during the activity the tutor focused on carbon individually for the purpose of explaining what was general and what was specific for carbon concerning its oxidation
state. This distinction led to confusion about how this was related to the task of determining the oxidation state of carbon in this molecule. It is important for the tutor to pursue this general purpose so that students can acquire a general understanding of structure and bonding.

To conclude, the tutor has an important role in supporting and guiding students to make relevant distinctions connected to specific purposes for accomplishing the task. However, other general purposes are also important to include for enhancing students’ learning of the subject matter. Moreover, these purposes help students to connect the task at hand to other important information and in turn enhance students’ learning of more general content. But, moving between purposes on different levels risks leaving students behind, since they cannot see why certain distinctions are made. Therefore, tutors need to think through what general purposes would be important to include during the activity and how they are included, so these purposes and related distinctions are made more clearly and, accordingly, made more intelligible and meaningful.

**Paper 3: The Role of Anthropomorphisms in Students’ Reasoning about Chemical Structure and Bonding**

Paper 3 explores how students use anthropomorphisms in their explanations during problem-solving classes and how students can be supported to make their explanations more chemically acceptable. The use of anthropomorphisms has been a subject of discussion in the literature due to their use by students at all levels within science education (Coll & Treagust, 2001; Nicoll, 2001; Taber & Adbo, 2012; Talanquer, 2013). Researchers have been concerned that the frequent use of anthropomorphisms may stand in the way of more scientific reasoning (e.g. Taber & Watts, 1996; Talanquer, 2013). But, their frequent use by students has led to a shift in how the use of such expressions is viewed. Particularly, the discussion in research has shifted from whether they should be allowed or avoided, towards an interest in what role they may play in supporting students’ understanding of chemistry (Dorion, 2011; Talanquer, 2013). This paper aims to contribute to a better understanding of how anthropomorphisms may support students’ grasp of chemistry using data from student discussions during problem-solving activities (data collection 1).

In the sequences analyzed, students explained chemical concepts and ideas by using anthropomorphisms. In part of these sequences students also invoked what we labeled as *technical relations* in addition to anthropomorphic relations, which together produced more or less chemically appropriate explana-
An anthropomorphic relation was defined as one in which students ascribe human characteristics to chemical concepts or phenomena such as “noble gases-satisfied-happy”. A technical relation was defined as one in which students use chemical terms, without ascribing to them human characteristics, such as “ionization energy – amount of energy required for removing an electron”. The ways in which these two kinds of relations interacted to support students’ explanations differed. In some sequences, the students managed to produce explanations through a fruitful combination of both anthropomorphic and technical relations. For example, in one sequence the students were trying to provide an answer to the question of what the electronegativity values of noble gases were and why. In this sequence, the students established the relations 1) “They don’t want to let go a single bit”, 2) “it takes a lot of energy to make an ion of a noble gas”, and 3) “they fight for their electrons”. The technical relation (2) was connected to the anthropomorphisms which came before (1) and after (3). Thus, the anthropomorphic and technical relations were made continuous with each other in the students’ reasoning, thereby reinforcing each other.

The analysis of other sequences, however, showed that students could not always make anthropomorphisms continuous with technical relations in this way. In these cases, the analytical focus was on the kind of support students would have needed to carry through with their explanations. As a hypothesis for how to support students to arrive at a more chemically satisfactory explanation, we suggested providing not only further technical terms but actively encouraging students to employ more anthropomorphisms. For example, two students were trying to elucidate the newly encountered concept of effective nuclear charge. They used the anthropomorphisms of “lower effective nuclear charge – easier” and “high effective nuclear charge – holds on tighter” to explain the concept. Then, they tried to explain it by relating it to another concept, shielding effect. This was followed by a technical relation “effective nuclear charge - atomic number minus shielding”. Shielding effect was, then, explained through additional anthropomorphisms such as “high shielding number – willingly let go”. However, the students never managed to make the two kinds of relations continuous with each other. A possible way to provide support to students could be to help them explicitly connect the anthropomorphisms already established to each other and even adding additional anthropomorphisms; specifically, connecting between “high shielding – easier to take them” and “lower effective nuclear charge – easier”. Then a more technical gap could be introduced such as “how does shielding influence effective nuclear charge?”.

Hence, a possibly fruitful way to support students to produce chemically relevant explanations, then, is through the emphasis on additional anthropomorph-
phisms and specifically help students to connect the concepts through the anthropomorphisms already established and, only then, to more technical relations.

Figure 4. A simple model for a chemical explanation constituted by the connection between both anthropomorphic and technical relations.

In sum, the findings show that the invoked anthropomorphisms constituted potentially productive points of departure for rendering students’ explanations more chemically appropriate. Therefore, students may benefit from the use of these expressions, and, particularly, early in their undergraduate studies. The students may then be supported towards providing explanations in which anthropomorphisms are increasingly tightly connected to relevant technical relations, without the need for dispensing with anthropomorphisms entirely (Figure 4).

Paper 4: Progression in Action for Developing Chemical Knowledge

Paper 4 aims to enhance our understanding of how to make the basics in chemistry more meaningful and intelligible to undergraduate students. Data from interviews with graduate students was used (data collection 3) as part of a theoretical discussion about what purposes, other than constructing explanations, may give meaning to the content being studied. In line with papers 1 to 3, this paper also discusses ways to provide support to students and teachers in the classroom.

Many chemistry students, including the students in this study, find their studies at the undergraduate level hard and troublesome (e.g. Carter & Brickhouse, 1989; Sözbilir, 2004; Woldeamanuel et al., 2014). They experience the chemistry content as a disconnected body of knowledge with a focus on learning facts, abstract concepts, and algorithms with little connection to the real-world
issues which influence their interest and motivation (e.g. Carter & Brickhouse, 1989; Sözbilir, 2004; Woldeamanuel, et al., 2014). It is also hard for students to see how concepts and ideas in chemistry can be applied, and they therefore end up memorizing “facts” without any deeper understanding. For example, one of the interviewed students talked about how he, as an undergraduate student, could accept, as a matter of fact, the use of palladium as a catalyst in the process of hydrogenation, but he did not acquire an explanation for why palladium specifically is used as a catalyst until his master’s studies. Similarly, another student was able to write reaction mechanisms by showing the flow of electrons, but she did not understand why these reactions actually occurred. These students came to understand the ‘why’ only during their advanced studies. At the undergraduate level they simply memorized the content without understanding it as a way to make it through their studies. Not receiving the explanations that were important to them at undergraduate level, made them experience their chemistry studies as unintelligible and meaningless.

Thus, the challenge of how to support students’ learning of the basics in chemistry, is discussed as being situated in a dilemma often encountered by teachers: should students learn the basic facts in chemistry before engaging with chemical explanations or should the explanations be taught in parallel to these facts? The provision of explanations is an epistemic aim in science education (e.g. Driver, Newton & Osborne, 2000; National Research Council, 1996) since students need to develop this ability in order to understand and make sense of scientific phenomena. However, it may be difficult for students to construct or appreciate explanations early at the undergraduate level since scientifically appropriate explanations build on a wide knowledge base which is still not acquired early at the undergraduate level. But then, how can students be supported to experience their undergraduate studies meaningfully when they have not yet acquired the necessary basics in chemistry for being able to appreciate complex explanations?

This question has commonly been discussed in terms of how to organize the progression of the chemistry content (Duncan & Hmelo-Silver, 2009; Duschl, Maeng & Sezen, 2011; Wickman, 2015). A common progression in chemistry involves providing students with explanations of increasing complexity together with the provision of necessary basic knowledge along the way (e.g. Gillespie, 1997; Lloyd, 1992). This kind of content progression may help students appreciate explanations despite their limited knowledge base. However, as the argument in paper 4 goes, progression does not have to be framed solely in terms of explanations and the basic knowledge to appreciate them. Instead, an alternative kind of progression is suggested to give meaning to the basics. This kind of progression is related to what chemists actually do in addition to providing explanations. This is a progression of increasingly competent action (Wickman & Ligozat, 2011). The idea behind such progression is that, instead
of introducing students to definitions of the basics or explanations which may not be intelligible at this level, teachers may offer the possibility of engaging in activities where such basics are used to deal with various chemical tasks. This implies that instead of focusing on what they need to learn in terms of concepts and ideas, as well as providing explanations, the focus shifts to engaging students in activities for solving problems through the use of these basics. One simple example is the learning and teaching of the electronegativity concept. Instead of introducing the concept through its definition, students can use this concept to accomplish different tasks, which involves predicting the type of bond, followed gradually by tasks which involve predicting nucleophilicity or electrophilicity as a way of predicting reactivity. This kind of progression, where basics are used for accomplishing various purposes, may help students to find these basics more meaningful.

In sum, the paper suggests that a potentially productive way for making early undergraduate studies more meaningful is to partly shift the focus from only explanations and their basics towards other purposes that are equally important to chemistry education. Particularly, focus should be on activities with purposes that contribute to the learning of the basics in chemistry where students can see the meaning of these basics by using them to accomplish chemical tasks.
7 Discussion and Implications

The ambition of this thesis is to contribute to an understanding of how to make learning and teaching of chemistry in the undergraduate classroom more intelligible and meaningful for students. To this end, the processes which make up the interactions between student, chemistry content, and tutor were investigated to provide thick descriptions of the actions of both students and tutor in relation to specific contexts and purposes of an activity. These interactions have been studied before (mainly in primary and secondary science education research), generating productive suggestions for supporting teaching and learning of science in the classroom. This thesis shows that the study of these interactions, what I have here described as a didactics approach, may also contribute important insights into and suggestions for improved teaching in the undergraduate chemistry classroom. The importance of studying the processes aims to go beyond students’ difficulties as such and study them in action in order to suggest what may be done to better support learning and teaching during these activities. In this thesis, the analyses of these interactions enabled suggesting ways to better support continuity and progression in the undergraduate chemistry classroom (papers 1 to 4) and to develop models for supporting the learning and teaching of chemistry content (primarily, papers 1 and 2).

Continuity and Progression in the Undergraduate Chemistry Classroom

The results show that progression and continuity in the classroom involve making the different aspects of an activity continuous with each other. These aspects include knowledge of chemical concepts and ideas, experiences and purposes brought by both students and tutors. The analyses of students’ discussions about chemistry tasks showed how students invoked previous experiences and knowledge, including familiar chemical concepts and structures, and tried to relate them to the current activity (papers 1 to 3). When discussing chemical structures the students drew analogies to familiar structures of chemical compounds (paper 1) and referred to other familiar concepts (papers 1 to 3) as a way of dealing with the activity. Students also referred to anthropomorphic expressions for explaining core concepts and ideas (paper 3). However, the students did not always manage to make these experiences and
knowledge continuous with other aspects of the activity, including the chemical concepts and ideas being taught and the purpose of the activity. It could be claimed that certain experiences such as analogies are incorrect, irrelevant, or inappropriate for dealing with a chemical task. At the same time, their very existence indicates that they are important for students to deal with the task. So, whether certain experiences constrain or block students’ learning and understanding of chemical concepts should not be the main concern, but rather how these experiences can be made continuous with other aspects of the activity. This does not imply that they may, on their own, be considered sufficient for reaching a meaningful understanding of chemistry, but my empirical results suggest that they are employed as a means of successively moving towards a better understanding.

It has long been acknowledged that to support continuity and progression of learning in undergraduate chemistry education, we need to help students connect the different aspects of the activity they are engaged in. However, research in chemistry education has mainly addressed this challenge through development of a variety of alternative curricula (e.g. Belt, et al., 2002; DiBiase & Wagner, 2002; Stieff & Wilensky, 2003; Talanquer & Pollard, 2010). For example, aligning lectures and laboratory activities makes the learning of observable phenomena in the laboratory more connected to the underlying concepts and theory and enhances students’ ability to connect macroscopic and microscopic phenomena (DiBiase & Wagner, 2002). Also, connecting content and context to make the chemistry content more purposeful has proven a useful strategy (Belt, et al., 2002; Sumter & Owen, 2011). Indeed, these kinds of developments are important for making chemistry more meaningful, relevant and intelligible (e.g. Bulte et al., 2006). Yet, the results in this thesis suggest that the intended alignment and connection is also, to a significant extent, dependent on what actually happens in the classroom, irrespective of the overall curriculum structure. Students and teachers are the heart of any teaching and learning situation and therefore the extent to which any change in teaching practices may be productive is influenced by aspects such as students’ experiences and teachers’ concerns and purposes. As the findings in this thesis show, experiences, including anthropomorphisms (paper 3) and familiar molecular structures (paper 2) are invoked by the students to complete the chemical tasks. These experiences are closely tied to the specific contexts of the activity and they influence students’ ways of coping with a particular task at hand. In my studies I show how making these particular, contingently arising experiences continuous with the other aspects of the activity is important for supporting progression in this activity. In a similar way, paper 2 shows how the general purposes invoked by the tutor are tied to the particular activity of learning to make relevant distinctions for dealing with molecular structures. The study shows the need to make these purposes continuous with the specific purpose of the task in order to enhance students’ understanding of
the chemistry content and help them solve the task at hand. Therefore, in addition to focusing on what the restructuring of curriculum content or teaching activities may offer for guiding and supporting teaching practices in terms of continuity and progression of chemistry learning, the contribution of this thesis is findings that also help teachers to support continuity and progression during the bit-by-bit teaching and learning processes in the classroom. In particular, it enhances our understanding about how students do or do not manage to make prior experiences continuous with present experiences and what may additionally be needed to support progression in a learning activity.

Apart from the need to connect previous knowledge and experiences to new and more scientific knowledge and experiences, continuity implies consistency between the aims, purposes and intentions of teachers and students in a teaching and learning activity. The analysis of tutor-student interaction showed that when dealing with molecular structures for determining oxidation states of atoms, the tutor guided students by making distinctions that entailed constant shifts of focus, zooming in and out on the different parts of the molecule (paper 2). These distinctions served different purposes as some of them were directly related to the specific task at hand, whereas others aimed at general learning of the subject matter being studied. However, these two kinds of purposes were not always made continuous with each other. Specifically, while students were primarily focusing on accomplishing the purpose of the task, the tutor made distinctions that served other, more general purposes by shifting focus between the different parts of the molecule. This sometimes created confusion among students. Indeed, it is important for good teaching practice to connect the specific task to more general purposes to enhance students’ understanding of the subject matter. But the issue is how these purposes, which also entail shifts in focus between the different parts of the task, may be organized to enhance learning progression (cf. Johansson & Wickman, 2011, 2018). The results from this thesis suggest that teachers need to think about how to make the specific and general purposes of the task continuous with each other to support learning progression. One option which I suggest on the basis of my analyses is that the tutor may first concentrate on accomplishing the purpose of the task and then invoke other purposes that he/she finds important and relevant for students to learn. As a result, students may be better able to follow the shift in focus between the different parts of the molecule and experience the chemistry content learned in a specific activity more meaningfully since it is connected to content taught in previous activities.

Finally, the thesis suggests that progression and continuity need to be discussed in ways which also give attention to other purposes in chemistry education than to provide explanations of chemical phenomena (paper 4). Specifically, I suggest a kind of progression which is purpose- and activity-based and which particularly may give meaning to the chemistry content early at
undergraduate level. This kind of progression is offered as an alternative to the typical content progression in chemistry education that is primarily concerned with how the chemical concepts and ideas can be organized for developing conceptual understanding. In this kind of content progression students are expected to successively articulate more sophisticated ways of thinking and explaining chemical concepts and ideas that gradually develop as students learn. However, as the interviews suggest, such a view of progression did not make it easy for the graduate students to develop meaningful learning of chemistry at the undergraduate level. The problem was that, as the graduate students were mostly focused on acquiring explanations, they found it difficult to appreciate or provide explanations at the undergraduate level, since they had still not developed the necessary basic concepts and ideas in chemistry at that level of education. As a result, the students ended up memorizing the content without understanding (e.g. Sözbilir, 2004). Instead of focusing on providing students with the basics for producing explanations of increasing complexity, the alternative progression that I suggest focuses on increasingly competent and complex action (Wickman & Ligozat, 2011). In such a progression the activity is key since it offers students opportunities to use the scientific concepts in fruitful and purposeful ways before they have incorporated these concepts into coherent chemical explanations, which inevitably requires time. Thus, the concern is to engage students in activities where they can better see the point of the concepts they are learning because these concepts help them better accomplish the tasks which are closer to their current knowledge and experiences at this early stage of the chemistry education.

Models for Supporting Learning and Teaching in the Undergraduate Chemistry Classroom

The analyses of the processes which comprise the interactions between the student, the specific content, and the teacher yielded two rather well-defined and two more tentative didactic models which aim to provide support for teachers and students in the classroom. In particular, the models are intended to help teachers analyze and reflect on the ways they teach specific content to make the learning of this content more intelligible and meaningful to students.

The first and most elaborate model concerns the learning and teaching of one of the basics in chemistry, namely, how to draw Lewis structures (paper 1). This specific example is a case in point of procedural learning of chemistry content and how the developed tool may support more meaningful learning. Although procedures generally aim to provide guidance and support to students to learn to deal with the new content, their use is neither easy nor straightforward as it is influenced by the contingent and the particular aspects
of the specific activity (e.g. previous experiences of specific students) (Hamza & Wickman, 2009). My classroom observations, concurring with other studies, showed that the participating students struggled with learning to draw Lewis structures (e.g. Ahmad & Omar, 1992; Cooper, et al., 2010; Nassiff & Czerwinski, 2015). The students tended to follow the steps mechanically without understanding how these steps were supposed to be used in relation to other important knowledge which made it difficult for them to construct accurate structures. The suggested model of construct, check, and modify constitutes a new conceptualization for drawing Lewis structures, and offers students opportunities to invoke other knowledge in an insightful way during the process rather than simply following the steps of the formal procedure. The model may increase students’ awareness of the role of the different steps in the formal procedure and the relation to other necessary knowledge. In this way, learning to draw Lewis structures may become less procedural and more meaningful. This model may also be useful to help teachers actively reflect on the way they teach any procedure; in particular to think about what other important knowledge they expect students to bring together with the procedure and how to support them to do so.

The second model provides insight into how teachers may work in order to guide and support learning progression in the classroom (paper 2). It offers a tool to analyze tutor-student interaction in relation to what distinctions need to be made in the form of zooming in and out on different parts of a molecular structure that serve different purposes. It particularly helps to keep track of distinctions made for purposes related to the specific task and other purposes for general learning of the subject matter. This kind of analysis may be considered a useful preparation for teachers/tutors since it encourages them to reflect and critically evaluate the different kinds of purposes, the related distinctions, and how they can be made continuous with each other. This, in turn, may help improve upcoming activities in terms of what general purposes are important to include or exclude, and how to sequence and productively connect purposes to support students during the activity. This model not only provides insights about how teachers may organize the different purposes to support progression in the classroom (Johansson & Wickman, 2011) but also, specifically, how teachers may organize the different purposes in relation to the various distinctions needed by zooming in and out on the different parts of a molecular structure.

In addition to these more elaborate models, papers 3 and 4 may also be considered to include tentative models to support continuity and progression in the chemistry classroom. One idea is presented in paper 3, namely, that a chemical explanation may be constituted by connecting both anthropomorphic and technical relations to each other. It accentuates the role of anthropomor-
phisms as part of an accepted chemical explanation if they are made continuous with technical relations. As a beginning model it aims to support the development of students’ explanations from those containing only anthropomorphisms to explanations where anthropomorphisms are made continuous with relevant technical relations. Moreover, the model suggests that students’ explanations may be rendered more chemically appropriate by, in fact, deepening the anthropomorphic relations invoked by the students and even adding new ones. Finally, paper 4 offers the start of a model for thinking about purposes in early undergraduate chemistry courses. In particular, it draws attention to the possibility that planning for chemistry teaching may involve considerations of what purposes other than providing explanations need to be included. This model is less abstract and includes some examples of activities with intelligible purposes that might make the learning of core chemical concepts and ideas in undergraduate chemistry more meaningful. The idea is to develop activities with purposes that are common to chemists to support progression in action in the undergraduate chemistry classroom.

Lastly, apart from developing and suggesting the models above, this thesis employed an existing didactic model as a primary tool for analyzing the data. Thus, the model of Practical Epistemology Analysis, PEA (Wickman & Östman, 2002) was used in papers 1 to 3, in order to analyze to what extent continuity was established between different aspects of the activities under study. This model enabled first an analysis of the gaps that were noticed and the relations that were established during the activity, and second, the suggestion of further gaps and relations that may be needed to support students to establish continuity in those instances where they failed to do so. For example, in paper 3, two kinds of relations were characterized – anthropomorphic and technical. As students did not always manage to make these two kinds of relations continuous with each other to provide satisfactory explanations, PEA enabled me to suggest additional gaps and relations that could potentially support such continuity; for instance, by connecting students’ existing anthropomorphisms to technical relations or by establishing additional anthropomorphisms before adding new technical or scientific ones. Such analysis allowed me to monitor whether students managed or failed to establish continuity during the activity and to suggest what could be done during the process to support continuity. The suggestions for additional relations extracted from this kind of analysis may, as a next step, be tested in new classroom situations.

In sum, the advantages of adopting progression in action and the models presented in this thesis is that they may contribute to making the chemistry content more meaningful and manageable in the classroom. Although there is evidence that changing the curriculum by reorganizing courses, modules, or whole transformed curricula contributes to improving student outcomes, we obviously still need to provide support for teachers to organize learning and
teaching in the classroom. Besides, transforming curricula may often be too complicated and demanding, and for that reason may not be an option for many colleges or universities to consider. This may be particularly demanding for university chemistry teaching considering that general chemistry classes have large numbers of students (Talanquer & Pollard, 2010). Therefore, what this thesis offers in terms of support in the classroom should satisfy a concern in chemistry education with finding ways of teaching chemistry without having to reconstruct major parts of the curriculum (Cooper & Stowe, 2018).

**Studying the Interactions in the Learning and Teaching Process**

There is agreement in the chemistry field that we need to find ways of teaching chemistry to make it intelligible and meaningful to students (e.g. Bodner, 1992; Hawkes, 2005; Johnstone, 2010; Lloyd, 1992). The results of this thesis show that knowledge of the processes which comprise the interactions between the student, the specific content, and the teacher in the undergraduate chemistry classroom is fruitful for suggesting ways of supporting teaching and learning. The study of these interactions is not primarily for identifying students’ difficulties in understanding core chemical concepts and ideas, which have been intensively investigated, but enhancing the understanding of learning and teaching process for the purpose of aiding students and teachers during the process. Research in chemistry education commonly focuses on assessing students’ learning, often through interviews, which is certainly important since it provides evidence of whether students have (mis)understood specific content and of how effective a curriculum design is in terms of changed outcomes. However, it may give little support to teachers about how to help develop their students’ understanding in the classroom. As Wickman (2012) states, assessing the outcome does not give clues to what affected this outcome and so gives us little idea of how to improve the teaching activity beyond trial and error. For example, formal assessment may reveal that the prior knowledge and experiences students bring to learning activities such as analogies to chemical structures (paper 1) and anthropomorphisms (paper 3) have a (negative) impact on students’ understanding of the chemistry content. However, the way this prior knowledge and experience influences students’ learning, and, particularly, how they manage or fail to make these experiences continuous with the relevant content and purposes of an activity, can be seen only through a study of the complex interactions in situ and the purpose of the activity, as done in this thesis.
Further Considerations and Future Direction of Research and Development

As the interest in this thesis is to study the processes which make up the interactions between the student, the specific content, and the teacher in the undergraduate chemistry classroom, data from observations of two problem-solving classes was obtained. These observations of authentic classroom situations gave rich qualitative data for conducting detailed and profound analyses of the different interactions in the classroom. As this kind of data is based on encounters that occur in specific situations where each situation is unique in relation to the particular experiences involved, it might not be considered statistically generalizable. But the in-depth analyses enabled the identification of general patterns of how students deal with the chemistry content and how teachers provide support during the process. Yet, the results obtained need to be examined and evaluated in new classroom situations to better understand how they can support teaching and learning of chemistry at the undergraduate level.

Moreover, as this thesis studied a limited number of processes and interactions in the chemistry classroom, the results may need to be studied in other contexts and with a focus on other chemistry content. Future research may be conducted together with teachers to examine how the different models suggested may help to support their teaching. Such studies may also contribute to further understanding of how to develop these models by adding other components. For example, the teacher may introduce the model of construct, check, and modify for drawing Lewis structures to students in parallel to the steps of the formal procedure (paper 1). Analyses of how students interacted with the new model may then be conducted together with the teacher to bring insights to how this model may be developed further. This may also help teachers reflect on how they teach procedures in general where they need to explicitly consider what and how other necessary knowledge and experiences can be made part of a procedure being taught. In a similar way, more targeted analyses of tutor-student interactions (paper 3) may be conducted to explore what particular purposes to include in a certain teaching activity, how to organize these purposes to help students understand what they are doing at the moment, and how this is related to other important knowledge of the specific subject matter being studied. In particular, future studies may be conducted together with teachers where they deliberately design their interaction with the students with a focus on specific features of the activity, such as how to align purposes and their related distinctions concerning molecular structures.

Moreover, to develop the idea of ‘progression in action’ (paper 4), further research may focus on extracting examples of activities with purposes that make core chemical concepts and ideas more intelligible and meaningful and how
these activities and their purposes can be made continuous with each other to support progression. The implementation of these examples can be studied in actual classroom situations to examine how they influence the learning processes of students. Also, these examples can be studied in terms of the development of students’ chemical knowledge and skills. In conclusion, including the teachers in the study of the suggested models in situ may well help to improve the teachers’ awareness of how they can better support the interaction between the student and the content. Supporting this interaction is the key task of the teacher in order to improve his/her teaching and enhance students’ learning of chemistry.

av de processer som sker i klassrummet när förstaårsstudenter blir undervisade i och försöker lära sig kemi. Dessa processer uppkommer i de interaktioner mellan studenter, kemiinnehållet och lärare som svarar mot de tre relationerna i den didaktiska triangeln. Genom att på detta sätt fokusera på de tre relationerna i den didaktiska triangeln, och vilka processer som bygger upp dessa, kunde jag skapa bryggor mellan kunskap om studenters lärande i kemi och hur denna kunskap kan vara till hjälp för att stödja lärare kemiundervisning.

Jag studerade de olika interaktionerna genom observationer av studenter och lärare under räkneövningar när de diskuterade kemiska begrepp och löste problem som handlade om kemisk bindning. Jag gjorde därefter detaljerade analyser av dessa interaktioner med hjälp av praktisk epistemologisk analys (PEA) för att synliggöra kontinuitet och progression eller frånvaro av dem i klassrummet. PEA möjliggjorde en detaljerad beskrivning av undervisnings- och lärandeprocesserna, d.v.s. hur studenterna gick till väga för att lära sig kemi under aktiviteterna och hur läraren stödde dem under processen. Det är två aspekter som jag har fokuserat särskilt på i analysen. Först analyserade jag vad studenterna och läraren gjorde under aktiviteterna och vad som saknades för att studenterna skulle förstå kemiinnehållet. Sedan analyserade jag vad som ytterligare skulle behövts för att studenterna skulle kommit längre i sina kemiska resonemang under aktiviteterna. Denna analys gjordes med hjälp av fyra begrepp som är centrala i PEA: möte, mellanrum, relation och stå fast. Utgångspunkten i analysen var att identifiera syftet med aktiviteten vilket kunde beskrivas genom de mellanrum som uppmärksammades och hur dessa fylldes med relationer mellan ord eller handlingar och det som stod fast. Sedan använde jag samma analysbegrepp för att föreslå vilka mellanrum och relationer som skulle behövas för att bättre stödja kontinuitet och progression i klassrummet. Utifrån dessa analyser föreslog jag hypoteser och modeller för hur lärare kan stödja studenter i kemiklassrummet. Dessutom har jag använt data från intervjuer med doktorander i kemi som utgångspunkt för en teoretisk diskussion om hur man kan hjälpa lärare att stödja kontinuitet och progression i studenternas lärande av kemi.

Resultaten från de olika klassrmsinteraktionerna visar hur studenter hante-rade kemiinnehållet genom ett samspel mellan kunskaper, erfarenheter och syften, som både studenter och lärare införde i aktiviteten. Dessa kunskaper, erfarenheter och syften kunde påverka studenternas lärande såväl positivt som negativt. Den första studien beskriver interaktionen mellan studenter och ett specifikt innehåll, nämligen att rita Lewisstrukturer för kemiska föreningar. Att lära sig rita Lewisstrukturer innebär att räkna totalt antal valenselektroner, rita en skelettstruktur som visar hur atomer är bundna till varandra, arrangera de resterande elektronparen runt atomerna och försäkra sig om att okettregeln är uppfylld för alla atomer i strukturen. Denna procedur presenteras i många kemiböcker och kan variera i antal steg eller detaljer. Analysen av proceduren

och tekniska relationer kontinuerliga med varandra. Dessutom indikerar resultaten att ytterligare antropomorfismer ibland skulle kunna vara till hjälp för studenterna. Läraren skulle med andra ord kunna uppmuntra och införa fler antropomorfismer för studenterna, innan de så småningom kopplas till de tekniska relationer som behövs för att konstruera en god kemisk förklaring.

Den fjärde studien diskuterar hur kemiundervisningen på grundnivå kan göras mer meningsfull för studenter. I intervjuer med fem doktorander och en masterstudent som just skulle påbörja sina doktorandstudier, framkom tydligt att alla hade saknat tydliga förklaringar av kemiska fenomen på grundutbildningen och att förståelse kom först långt senare, under kurser på avancerad nivå. Det kan vara svårt för studenter att formulera och uppskatta förklaringar tidigt på grundutbildningen eftersom kemiska förklaringar ofta bygger på en bred kunskapsbas som studenterna inte har utvecklat än. Denna studie argumenterar för att kemiundervisningen även behöver uppmärksamma andra syften än förklaringar, syften som är relaterade till andra saker som kemister gör utöver att förklara den kemiska världen. Genom att engageras i andra, mer närliggande syften, kan studenterna få möjlighet att börja använda nya kemiska begrepp i sammanhang som de kan hantera redan innan de har förställt begreppen fullständigt. Detta kan in sin tur göra kemiundervisningen på grundnivå mer meningsfull för studenter, långt innan de är redo att använda begreppen för att formulera avancerade förklaringar av kemiska företeelser.

kemisk förklaring om de görs kontinuerliga med varandra. Denna tentativa modell syftar till att stödja studenters förklaringar från att endast innehålla antropomorfismer till förklaringar där antropomorfismer kan göras kontinuerliga med relevanta tekniska relationer. Dessutom antyder modellen att läraren ibland skulle kunna betona de antropomorfismer som studenterna spontant inför och föreslå ytterligare antropomorfismer för att hjälpa studenterna att förstå och förklara kemiska begrepp och fenomen. I den fjärde studien formulerade jag hypteser om vilka andra syften än förklaringar som kan behöva uppmärksammas i grundkurser i kemi, särskilt för att lärare ska kunna stödja progression i klassrummet. Den typen av progression kallas ’progression in handling’ vilket syftar till att engagera studenter i aktiviteter där de kan se meningen med kemiska begrepp genom att använda dem för att förstå och förklara kemiska begrepp. Modellen presenteras genom några exempel på aktiviteter där elektronegativitetsbegreppet kan användas för specifika syften. Ett sådant syfte kan vara att förutsäga olika egenskaper hos molekyler istället för att förklara varför vissa molekyler har specifika egenskaper eller varför de reagerar som de gör. Exempelvis kan elektronegativitetsvärdet användas för att förutsäga vilken typ av bindning som kommer att bildas mellan två element. Därefter kan elektronegativitetsvärdet användas för att bestämma elektrondensitet för att förutsäga hur molekyler kommer att reagera med varandra. På det sättet får studenterna möjlighet att börja använda grundläggande kemiska begrepp på ett mer meningsfullt sätt.

Resultaten från de fyra studierna bidrar alla med aspekter för att ge svar på den övergripande frågan om hur kemiundervisningen på grundnivå kan stödjas för att göra kemin mer begriplig och meningsfull för studenter. Sammanfattningsvis visar resultaten vikten av att beakta de kunskaper, erfarenheter och syften som studenter och lärare inför under en lärandeaktivitet och hur de kan göras kontinuerliga med varandra. Resultaten visar hur studenternas kunskaper och erfarenheter kan göras kontinuerliga med de olika stegen i en procedur, hur olika syften kan göras kontinuerliga med varandra och hur andra syften än förklaringar kan behövas för att stödja progression i kemiklassrummet. De föreslagna modellerna syftar till att hjälpa lärare med planering, genomförande och utvärdering av undervisningen för att stödja kontinuitet och progression i klassrummet och därmed göra keminnehållet mer begripligt och meningsfullt. På ett övergripande plan visar avhandlingen att kunskap om de olika interaktionerna mellan studenter, innehållet och lärare är viktig och nödvändig genom att den kan utgöra grund för praktiskt användbara didaktiska modeller och hypoteser för att stödja studenter och lärare i kemiklassrummet.


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