Relationships between models used for teaching chemistry and those expressed by students
RELATIONSHIPS BETWEEN MODELS USED FOR TEACHING CHEMISTRY AND THOSE EXPRESSED BY STUDENTS

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Abstract

This thesis is focused upon chemistry as a school subject and students’ interpretations and use of formally introduced teaching models. To explore students’ developing repertoire of chemical models, a longitudinal interview study was undertaken spanning the first year of upper secondary school chemistry. *Matter in its different states* was selected as the target framework for this study. The studies were undertaken from a constructivist paradigm where learning is seen as the individuals’ active interpretation of the environment (here a learning environment). Data was collected using a technique referred to as “interviews about instances and events”, a method especially developed to explore students’ understanding. Data analysis was performed using a method informed by grounded theory. The results presented are derived from both generalisations of groups of students as well as a case study describing an individual learner’s interpretation of formal content. The results obtained demonstrated that the formal teaching models provided to the students included in this study were not sufficient to afford them a coherent framework of matter in its different states or for chemical bonding. Instead, students’ expressed models of matter and phase change were to a high degree dependent on electron movement (Paper I), anthropomorphism (Paper II) and, for one student, a mechanistic approach based on small particles and gravitation (Paper III). The results from this study place focus on the importance of learners’ prior learning (previous experiences) and the need to develop a coherent framework of formal teaching models for the nature of matter and phase change.

**Keywords:** chemistry didactics, particulate nature of matter, phase transition, student expressed models, Swedish school, teaching models
Till min familj
## Table of Contents

LIST OF PUBLICATIONS .................................................................................. 3  
Introduction ........................................................................................................... 5  
Different types of chemical models ................................................................. 6  
  Scientific models .............................................................................................. 6  
  Educational models ......................................................................................... 6  
Learning as an individual and social event ....................................................... 7  
Using teaching models as tools for deriving different types of explanations ...9  
  Descriptive explanations ............................................................................... 10  
  Causal explanations ...................................................................................... 10  
  Students expressed models .......................................................................... 13  
Some general challenges associated with chemistry’s teaching models .....13  
  The gap between student experience and the abstract level of teaching ..13  
Animism, anthropomorphism and teleology .................................................... 15  
Analogy ............................................................................................................. 15  
Technological teaching tools ........................................................................... 16  
The chemical bonding framework addressed in this study & some of its  
specific challenges......................................................................................... 17  
Previous suggestions for improving the framework of chemical bonding....20  
Context of this study ....................................................................................... 24  
Educational models .......................................................................................... 24  
  Swedish national curriculum ....................................................................... 24  
  The general structure of Swedish upper high school chemistry .............. 27  
  The chemical bonding framework used in this study -general aspects ...28  
  Specific models of the framework ............................................................... 29  
Aim of this study ............................................................................................... 33  
Method .............................................................................................................. 34  
  Data collection ............................................................................................... 36  
  Student context of the first study ................................................................. 38  
  Student context of the second study ............................................................ 38  
  Interview design ............................................................................................ 39  
  Design of interview questions for the first study ...................................... 40  
  Design of interview questions for the second study .................................. 42  
  Data analyses ............................................................................................... 44  
Summary of results and general discussion .................................................. 61  
Conclusion ....................................................................................................... 63  
  Possible consequences for chemistry teaching .......................................... 63  
Future outlook .................................................................................................. 67  
  Acknowledgements ..................................................................................... 68  
References ....................................................................................................... 69
LIST OF PUBLICATIONS

This thesis is based on the following articles (all published papers are reproduced with permission from the respective publisher):


Additional published work outside the scope of this thesis:


INTRODUCTION

This thesis is focused on the learning of chemistry as an upper secondary school subject, and in particular the relationship between the formal educational models employed in chemistry teaching and students’ expressed models. To explore this relationship, students’ developing repertoires of models for the different states of matter and for phase transitions have been studied.

The studies were undertaken from a constructivist paradigm, and were based upon a longitudinal interview study. Data were collected using a technique referred to as “interviews about instances and events”, an interview strategy that was developed for the exploration of an individual’s understanding (White and Gunstone, 1992). Data were analysed using a method informed by grounded theory. This method of analysis provides the researcher with tools for interpreting, conceptualising and describing data in more general perspectives (Paper I and II). The choice of conceptualising data in a more general manner was made because common features can reflect characteristics derived from the theoretical content of the chemistry course. Although the conceptualisation of data in this manner can provide valuable methodological information, it does not afford significant insight concerning the nature of the individuals’ interpretations. To explore the interrelatedness and complexity of a specific individual’s learning, a case study was performed (Paper III).

The introduction to this thesis has been divided into two parts. This first describes the complexity, interconnections and use of the many theoretical models of chemistry related to this study, in particular the models used in teaching (Taber, 2002, p33). The second summarises previous research on student interpretations of models and presents the formal subject specific models employed in chemistry teaching.
Different types of chemical models

Both chemistry as a science, and chemistry as a school subject are based on models, as described by Oversby (2000, p227): “The discipline of chemistry occupies a special place in science since few of the macroscopic observations can be understood without the recourse to sub-microscopic representations or models”. Accordingly, the learning of chemistry necessitates the development of both an understanding of chemical models as well as an understanding of their use in specific contexts. This is a process that is challenging for both teachers and students since it is multifaceted, and often time consuming.

The chemical models in focus here can be generalised and separated into three different categories. These different categories, which are differentiated through their intent and use, are referred to as “scientific models, educational models” and “students' expressed models” (Gilbert, 2005). With scientific models as a background, educators derive simpler models for educational purposes. Here such models are referred to as educational models. The third class of models, categorised as students’ own expressed models, is in this study used for gaining insight in to students’ growing repertoire of models, and their use of educational models.

Scientific models

Scientific models are used for describing, and presenting scientific findings and are intended for the scientific community. These scientific models develop, and their use changes progressively over time. The succession of models used for explanations and predictions can be seen even over relatively short time spans. A good historical example of this progression can be found in the development of models of the atom. In J. J. Thompson’s model for the atom that he presented in 1904 (Thompson), the atom was seen as consisting of a mass of positive charges with electrons imbedded within. This model was, after only a little less then a decade, succeeded by Rutherford’s model of the atom (Rutherford, 1911). Here, the atom was seen as having a central electrical charge with equal but opposite charges surrounding it. Rutherford’s model is regarded as the basis of our present atomic models.

Educational models

The second category, educational models, is comprised of a manifold of models under the following headings: curricula models, consensus target models and teaching models all intended for educational purposes. These models are all altered through interpretation. Curriculum developers interpret scientific
models and transform them into school science curricula, i.e. curricula models (Justi & Gilbert, 2000). Textbook writers then interpret the curricula models and these are subsequently transformed into consensus target models (Gilbert, 2005) designed for different educational levels. These consensus target models are commonly used for learners at different levels of education and can be deduced from textbooks. Examples of consensus target models from chemistry at this educational level (upper secondary high school) are; the general composition of an atom and placing of its subatomic particles or symbolic representations, for example “chemical symbols, formulas and equations” (Talanquer, 2007). Within some parts of chemistry, textbooks make more then one-consensus target model available to the learner. The atom is one example where multiple consensus models frequently occur, especially when the historic atomic models are addressed (Justi & Gilbert, 1999). Acids and bases may also be described using different models such as the Arrhenius model or the expanded definitions provided by the Lowry-Bronsted model. Dealing with multiple models can be difficult for both teacher and student, and has been found to sometimes lead to “model confusion” (Carr, 1984) of target models within textbooks, or lead to “hybrid” teaching models (Justi & Gilbert, 1999). Teachers subsequently interpret the consensus target models and transform them into teaching models. Teaching models can involve yet further simplifications such as teaching analogies that are “illustrations of an idea, object, event, process or system” (Gilbert, 2005, p31). Teaching models can utilise phenomena from the macroscopic to sub-microscopic levels (Johnstone, 1993) are interrelated into “frameworks”, i.e. “a web of ideas within a particular scientific subject” (Watts & Taber, 1996).

**Learning as an individual and social event**

Learning is here viewed from the perspective of constructivism, which is a learning theory that originally stems from Piaget (Piaget, 1969). Learning is within this perspective viewed as an “active process of constructing personal knowledge” (Taber, 2009b) when engaging with the environment. This perspective also includes the social and cultural aspects of a learning situation as proposed by Vygotskij (1999). Studies derived from a learning environment include factors such as “the individual's conceptual ecology […] in a social context” Taber (2009b, p330), where the social context is a multifaceted domain including factors such as classroom, peers, artefacts, media and family. The choice to explore formal content and student interpretations thereof was therefore made out of professional interest. When adopting this research perspective some initial assumptions regarding learning are necessary Taber (2009b, p123):
Learning science is an active process of constructing personal knowledge.

Learners come to science learning with existing ideas about many natural phenomena.

The learner’s existing ideas have consequence for the learning of science.

It is possible to teach science more efficiently if account is taken of the learners existing ideas.

Knowledge is represented in the brain as a conceptual structure.

Learners’ conceptual structures inhibit both commonalities and idiosyncratic features.

It is possible to meaningfully model learners’ conceptual structures.

The formal content of chemistry education includes a veritable plethora of abstract theoretical models (above), and learning them “relies very much on student engagement with the concepts” (De Berg, 2006). It is here assumed that students had not previously been exposed to all models examined in this study. Accordingly, commonalities in student answers can be attributed to experience from formal teaching.

Previous research in the field of science education shows that students often maintain their prior understanding after formal school education (Driver & Ericsson, 1983). This results in formal models commonly being used alongside, and sometimes combined with, previous understanding. Research focusing on discrepancies between expert and novice ways to solve scientific problems has provided important insights into learning (Chi, Feltovich & Glaser, 1981). A significant finding from this research was that experts apply scientific principles to abstract representations, they can easily shift between different levels of abstraction, and the expert has a structured approach towards problem solving that includes a multitude of connections between models/concepts. In contrast, novice learners use “isolated definitions” (Hsu, 2006) and have a more shallow knowledge of concepts. As learning progresses the novice learners’ concepts/models become more structured and integrated (Glaser, 1989). Within this thesis learning is seen as the evolution of the student model repertoire.
Using teaching models as tools for deriving different types of explanations

The term teaching model is, within the context of this thesis, used in a general sense: a theoretical construct intended for educational purposes. All theoretical constructs are seen as models. Accordingly, within this thesis no differentiation is made between what can be defined as a law, for example Coulomb's law, or a visually depicted image, for example, that of an atom. The choice of using this strategy was made in order to simplify the description of the content of chemistry high school education.

Teaching models are used for different purposes at different educational levels and can be seen as tools for deriving different types of explanations. Initially they may be used for simple descriptions of, for example, atomic structure. As teaching progresses these simple descriptions, their interrelations and connecting ideas are used as bases for forming different types of explanations. Gilbert & Boulter (2000, p196) defined different types of explanations namely; intentional explanations, descriptive explanations, interpretive explanations and causal explanations. Although the definitions presented by Gilbert were formulated for specifying explanations caused by specific research questions, they are here seen of value for both science as well as science education, since they can be used as tools for distinguishing between some of the different types of explanations that are formally introduced to the learners. Gilbert define an intentional explanation as the response to the question "why is this phenomenon being explained?" The interpretative explanation provides the answer to the question "of what is the phenomenon composed?" and the predictive explanation answers the question "how will the phenomenon behave under other, specified, conditions?" (Gilbert & Boulter, 2000, p197). The above explanations are here seen as having a broader content than students would encounter in a school setting.

The remaining two, namely descriptive and causal explanations (expanded upon below), are here used as tools to characterise some of the different types of explanations that students encounter in school. They were selected in order to place focus on the use of the different types of teaching models at this introductory level. This was considered necessary, as the Swedish national grading criteria that frame the learning situation for the students who participated in this study require differentiating between description and explanation.
Descriptive explanations

The general focus of chemistry “is matter and its transformations” (Liu & Lesniak, 2004). As the term matter includes almost everything in our world, it is necessary to make initial categorisations with well-defined descriptions of what they include. Many of these preliminary categorisations and descriptions can be undertaken as observations drawn from the visual macro-level. Other categorisations are made on the sub-microscopic-level. A descriptive explanation is defined by Gilbert et al. (2000, p196) as, “a response to the question, ‘what are the properties of this phenomenon?’ ” Many of the models presented to learners at compulsory school level are classifications and fall under this category of explanation. Initially, they may be macro-level classifications such as the visual classification of acids, e.g. through the colour change of indicators, or their effects on metals. Classifying and differentiating between the different states of matter can also be generalised to a visual macro-level view in terms of whether they are associated with a change, e.g. in shape and volume:

> Matter in the solid state maintains its shape and volume regardless of the container it is placed in. Liquids when placed in a container change their shape to that of the container, but their volume remains the same. Gases, when placed in a container, change shape and volume to fit that of the container (paraphrased and translated from Andersson et al., 2003).

As teaching progresses other classifications and definitions on sub-microscopic levels are introduced, for example, specific atoms, characterized by properties, the number of protons within the nucleus. Atoms with the same number of protons in the nucleus are given a label, a chemical “symbol” (Talanquer, 2007, p858), such as the letter H for hydrogen. Descriptive explanations for chemical categories are an important part of the chemistry teacher’s path for guiding students towards causal explanations.

Causal explanations

A causal explanation is defined as a response to the question “why does the phenomenon behave as it does?” (Gilbert et al., 2000, p1996). Causal explanations holding scientific status are not what are referred to here, since focus is placed on educational models for upper secondary school level. A causal explanation in chemistry education requires the use of many models as support for answering the why question. A similar path of models, “stories” (Driver et al., 1996, p114) or “frameworks” (Watts & Taber, 1996) supports even the experienced chemist’s answer to a why question. The frameworks formally introduced to students are composed of many descriptive explanations with their respective categorisations. A schematic and general
A representation of a framework for chemical bonding is presented below in Figure 1.

Figure 1. Schematic representation of some of the many models included in a general “framework” for chemical bonding (Andersson et al., 2003).

Figure 2. Concept map presenting some of the descriptions included in the model of the atom (Andersson et al., 2003).
To further emphasise the inherent complexity of the models included in the framework of chemical bonding, one of the models included above, that of the atom, is further explored above in Figure 2.

The intention here is not to provide a full account of descriptions and models included in answering a *why* question. Instead the aim is to display the interrelated nature of the multitude of formal models introduced to the students included in this study. If the question “Why is a sodium chloride crystal at room temperature in the solid state?” was posed to a chemistry teacher of the upper secondary level, the response could include; the chemical classification and symbol for, sodium and chloride atoms, a descriptive model of the general atom and its electron configuration, knowledge of the construct of atomic numbers and neutrality of the periodic table, a model of electron formula, the octet rule, electronegativity, the descriptive classification of ions to visualise the electrostatic interactions and knowledge of the relative strength of the ionic bond.

Progressing from descriptive explanations and definitions to causal explanations is by no means a straightforward undertaking, neither for students nor teachers. It is also a time consuming process, since there are many models involved in forming a causal explanation. Driver et al., pointed to an important issue when they wrote “we learn from experience what counts as an explanation” (Driver et al., 1996, p26) and thereby placed focus on the importance of introducing students to the nature of “scientific knowledge claims”. This is an issue that is directly related to a student’s own epistemological reasoning, i.e. “what counts as an explanation?” Driver et al. (1996) focused attention on students’ epistemological reasoning in science and elicited three different levels of reasoning with regard to students’ explanations, namely:

1. “Phenomenon-based reasoning: students showed no distinction between description and explanation”  
2. “Relation–based reasoning: explanation is viewed as a relation between features of the phenomena”  
3. “Model based-reasoning: explanations’ involve coherent stories involving posited theoretical entities” (Driver et al., 1996, p113)

The issue of guiding students from descriptive explanations to causal explanations becomes inherently important when applied to chemistry education. The extended period of time that elapses between the students receiving initial descriptive explanations and the subsequent introduction to
causal explanations may leave students in an “explanatory vacuum” (Taber & Kind, 2005) were students’ “epistemic hunger” (Paper II) may cause them to construe transitional causal explanations that deviate from the intended.

**Students expressed models**

It is intended that students learn the formally introduced teaching models and their respective frameworks so that they become of use when forming explanations. The learning of teaching models can be seen as yet another interpretation. Students’ own interpretations of teaching models, presented both visually and verbally are here referred to as students “expressed models” (Gilbert, 2005), which represents the third category of models.

**Some general challenges associated with chemistry’s teaching models**

Extensive research in this field over recent decades has identified further challenges for chemistry teaching in addition to those described above. For chemistry in general many of the problematic issues can be identified as a mismatch between the abstract nature of teaching models and the experienced macro-level view of students (Gabel, 1999). In their attempt to make sense of formally introduced theoretical models, students not only make use of previous experiences, they also make their own assumptions (Driver, 1983). This possible mismatch between the abstract nature of teaching models and the experienced macro-level view of students has gained much attention within educational science (Talanquer, 2006). A number of ways to bridge the gap between experience and theoretical models have been suggested. A summary of some of these conclusions is provided here. Importantly, although previous research in the field of student reasoning or students’ explanations has been performed at different educational levels and in varying educational settings, commonalities in student reasoning can be found in researchers interpretations of data.

**The gap between student experience and the abstract level of teaching**

The “major barrier to understanding chemistry”, which Gabel (1999) defined as being the abstract level of educational models, is well supported in the scientific literature. Research findings from many different educational settings, including students of different ages, show how students commonly
place their own experiences of the world, on to the sub-microscopic level of teaching models:

- Students often perceive matter as continuous and static (Novik & Nussbaum, 1981; Andersson, 1990; Renström, Andersson & Marton, 1990).

- Students (age 14-15) think of soft substances as made up of soft particles (Andersson, 1990, p67).

- Students suggest that copper atoms are malleable and have colour (Ben-Zvi et al., 1986).

These results display the difficulty of making the transition between experienced macro-level phenomena and abstract sub-microscopic teaching models. There are numerous examples provided in the literature where students’ expressed models do not match the intended teaching target model. These phenomena have been given many general labels, such as: alternative explanations, alternative conceptions, misconceptions, naïve theories and common sense reasoning (see Özmen, 2004, for a more complete list). For example, observations have been reported for student understanding and use of specific models, such as for the atom (Griffiths & Preston, 1992; Cros et al., 1986). Furthermore, Taber (2002) elicited the interrelated nature of a student alternative conceptual framework through the “the octet framework”. Subsequently, Talanquer (2006) derived “the common-sense framework” from an analysis of research reports concerning students’ alternative conceptions. Talanquer found this framework to be useful tool for describing student reasoning patterns. Bridging the gap between the student experienced world and the abstract level of chemical models is indeed a challenge, where the various means to resolve this issue, for example the use of analogies, can in themselves become a hindrance.

Through a survey of current literature one can identify four possible general strategies for bridging the gap between the macroscopic and sub-microscopic models of chemistry: anthropomorphic and teleological formulations (Taber & Watts, 1996; Talanquer, 2007), analogy (for example: Aubusson, Harrison & Ritchie, 2006, p6), development of teaching models (Levy Nahum et al., 2008; Taber, 2001b) and technology-based approaches (for example: Chang et al., 2010).
Animism, anthropomorphism and teleology

One common way for textbook writers to approach the issue of bridging the gap is through the use of anthropomorphic and teleological formulations (Taber & Watts, 1996; Talanquer, 2007). This approach can be seen as a two-edged sword as anthropomorphism, teleology and animism are also common features in student reasoning (Zohar & Ginossar, 1996 p680). Animism was initially a concept described by Piaget as “the tendency among children to consider things as living and conscious” (Quote from Looft & Bartz, 1969, p1 - derived from Piaget, 1933). Anthropomorphism is here the term used when things are not only considered living, but also as having human qualities, such as emotions and logic. In an analysis of chemistry textbooks (college level) performed by Talanquer (2007) it was found that anthropomorphism was commonly used in descriptions like “atoms and molecules donate, share, attack, want, like, try or are happy or are satisfied” Talanquer, (2007). Anthropomorphism viewed in this manner may give “apparent explanatory value” (Zohar & Ginossar, 1996, p680) and its use has been discussed in the scientific literature. For example, Taber and Watts (1996) focused on student use of anthropomorphism. The authors differentiated between “strong and weak anthropomorphism” (Taber & Watts, 1996). Weak anthropomorphism were used to define the occasions’ were students used anthropomorphism as a temporary explanation that later progressed towards more suitable teaching models and their relationships. Strong anthropomorphism was used for describing the situation where students used anthropomorphism as a satisfactory explanation that was not replaced later on.

The term teleology is used when things and processes are also attributed a conscious purpose, or a “divine direction”. Talanquer (2007) found that while teleological explanations were found to be less frequent in textbooks, they were mainly found in explanations concerning transformations and laws for predictions were the system “strives to become more stable, or reach equilibrium”. Talanquer also suggests that these types of formulations have heuristic value and aid students in structuring their knowledge, “help the students organise their knowledge around major ideas with significant explanatory and predictive power”.

Analogy

Another strategy used to bridge the gap between macro- and sub-microscopic levels is the use of analogy. Analogy in its simplest form can be defined as when “A is said to be like B” (Aubusson, Harrison & Ritchie, 2006). The difference between analogy and the previously mentioned animism,
anthropomorphism and teleological formulations is based in, use. Whereas
animism, anthropomorphism and teleological formulations are commonly
used as the cause (driving force) behind chemical processes such as chemical
reactions, analogy is used for illustrating an event. The role of analogies has
been frequently discussed in scientific literature. Analogies are by some
authors considered to be valuable links between student experience models and
abstract teaching models (Harrison, 2001). Other authors see analogies as
possible obstacles for learning (Thiele & Treagust, 1994), since they may
generate a way of understanding that deviates from the intended. Analogy is
also both commonly used by teachers as well as generated by the students
themselves (Harrison & Treagust, 2001). To aid teachers in their use of
analogy to bridge the gap between the abstract sub-microscopic level of
teaching models and students’ experienced macro-level world views, Glynn
(1994) suggested six steps on the path towards a “Teaching-with-Analogies
Model”:

1. Introduce target model.
2. Cue retrieval of analog concept.
3. Identify relevant features of target and analog.
4. Map similarities between target and analog.
5. Indicate where analogy breaks down.
6. Draw conclusions.

Other authors, for example Harrison and Treagust (2001), identified student
own use of analogies derived from inquiry-based learning. The authors place
emphasis on analogy as a powerful tool for structuring knowledge and
conclude that good examples of analogy may be derived from “the history of
scientific discovery” (Harrison & Treagust, 2001).

Technological teaching tools
As technology advances more practical approaches towards bridging the gap
between the levels of chemistry have become available. Advances in visualizing
the sub-microscopic level have been made possible through the use of
computer-based technology. The rapid technological development of the last
decades has made a wide variety of resources available for education. Butler
Songer (2007) differentiates between what is referred to as digital resources and
cognitive tools. Digital resources are defined as “any computer available source
containing facts, perspectives, or information of a topic of interests […] often
contain valuable information such as science information presented in the
form of text, pictures, simulations, video or other interactive formats”.
Cognitive tools, on the other hand, are “a computer available information
source or resource presenting focused information specifically tailored for particular learning goals on a particular target audience”. Butler Songer (2007) also defines areas where technology can play an important role, such as:

- Critical thinking - aided by visualisations, simulations and modelling.
- Critical evaluation - online discussions.
- Formulate knowledge - online scaffolding tools.
- Analysing data - computer based collection and analysis.

Computerised molecular modelling (CMM) was used by Barnea and Dori (1999) in an attempt to aid students in visualising molecules as three-dimensional. Three-dimensional visualisations are an important part of the framework for chemical bonding and results showed that CMM increased student understanding of the concept of molecular models, and even provided an enhancement of their spatial perception abilities, Chang et al. (2009) used an animation tool where students could design and peer evaluate animations concerning the particulate nature of matter. Three student groups were presented with three different tasks, the first group was provided with the task of designing, evaluating and interpreting animations while the second group designed and interpreted animations. The third group evaluated premade animations. Pre- and post-tests were performed and evaluated and results showed that the combination of all three tasks (designing, evaluating and interpreting animations) was an effective way of improving students’ learning.

Peter Atkins (2011) goes further, and predicts the future of science education in the form of further developed interactive e-texts; “three dimensional displays, animations and audio and video content” which could include selection of “tutorial wizards” or “avatars”. He suggests that such tools in combination with online social networking would have the possibility to bring good science education to young people anywhere in the world. Indeed there are many reports that show that computer based visualisations/modelling/interactive tools improve student understanding and three-dimensional visualisation skills in chemical education (Barnea & Dori, 1999; Chang et al., 2010; Ardac & Akaygun, 2003; Papageorgiou et al., 2008).

The chemical bonding framework addressed in this study & some of its specific challenges

Due to the significant volume of research in the field it is possible to identify more specific and detailed challenges for students and teachers using the
teaching models included in the “framework” (Taber & Watts, 1996) of chemical bonding. In this study, the specific models addressed are: the atom model, and models for chemical bonding, including intra-molecular bonding (the octet rule, electronegativity, Valence Shell Electron Pair Repulsion Model (VSEPR)-model) and some types of inter-molecular bonding (dipole-dipole, van der Waals and Hydrogen bonding).

The atom
The role of the atomic model in teaching has long been the topic of discussion. Some authors see it as playing “a central role” (Ben-Zvi, 1986) others (Taber, 2003) have referred to it as a “conceptual fossil”.

Sub-atomic particles and their relative charge have also been found to be a difficult area for students. It is not uncommon for students to fail to apply electrostatic interactions to sub-atomic particles (Taber, 1997) or even to make use of electrostatic interactions in other ways then the intended, for example by viewing the forming of bonding electron pairs as implausible, as they would repel (Taber, 2002). Word use has also been shown to be misleading. Schmidt (1991) defined what he referred to as a “hidden persuader” when finding that students saw the neutron as have a neutralising effect. Other issues relating to the structure, shape and size of atoms can also be found, for example Park & Light (2008) identified several issues such as atoms being perceived as: being two dimensional, all of similar size, animistic, larger then molecules and their size being affected by heat. Studies show that when the initial introduction to chemistry places focus on the atom as a teaching model, it leads learners towards “an atomic ontology” (Taber, 2003).

The consequences of the atomic ontology are manifest in various forms. If students originate from an atomic perspective instead of a molecular perspective they even tend to place the octet rule as the basis for motivating chemical reactivity. This approach may also cause students to look for the history of molecules, where students attempt to establish the first reaction i.e. when the molecule was formed from its original atomic constituents (Taber, 1997). Students using the “atomic ontology” can perceive a chemical reaction as the formation of single ions (Taber, 2001a). Formation of single ions can in turn lead to ionic-bonding involving the interaction of two ions which, in turn, leads to the formation of an ion-derived molecule (Butts & Smith, 1987). The atomic ontology when used in conjunction with the octet structure can also impact students’ views of chemical stability (Taber, 2009a).
Chemical bonding

Chemical bonding is of critical importance in chemistry and is seen as “essential for understanding almost every other topic in chemistry” (Levy Nahum et al., 2008). A summary of some of the many challenges for this framework is provided below.

The octet rule

The octet rule is an important model for initial predictions of intra-molecular bonding. Unfortunately, students seem to over generalise the octet rule and use it as basis for understanding inter-molecular bonding as well (Taber, 2003). Taber (1996, 1997, 2000) defined this over-generalisation as the “octet framework”. In addition the wordings used in textbooks for the introduction of the octet rule are commonly teleological or anthropomorphic in nature and formulations such as atoms “wanting, needing or striving for” are common (Taber & Watts, 1996, Talanquer, 2007). This use of teleological or anthropomorphic formulations in conjunction with the octet framework contributes to the frequently occurring use of anthropomorphism, animism and teleology in students’ explanations in related to many areas in chemistry (Paper II).

Electronegativity

Due to its general use electronegativity is an important theoretical construct used for determining partial charge distributions in intra-molecular bonds. It importance is highlighted by Boo (1998), who found that students that did not use electronegativity as part of their framework for chemical bonding failed to be able to apply any rules to chemical bonding. However, the use of electronegativity can be problematic, in particular when its use is either under- or over-emphasised (Levy Nahum et al., 2008).

Valence shell electron pair repulsion (VSEPR)-model

The VSEPR-model constitutes a tool for determining molecular geometry, something that in combination with electronegativity determines partial charge of a molecule. Peterson & Treagust (1989) identified two key problems that can arise in association with student use of VSEPR. Firstly, students do not take non-bonding electron pairs into account when determining molecular shape, and secondly, that students use electronegativity to understand repulsion whereby non-bonding electrons are ignored and repulsion between covalent bonded entities is steered by the polarisation of the covalent bonds.
Types of bonding

One problematic aspects of understanding chemical bonding is the nature and nomenclature for the various types of chemical bond. Peterson et al. (1986), for example, found a number of student alternative conceptions in conjunction with covalent bonding, in particular that valence electrons in covalent bonds are always equally shared, and that the polarity of the bond is due to the number of valence electrons in the bond. Boo (1998) described how some of his students saw covalent bonding, irrespective of bond order (single, double, triple), as the sharing of only one pair of electrons. Taber (2001) found that some students view the metallic bond as either covalent or ionic, not a real bond, no bonding, or as a sea of electrons. Taber (1997) also observed that students often view bonding as mainly being of two types, namely ionic- and covalent bonding, which can complicate the introduction of inter-molecular bonding. Taber (2002) found that inter-molecular bonding was commonly considered by students to be interactions that are due to “just forces” thereby distinguishing inter-molecular bonding from “proper” chemical bonding. Hydrogen bonding is also an area of confusion for students and it has been found that hydrogen bonding is commonly seen as a bond between hydrogen and oxygen in a molecule (Taber, 2002).

Previous suggestions for improving the framework of chemical bonding

Taber (2001) and Levy Nahum et al. (2008) (expanded upon below) have suggested implementation of altered frameworks, especially designed to help students avoid some of the previously described challenges. Commonalities in the suggested altered frameworks included recommended focus on molecules and lattice structures with an emphasis on electrostatic interactions. Taber (1996, 1997, 2000) suggests, based upon empirical studies examining students' use of the “atomic ontology”, that ionic and molecular lattices may be a better point of origin for the introduction to chemistry, and that lattices can be introduced as “systems of cores (positively charged spheres comprising the nuclei surrounded by symmetrical electron density) and valence electrons” (Taber, 2001b). Although this alternate approach has not yet been implemented, it offers an alternative to the traditional atomic approach, and could aid students' appreciation of electrostatic interactions and even provide them with a more scientific view of matter as composed of a system of particles, Figure 3. This framework has three major focal points; physical principles (e.g. Coulomb's law), avoiding emphasis of atoms and bonding introduced as an electrical concept.
Levy Nahum et al. (2008) also suggested a new framework for introducing chemical bonding namely the “bottom-up framework”. This framework is based on five steps with a focus on Coulombic forces and chemical stability expressed as being reduced energy levels. The most significant difference between this framework and that suggested by Taber (2001) is that the “Bottom-up framework” takes its stance in a single atom, Figure 4.

Figure 3. An alternative chemical ontology (adapted from Taber, 2001).

Figure 4. The “bottom-up framework” (adapted from Levy Nahum et al., 2008).
In the bottom-up framework of Levy Nahum et al., bonding is introduced from the perspective of nuclei held together with proton-electron attractions. Stability is also immediately introduced, as a reduced energy level instead of using the octet framework - where stability is more or less implicitly introduced through the concept of “a full electron shell” (Taber, 2000). Electrons are introduced from the perspective of their wave character and with an emphasis on probability clouds. The framework sets out to introduce bonding as a “continuum approach” of related concepts instead of a set of different types of bonding, Figure 5. The traditional separation between intra- and inter-molecular bonding can complicate the understanding of the relationships between bond strengths. Both suggestions can be useful for avoiding the previously addressed “just forces” (Taber, 2002) conjecture.

Figure 5. A continuous scale of bond strengths (adapted from Levy Nahum et al., 2008).

The advantages of the bottom-up approach (Levy Nahum et al., 2008) include: the possibility to show different models (valence bond and molecular orbital theory) for chemical bonding, allowing an immediate emphasis on electrostatic interactions, stability and focus on the nature of the chemical bond. Authors suggest that this approach may avoid focus on the octet rule and can also contribute to minimize the extended period of time that usually elapses between the introduction to intra-molecular and inter-molecular bonding thus minimizing the resultant explanatory vacuum (Taber, 2005) regarding chemical bonding for students (Levy Nahum et al. 2008). Presenting one single framework for students may also be a way to reduce “model confusion” (Carr, 1984). However, Levy Nahum et al. also suggest that the initial abstract level of the “bottom-up framework” can present some difficulties for learners.
While much of the research performed in this field has been focused on student misconceptions or alternative conceptions, only a few studies have reported on students’ alternative conceptual frameworks. This thesis places focus on the content of aspects of the chemistry curricula at the upper high school level in Sweden, in particular in terms of the teaching models used in association with the framework of chemical bonding and phase change, and how these teaching models contrast with those used by students. The results presented here are of importance for our appreciation of the learning process in chemistry, and may provide valuable support for curriculum developers, textbook writers, teachers and students at different educational levels.
CONTEX OF THIS STUDY

As the aim of this study is to explore students’ developing models of matter and phase change at upper secondary school level, learning, within this thesis, is seen as students’ own growing repertoire of models within the discipline of chemistry. Such an approach places a focus on the content of the particular learning situation.

Educational models

Swedish national curriculum

The Swedish national curriculum that framed the learning situation for the teachers and students included in this study was Lpö-94 (The Swedish national agency for education, 2001). This curriculum was formulated in a prescriptive nature with the intention to provide schools and teachers with the necessary flexibility to structure their teaching at the individual student level. The national curriculum that prevailed over the course of the studies underlying this thesis (The Swedish national agency for education, 2001) includes three sets of guidelines:

- "goals to aim for", which are outline the minimum content level for the teaching of a subject.
- "goals to attain", which define the minimum level of knowledge to be attained.
- "grading criteria".

With respect to the "goals to aim for", the official English version of the national curriculum for chemistry (The Swedish national agency for education, 2001) states (extracts of relevance to this thesis):

*The school in its teaching should aim to ensure that pupils:*

- develop an understanding of the relationship between structure, properties and functions of chemical elements, as well as why chemical reactions take place,
develop their ability, on the basis of the theories and models of chemistry and their own discoveries, to reflect over observations in their surrounding environment

The “goals to attain”, and in particular those relevant to the aspects of upper high school chemistry examined here, are formulated as follows:

Pupils should:

- Be able to describe how models of different types of chemical bonding are based on the atom's electron structure and be able to relate the properties of elements to type of bonding and its strength, as well as to the structure of the element,

- Have familiarity with and be able to discuss how electromagnetic radiation interacts with matter

- Have familiarity with some basic elements, chemical compounds and modern materials, their properties, and occurrence and processes, as well as their importance e.g. on the earth's crust or in different areas of society

Evaluating goal fulfilment is performed on an individual basis. The national syllabus states that “at each school and in each class the teacher must interpret the national syllabuses and together with the pupils plan and evaluate teaching on the basis of the pupils preconditions, experiences, interests and needs” (The Swedish national agency for education, 2001). Further specifications regarding content can be found in the national grading criteria as described below (italics have been added for emphasis):

Criteria for pass

Pupils use concepts, models and formulae to describe phenomena and chemical processes.
Pupils carry out experiments and investigate tasks in accordance with instruction, and use appropriate laboratory equipment, as well as apply existing safety provision.
Pupils present their work and co-operate in interpreting results and formulating conclusions

Criteria for pass with distinction

Pupils combine and apply their knowledge in chemistry in order to illuminate the relationship between different areas of activity in society.
Pupils work together over the choice of method and design of laboratory experiments.
Pupils process and evaluate results on the basis of theories and hypotheses set up, and carry out simple calculations with accuracy.
Criteria for pass with special distinction

Pupils integrate their knowledge in chemistry from different sub-areas in order to explain phenomena in the surrounding world.
Pupils apply scientific ways of working, plan and carry out investigatory tasks, both theoretically and in the laboratory, interpret results and evaluate conclusions, as well as contribute their own reflections.
Pupils analyse and discuss approaches to problem solving using knowledge from different fields of chemistry.

Noteworthy is the phrasing of grading criteria for pass with special distinction where the word explain is used once. Criteria for pass do not include the word describe; instead the word describe is used in conjunction with concepts and models. To visualise some of the challenges that teachers face when interpreting the national grading criteria, an interpretation of the words describe and explain is here attempted.

If, what above were defined as descriptive explanations are applied to the word describe, the criteria for pass should then be fulfilled if students can identify the properties of a phenomenon by the use of concepts, models and formulae. Definitions or examples of what can be viewed as a phenomenon are not provided within the curriculum. For pass with special distinction, students “should integrate their knowledge in chemistry from different sub-areas in order to explain phenomena in the surrounding world” (The Swedish national agency for education, 2001). Applying the definition of causal explanation to the word explain, to attain this grade would require that students here could rationalise why a phenomenon behaves as it does. The why explanation would then be supported with a framework of models.

Given the prescriptive nature of the curriculum goals, variations in interpretations of the national curriculum between teachers and schools can be found regarding content and grading. Teachers included in this study chose to turn to teacher-selected textbooks for guidance concerning course content and their structuring of this content. A practical consequence of this approach is that there were limited differences between consensus target models and teaching models for the students included in this study. Furthermore, the teachers in general upheld the timing (sequence of presentation) of the models in accordance with that employed in the textbooks. Accordingly, teaching models and the timing of their introduction can be deduced from the textbooks used.
The general structure of Swedish upper high school chemistry

Chemistry at the upper high school level is divided into two courses, Chemistry A and Chemistry B, where Chemistry A includes:

- Introduction to chemistry in general
- Chemical bonding
- Introduction to acid-base theory
- Stoichiometry
- Introduction to organic chemistry
- Gas laws and thermodynamics

Chemistry B includes, amongst other things:

- Chemical equilibria
- Further acid-base theory
- Further organic chemistry
- Biochemistry.

The chemistry courses of the classes studied here were in essence identical with respect to time allocated for teaching and general structure of content. Students were during this time participating in the first of the two chemistry courses (Chemistry A). All teachers who participated in this study chose to structure the content of the chemistry course in accordance with the outline of the course textbook. A summary of the structure, approximate timing of formally introduced concepts and timing of interview sessions are presented below (see Table 1). The total time allocated to the chemistry course was 86 h for the year. These hours were divided between laboratory exercises and theory classes so that the students received a total of 62 h of theory and 24 h of laboratory exercises over the first year. This meant that, on an average weekly basis, chemistry was for the students comprised of 2 x 40 min of theoretical classes (sometimes combined in to 90 min including a 10 min break) and 40 min of laboratory exercises (laboratory exercises’ were combined into one 80 min class every second week). Students’ voice (Jenkins, 2006) is important in Swedish schools and students are invited to participate in decision making at all levels. The extent of student impact on individual course content is in practice decided by the individual teachers. One student group was given the opportunity to decide on what weekday they wanted their written exams; the two remaining groups were given the possibility to decide the number and content span of written exams. All students included in the studies received written exams, though no final exams were performed. In one of the classes, students were offered a final exam on a voluntary basis, intended for those who wanted to improve their final grade. For the majority of students this meant that not all (first year) course content was covered in a formal final written exam.
The school year began in August for all the students included in this study (see Table 1). Students were introduced to matter and its different states early
on in the course. The introduction of the general model for the atom and the periodic table took place before chemical bonding. Intra-molecular chemical bonding was introduced in October. Focus was then turned towards stoichiometry that took the major part of two months. This was followed by the introduction to acid-base theory and organic chemistry, before progressing to inter-molecular chemical bonding, which was not introduced until April. This structuring of course content lead to that the time that had elapsed between the introduction of intra- and inter-molecular bonding was some six months. Over these six months, areas that provide many opportunities to focus on inter-molecular bonding were addressed, such as acid-base theory and its related solutions as well as ionic solutions and precipitations and not least organic chemistry. This postponement of the introduction of inter-molecular bonding left the students in an explanatory vacuum for around a half a year with regard to causal explanations of chemical bonding. It is interesting to note that concepts such as the states of matter are introduced several years earlier during compulsory school, without any presentation of inter-molecular interactions until the end of the first year of upper secondary school.

The chemical bonding framework used in this study -general aspects

The framework (Taber & Watts, 1996) or story (Driver et al., 1996, p114) for eliciting chemical bonding within an implicit and limited temperature span for the students included in this study is an approach that has been entitled, “the electrostatic model” (Coll & Teagust, 2003, p471), “the traditional approach” (Levy Nahum et al., 2008) or “folk molecular theory” (Sanchez & Martin, 2003). This “traditional approach” is, in the context of the students in study, comprised of: the different states, the general atom, specific atoms, electron configuration, electron formula, octet rule, intra-molecular-bonding (metallic, ionic, covalent, and polar covalent bonding), electronegativity, the mentioning of electrostatic interactions, some examples of molecular geometry, dipole-dipole bonding, hydrogen bonding, and van der Waals bonding (see figure 6).

Figure 6 depicts a representation of the models introduced to the students included in this study during Chemistry A. Discrepancies between the framework as outlined by Coll & Treagust (2003) and that introduced to the students included in this study are; the limited mention of electrostatic interactions (with no reference to Coulombs’ law), use of electron formulas instead of Lewis structures, and lack of introduction of the VSEPR-model.
For the students included in this study, the VSEPR-model was replaced by some examples of molecular geometry.

![Diagram of Chemistry A content](image)

**Figure 6.** Schematic representation of the content of *Chemistry A* (ovals = models included in the specific framework of chemical bonding for students included in this study, rectangles = models/areas not included).

### Specific models of the framework

The way specific models were introduced to the students included in this study is described below. This is done because specific models represent interpretations of the textbook (Andersson et al., 2003), and the descriptions also illustrate the extent to which the teachers adhere to the presentation and timing of the chemical bonding framework models included in the textbook.

**Initial introduction of matter**

The differences in states of matter for the students included in this study were initially described in a comparative manner, e.g. as differences in movement ranging from vibrations (solid state, s) to free movement (gaseous state, g), or where matter in the solid state exists in highly structured arrangements and in the vapour phase (g) with no structure present. Differences are also visualised with images (see Paper I). After this initial categorisation of solids, liquids and gases, attention was turned towards a general description of the atom.

**The atom**

Introducing an illustration of an atom to students included in this study was done by the use of the “shell model” (see Taber, De Jong, p 637). Here the atom is presented as having a central positive nucleus with negatively charged electrons surrounding it in shells designated as K, L, M and so on. The visual image presented of this model displayed both nucleus and electron shells. Much of the teachers’ emphasis was placed on electron arrangement in electron shells. An alternate image of the atom was described, aimed at
visualising electron arrangement as a “probability cloud” and illustrated with the help of an image. Focus was then turned towards electron movement between shells during energy transferral. Protons and neutrons were addressed with a focus on charge and mass.

**Electron formulae**

Electron formulae were presented using electron dots as a means to visualise valence shell electronic configurations of single atoms. The model is introduced as “a special way to write valence electrons for an atom” (Andersson et al., 2003). This model was presented by the use of electron configurations for the first ten elements in the periodic table. Electrons were placed at equal distances surrounding the chemical symbol for the elements until there were eight valence electrons arranged in four pairs surrounding the chemical symbol for Neon (Ne). Introduction to the periodic table by the use of periods and groups followed, with focus on group similarities deriving from electron configuration and reactivity.

**Octet rule**

The octet rule was for these students presented in a teleological manner as the “atoms strive to form noble gas electron configuration” (Andersson et al., 2003, p 45).

**Intra-molecular bonding**

For the students included in this study intra-molecular chemical bonding was introduced with ionic bonding and the chemical reaction between sodium (Na(s)) and chlorine (Cl₂(g)). The cause of this reaction was presented as: “it has been found that the driving force for many reactions is the atoms strive to react so that they achieve noble gas configuration” (Andersson et al., 2003, p42). This citation places the octet rule as the driving force behind many reactions, although atomic reactions are scarce. The purpose of this citation was to introduce ionic formation. This approach although introduced with sodium metal lattice and chlorine molecules, focus was swiftly turned to the electronic configuration of the individual ions.

Ionic bonding was introduced as (Andersson et al., 2003, pp44-45):

“In an ionic crystal ions with opposite charge are bonded to each other with ionic bonding”

“The explanation is that the ions in the solid substance are held in their places by the strong bonding forces”
Both of the above citations afford incomplete descriptions of the ionic bond. The first citation addresses opposite charges, but does not describe the attraction between opposite charges as being ionic bonding. The second citation uses the words strong bonding forces, but fails to define what they are. The most time consuming parts of the formal introduction to ionic crystals were chemical symbols, the nomenclature of different ionic compounds and ways to write the chemical formulae for ionic compounds composed of ions of different charge.

**Covalent/polar bonding**

Covalent bonding was introduced as an electron pair bond where covalent means “same value” and suggests that the “electron pair is shared equally between the atoms that are bonded” (Andersson et al., 2003) This definition was also used in a comparative manner when introducing polar covalent bonding: “a covalent bond where the electrons are not shared equally between the bonded atoms are called polar covalent bonding” (Andersson et al., 2003, p56). Molecular geometry was introduced using four examples of molecular structure, namely; hydrogen chloride, methane, ammonia and water.

**Electronegativity**

In order to introduce polar covalent bonding electronegativity is required. For the students included in this study electronegativity was introduced (once) as “a substance specific electronegativity value, which is a measure of the atoms capability to attract electrons” (Andersson et al., 2003, p57), and was presented in conjunction with polar covalent bonding.

**Metallic bonding**

Metallic bonding was presented as, “in a metal one or more valence electrons from each atom forms an electron cloud common to all atoms in the crystal” (Andersson et al., p61). A comparison was then made between metallic and ionic bonding with respect to malleability and electrical conductivity.

*The following 101 pages of the textbook corresponding to approximately six months of study during which focus was placed upon: stoichiometry, basic calculations, law of mass action, and chemical reactions which were addressed at a purely representative level (without any mechanistic detail). No further causal explanations for chemical reactions besides statements of fact were provided, e.g. “When hydrogen burns in air, water is formed” (Andersson et al., 2003, p83). This aspect of the course was followed by calculations of solute concentrations in liquid solutions, then by acid-base theory, electrochemistry and finally organic chemistry.*
**Inter-molecular bonding**

Inter-molecular interactions were presented after organic chemistry, toward the end of the course (graphically depicted in Figure 6). Dipole-dipole interactions were introduced as “dipolar molecules bind to each other through attractions between the positive part of one molecule and the negative part of the other molecule” (Andersson, p177). van der Waals interactions were presented as bonding due to unsymmetrical electron clouds, as “a temporary dipole” (Andersson, p177). Hydrogen bonding was described as arising from “bonds active between molecules that contain one or several hydrogen atoms directly bonded to fluorine, oxygen or nitrogen atoms” (Andersson, p179). In total 1½ pages of the textbook (with in total 306 pages) were devoted to inter-molecular bonding.
AIM OF THIS STUDY

This study aimed to explore the nature of students’ developing models of the particulate nature of matter, in particular with respect to the different states of matter, phase transitions and connections between the two. Grounded theory, as presented by Strauss & Corbin (1990) was initially intended to be used for data analysis. As exploratory research does not intend to answer specific and well-defined research questions, an “area of interest” (Taber, 2000) and an aim were established. The motivation for the research foci was what Strauss and Corbin refer to as “personal and professional experience” (Strauss & Corbin, 1998, p38). As an active teacher of chemistry at the university level, the importance of an understanding of chemical bonding for a general understanding of chemistry, and for facilitating a student’s progression to more advanced levels within chemistry, is very apparent. The aim of this research project thus developed from professional curiosity.
METHOD

A longitudinal interview study spanning the first year of chemistry education at upper high school level was designed as a tool to achieve the aims of this thesis. Permission from school authorities and informed consent was obtained, i.e. all parties were informed of the objective of the project and participation in the project was undertaken on voluntary basis. Both parental and student consent were necessary for participation, and subsequent publication of data. Students were informed that they could choose to terminate their participation in the project at any given time, and that all parties would be anonymous throughout the process. To minimize interference with school activities, all interviews were undertaken outside of school hours. All interviews took place in Swedish, and were subsequently translated into English for the preparation of the publications included within this thesis.

Interviews were designed using an interview technique entitled “Interviews about instances and events” (White & Gunstone, 1992, p65). This approach provides the researcher with the opportunity to explore individual interpretations of phenomena, or concepts through focused discussions. The approach was described by White & Gunstone as a useful method to explore and probe student interpretations of single concepts and their “ability to explain a phenomena” (White & Gunstone, 1992, p66) Others, such as Gilbert, Watts & Osbourne (1985, p17) used the approach as a way to perform case studies.

As a means to introduce the topic of the coming discussion items, practical tasks or drawings were used together with interview questions of a general type such as, “What is this?” and “What does it represent to you?” The subsequent discussion was semi-structured, meaning that the interviewer has a general outline of additional items or questions to be addressed, but uses phrases and probing questions to explore word meaning. Examples of follow up, probing questions are “Why do you say that?”, “What sort of force?”, “Which way is it
acting? (White & Gunstone, 1992, p66). Of essence to this approach is to establish a mutual trust between the interviewer and interviewee. Probing interview questions was used since it is here assumed that the interview situation is an “interpersonal relationship” (Kvale, 1997) that will have an impact on both the interviewer as well as the interviewee. Interview question that can be seen as leading were used for validating interpretations an approach that were suggested by Kvale (1997).

Data analyses were intended to be performed using Grounded Theory (Gt) as proposed by Strauss & Corbin (1990). The choice of this research strategy was based upon the following factors:

- The exploratory nature of the research strategy
- The method provides an approach for fragmenting and conceptualising data in more general ways, while maintaining closeness to data.
- The theory or the conceptual ordering that is a result of the method provided in Gt is viewed as the researcher's interpretation of data.

The researchers' interpretations were further investigated during subsequent interview sessions as the main interview topics were again covered at all following interview occasions, and also through the use of “constant comparisons” (Strauss & Corbin, 1990). Constant comparisons in Grounded theory means that the researchers interpretations are continuously checked against new data and interpretations are transformed until saturation is reached. Saturation is reached when additional data no longer changes the interpretation (Strauss & Strauss 1990). Gt as a research method provides the opportunity to conceptualise data in a more general manner. It was here assumed that common features in data would reflect characteristics from the theoretical content of the chemistry course.

Participation in the study was on voluntary basis, for ethical and validity reasons. For ethical reasons it was of importance that the informants agreed to share their time and knowledge with the researcher. In each case the interview process was extended over a full year and it was here assumed that information provided on a voluntary basis would be valid. Only eighteen students volunteered to participate in the first part of the project, which may not be enough to ensure the requirement for saturation within Gt. We therefore elected to use Gt as a method for description and conceptual ordering, as has been done by others (Colnerud, 1995) and was even envisaged by Strauss and Corbin themselves (1998, p9):
“Some will use our techniques and procedures to generate theory, others for the purpose of doing very useful description or conceptual ordering (classifying and elaborating). Some will blend our techniques with their own.”

The method of use here is instead described as informed by Grounded theory. Data analysis performed using Strauss and Corbin’s coding approach develops in an entwined manner as data collection and analysis progress simultaneously, with the concomitant development of “theoretical sensitivity” (Strauss & Corbin, 1998). Theoretical sensitivity is the concept used for describing the process of immersing in data, including the additional literature studies prompted by the analysis itself. Accordingly, the method description is integrated with data and the choices made by the researcher are made visible.

Data collection

All data presented here derive from students attending the first year of upper secondary school (students of between ages 16–17 years). Data was collected from schools in two Swedish towns and derive from three different student groups, in total 29 students. The first study included a total of 18 students from classes at two different schools that were interviewed over a full school year. Parts of the results from this study are presented in Paper I. The second study included 11 students from a single class (of 21); again the students were interviewed over a full school year (Paper II & III).

Swedish students have the opportunity to choose between all upper secondary schools within their region. Therefore, upper secondary level classes are normally comprised of students from several compulsory schools, as was the case of the participants in these studies. The sample included girls and boys, as well as native and non-native Swedish speakers, a reflection of both the class and national demographics. Both non–participant classroom observations and ad hoc interviews with teachers were performed to obtain a better description of the student context and to ascertain the intended nature and timing of the formally introduced concepts and chemical models. An estimate of structure and timing of course content covered by both parts of the project is presented in Table 1. (Table 1 also includes timing of interview sessions for study two.)
<table>
<thead>
<tr>
<th>Time of introduction</th>
<th>Concept</th>
<th>Concept content</th>
<th>Time of interview session</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial introduction (first week of school year, August)</td>
<td>Matter</td>
<td>Differences between particle movement in the different states: ranging from vibrations (s), more restricted movement (l) to free movement (g). Matter as ranging from a highly structured arrangement (s), particles with less structure (l) to of particles with no structure</td>
<td>Interview session 1</td>
</tr>
<tr>
<td>September</td>
<td>The general atom, periodic table</td>
<td>Subatomic particles, their relative mass and charge, electrons in shells marked K, L, M etc. Lewis dots for valence electron configurations</td>
<td></td>
</tr>
<tr>
<td>September</td>
<td>The periodic table</td>
<td>History of its creation, periods and groups, general trends such as number of protons, valence electrons, ion formation, general descriptions of group significant properties</td>
<td>Interview session 2</td>
</tr>
<tr>
<td>October</td>
<td>Chemical bonding</td>
<td>Ionic bonding, metallic bonding, covalent bonding, polar covalent bonding, electronegativity and four examples of molecules to visualise molecular geometry</td>
<td></td>
</tr>
<tr>
<td>November and December</td>
<td>Chemical calculations</td>
<td>The mole concept, chemical equations, basic calculations</td>
<td>Interview session 3</td>
</tr>
<tr>
<td>January</td>
<td>Introductory acid base theory</td>
<td>Acids and bases, concentration, basic calculations, pH-scale, neutralisation, buffer solutions,</td>
<td></td>
</tr>
<tr>
<td>February</td>
<td>Introductory electrochemistry</td>
<td>Redox-reactions, galvanic cells,</td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>Introductory organic chemistry</td>
<td>Introduction to IUPAC-naming of organic compounds,</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>Aggregation forms</td>
<td>Gas law, dipole bonding, Van der Waals bonding, hydrogen bonding</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>Energy</td>
<td>Energy</td>
<td>Interview session 4</td>
</tr>
<tr>
<td>First week of June (end of school year)</td>
<td>Modern materials</td>
<td>Development of ceramics, glass etc. Introduction to polymers.</td>
<td></td>
</tr>
</tbody>
</table>

The primary difference between the content presented to the classes was the difference in emphasis (the amount of time) teachers placed on particular aspects of the course. To exemplify, in one class a lot of emphasis was placed upon historical models (a single group of students using a text book by Henriksson (2001)), students in this class did not receive a formal introduction to electrochemistry other than that they obtained through their own reading of the content of the chapter. In all cases, the presentation of the framework for matter in its different states and phase transitions, which included chemical
bonding, was introduced to students using the “traditional approach” (Levy Nahum et al., 2008) as described earlier.

**Student context of the first study**

For the first part of the study, classroom observations were performed with a focus on teaching models. This part of the study included two classes of students, for which quite different teaching methods were employed, though the context spans of the exams taken by the two classes were quite similar.

One class had a structured teacher-centred approach. Course planning was highly organised and timing of content introduction was structured on a weekly basis. These students’ influence on course content and structure was effectively limited to the opportunity to choose if they wanted their written exams, which were frequent, on either Mondays or Thursdays.

The second group of students was subjected to a less-structured approach and much of the theory classes were based around self-study, and students working in pairs reading and solving textbook problems. This approach meant that students did not spend much of the chemistry class time in classrooms, and were instead working alone or in groups in adjacent rooms and hallways. Course planning was structured around four points in time over the year, namely, the fall-break (höstlov), Christmas, Easter and end of the school year. Students in this group were given the opportunity to choose the number and content span of their written exams. It was commonly decided to have many exams with limited course content. Due to the organisation of formal teaching in this class, it was difficult to include a focus on students’ verbal activities in class and, accordingly, to assess progression in content. The timing of interview sessions over the first part of the study is presented as a time estimate (in % of the length of the course - approximate).

**Student context of the second study**

In the second part of the study, non-participant classroom observations were performed with a focus on both student opportunities for verbal activities and theoretical content. The students in this study were from the school that was described above as having a teacher centred approach, and were following the same course of study as previously described, though two years later. As many theoretical classes as possible were attended (49h of 62). The theoretical classes were to a high degree teacher-oriented and questions were given to those who showed a willingness to respond (by raising their hand). As a result,
25% of the teacher’s questions were answered by three of the students, two of which are included in this study. The students themselves only asked a few questions on each occasion. Numbers of questions asked by the teacher varied to a high degree, but on average 17 questions were directed towards the students over each 90 min class. The majority of the questions were of a kind where six words or less could be used to provide the answer. To provide the reader with some examples:

Teacher – What is this?
Student - It is an ion

Teacher – What charge does it have?
Student- It has a positive charge

During problem solving sessions the students were given the opportunity to work together to solve problems. The time the teacher had to spend with each student was limited due to practical issues, such as the number of students and the time allocated for these sessions. These problem-solving sessions were usually held during the last 20 min of a 90 min theory class.

**Interview design**

An initial interview question was designed and tested out in a small, preliminary pilot study. Based on this study, the interview question and follow-up questions where then further developed and the students were also provided with pen and paper. The reason for this addition was that the interviewees in the preliminary study either specifically asked for a paper and pen, or attempted to visualise chemical models, such as the atom, with the use of their hands. Asking students to draw an image of how they perceive formal models turned out to be useful in many ways. Firstly, it provided an opportunity to focus the following discussion. Secondly, it simplified follow-up questions. As a consequence of the pilot study the interview questions were either based on students’ own drawings, or the students were provided with schematic diagrams, chemical equations or focal items (props). The interviewees were at all interview sessions provided with a pen and paper to aid them in the discussion.

After each round of interviews, data was transcribed and initial analyses were performed. Based on these initial analyses further research questions were developed with two purposes. The primary purpose was to follow up the prior
interview and the second motive was to include additional areas that had been formally introduced since the time of the last interview session.

Categories and connections between categories that were reported in the first article were used as basis for the second data collection. For the second data collection interview questions were again developed as the analysis progressed and probing follow up questions used in order to explore students expressed models.

**Design of interview questions for the first study**

Due to the exploratory nature of the project, only a few open-ended interview questions based on the students’ own drawings were used in the first study. Much focus was placed on using students’ own words as follow-up questions. Approximate timing and main topics of interview sessions are presented in Table 2 (adapted from Paper I, Adbo & Taber, 2009).

<table>
<thead>
<tr>
<th>Interview topic</th>
<th>Approximate point in course of interviews</th>
</tr>
</thead>
<tbody>
<tr>
<td>The atom</td>
<td>before teaching at upper secondary level</td>
</tr>
<tr>
<td>The different states</td>
<td>5% into Chemistry A course</td>
</tr>
<tr>
<td>Chemical reactions</td>
<td>10% into Chemistry A course</td>
</tr>
<tr>
<td>Phase changes</td>
<td>25% into Chemistry A course</td>
</tr>
<tr>
<td>Electrochemistry</td>
<td>75% into Chemistry A course</td>
</tr>
</tbody>
</table>

In the first interview sessions the students were asked to draw an image of a general atom. Follow up questions were asked to explore sub-atomic interactions and movements.

During the second interview sessions the students were asked to draw an image depicting the solid, liquid and gas states. The follow-up questions were *Why is a solid solid?*, *Why is a liquid liquid?* and *Why is a gas gaseous?*, together with questions to establish word meaning. This question series turned out to be so rewarding that it was maintained for the second part of the project. A possible benefit with this question was that it provided an opportunity to return to the general atom and re-explore data derived from the first interview session.

Due to responses from prior interviews, the third interview round of the year was focused on chemical reactions. Two reactions were chosen: the combustion of methane to yield carbon dioxide and water, and the precipitation of barium sulphate from a solution containing sodium, chlorine,
barium and sulphate ions. As all three states of matter are represented in one or the other of these two reactions; this provided the opportunity to revisit and explore the differences between the three phases and phase transitions.

In the fourth interview session a focus was again placed on phase transitions and the students were again asked to draw the different states of matter. Phase transitions were addressed at constant temperature.

At the fifth interview session, students were shown a schematic drawing, of a galvanic cell, Figure 7, which was used as the focal point for interview questions.

![Figure 7](image)

Figure 7. Schematic representation of a galvanic cell as presented for students

The ensuing questions around electrochemistry also included reference to substances in the solid, liquid and gaseous states, which again provided an opportunity to include these models as well as phase change in the interview session.

Data from three of these interview sessions are presented in Paper I. During ad hoc interviews with the two teachers, they stated that they found the national curriculum difficult to interpret, and that insecurity regarding content and structure caused them to rely on the interpretations provided by the textbook authors.

A second interview study was thereafter initiated. The focus of this second study was placed on students’ developing models of chemical bonding with regard to phase change (Paper II & III).
Design of interview questions for the second study

Interview sessions for the second part of the project were again semi-structured, but this time questions were focused on items/props or schematic drawings. The students were provided with paper and a pen on all of the interview occasions and were invited to draw when needed. The following interview questions (see below) were open ended and establishing word meaning was a priority. The focal items and schematic drawings that was used for the four interview sessions are described below:

**Interview session 1:**
The focal items of this first interview series were:
- A vial with lid (representing a gas).
- A bottle marked ethanol and containing a liquid (representing a liquid)
- A piece of metal and metal powder (representing solids)

The choice to label the liquid with ethanol was made so that water would not be their immediate association.

Interview questions were:

- How would you describe this?
- What is the difference between them?
- Why is a solid solid; a liquid liquid; and a gas gaseous?
- Can you draw them for me?
- Can you draw an atom for me?

Subsequent, follow-up, or probing, questions were commonly based upon *How? Why and What?* question constructs.

**Interview session 2:**
As focus for this interview, two chemical reaction formulae were chosen. The formulae were not balanced and the students were asked to assume the different states of the substances included. The first formula was for the combustion of methane to form carbon dioxide and water, and the second was the precipitation of barium sulphate from a solution of sodium, chlorine, barium and sulphate ions.

The interview questions were:

- What is this?
- Where would this happen?
- Why would this happen?
- How does it happen?
- What state would you assume for these substances?
The interview included asking the students to draw images to depict the states. Asking the students to assume states was done in order to steer the students from a discussion concerning specific substances to a more general discussion concerning the different states of matter.

**Interview session 3:**
The third interview session was conducted after the presentation of acid-base theory to the students.  
The foci of this interview were:
- sodium chloride crystals  
- a solution marked with Na\(^+\) and OH\(^-\)  
- a solution marked H\(^+\) and Cl\(^-\).

Follow up questions were:
- *What is this?*
- *Would you draw that for me?*
- *How do you think I made it?*
- *Why?, how? and where?*

**Interview session 4:**
The fourth and final series of interview sessions were held approximately two weeks after the completion of the presentation of inter-molecular bonding. Here, both a physical device and an image provided the focal points, and the interview was conducted employing a semi-structured question regime. At the outset of the interview, two drops of acetone and two drops of water were placed on a glass microscope slide and left to evaporate, Figure 8.

![Figure 8. Schematic representation of the phase change demonstration equipment employed in interview session 4.](image)

The students were then shown an image, Figure 9, depicting four scenarios:
- a container with a liquid  
- a container with a liquid and a candle as a heat source beneath it  
- a container with a liquid, the container having a lid
- a container with a solid substance.

Figure 9. Image presented to students in interview session 4.

The interview questions asked were:

- What happens?
- What is the difference? (between the quickly evaporated acetone and the water that remained)
- What happens when we heat it?
- What happens when we put the lid on?
- What happens here? (solid)

Follow-up questions were structured as described above.

Data analyses

Data analyses began at the interview sessions, with the use of follow-up questions to establish word meaning. Data was transcribed after each interview and later translated to English for publication purposes. As the papers included in this thesis demonstrate, data have been analysed both from the individuals' perspective, as well as conceptualised and presented in more general perspectives. This is in itself, a reflection of the data sample that contained both common features as well as individual characteristics.

Within this method for analysis data is reduced and interpreted through a process that contains three main steps: fragmentation, conceptualisation and reassembly. Fragmentation of data is achieved by coding. In the first step, called open coding, focus is turned towards finding events in data (Strauss & Corbin, 1990). Tools provided to achieve this fragmentation are composed of a series of questions, e.g. “What is going on here?”, “What is intended?” Through line-by-line analyses of interview transcripts, more general, descriptive and symbolic labels (concepts) are placed on “meanings, feelings, actions and
events” (Cohen et al., 2007, p493). Labels can be either in vivo, as found in data, or in vitro, of a more theoretical nature. Through this coding process a number of concepts are thus interpreted from data. Concepts are then constantly compared and contrasted in order to identify similarities and differences. Concepts describing the same phenomena are clustered together in a category and the category is then given a conceptual name. As relevant features emerge in data they are further explored through the use of additional interviews or data collection from alternate sources.

Results presented within this thesis derive from two separate data collections including 2 different groups of students. As the study progressed general patterns (Papers I and II) as well as individual features were explored (Paper III).

Results presented here must be viewed in light of the fact that they are interpretations of data, derived from parts of formal chemistry learning. The students included in this study were interviewed over one year of their two-year chemistry course. Accordingly, these results do not include the entire high school education, and no conclusions can therefore be drawn regarding the final outcome of this educational approach. Nonetheless, conclusions can be drawn regarding teaching models and students’ expressed models.

**Data analysis in Paper I**
A selection of excerpts from interviews is presented below to illustrate the analysis process. Examples of the coding procedure are provided in the interview transcripts below (S = student, K = interviewer, [line-by-line analysis within brackets]).

K - Could you describe your view of the atom for me?
(The student takes a paper and a pen and draws an image of the atom and simultaneously begin providing the description.)

S - The atoms has a nucleus and then it has electrons [describing abstract particles] that are electrically neutral I think or I mix it all together, protons have a positive charge, [placing positive charge on protons] neutrons are neutral [placing neutrality on neutrons] and electrons are negatively charged [placing negative charge on electrons] they are supposed to cancel each other out somehow [sub-atomic particles’ cancel each other out somehow] then it depends on what substance it is [recognising differences between substances] but this is how it looks (draws) [visualising abstract item] and then it depends on how many shells it has and how big they are since in the first shell
there is room for two [recognising difference between shells, number and size of shells - amount of space] always [describing a rule] and there are only two of those I can’t remember, electrons and then there are eight.

K - You said “nucleus”?
S - Here (pointing at the nucleus) you have protons and neutrons they make sure that you can find out the name of the substance [name of substance due to protons and neutrons].

Students used illustrations in a way similar to the use of maps; “Here (pointing at the nucleus) you have protons and neutrons”. Since images were such an integral part of the students’ explanations their expressed models were in the subsequent analysis related to their own drawings.

As data collection and analysis progressed, commonalities in students’ visualisations and verbal descriptions were identified and connections between different descriptions explored. The interview excerpts below show students’ descriptions of atoms and subatomic particles.

K Could you describe your view of the atom for me?
S This is the nucleus (drawing) neutrons are neutral [nucleus have neutral neutrons] and protons are positive [protons are positive] then around the nucleus there are electrons that are much smaller…may be not so much smaller they have roughly the same mass but it has a negative charge [electrons outside of nucleus have negative charge]… the electron that is… and it moves in shells [electrons move in shells] and the simplest form of atom is the hydrogen atom [recognising differences between particles].

K Could you explain a bit more about the movements?
S The electrons move, the nucleus don’t move [electrons’ move, protons and neutrons don’t move]…the atoms move [atoms move] but that depends on if it is solid liquids or something…it moves more depending on… if it is in gas then it move more then if it is liquid [atoms move depending on s-l-g, comparative manner].

K Could you describe an atom for me?
S Here is the nucleus (Student is drawing) and here are electrons moving in shells. [placing electrons in shells outside the nucleus].

K What is the nucleus?
S There are protons and neutrons like this (drawing) and they have positive charges and no charges. [placing name and charge on nucleons].

K How about movements?
Protons and neutrons do not move, it is the electrons that move like this (draws more circles around the nucleus) \textcolor{red}{[placing movement on electrons, no movement of nucleons]}

During the second interview session students were asked to draw matter in its different states. One of the follow up questions was, \textit{“Why is the solid solid, the liquid, liquid and the gas, gaseous?”} Variations in student descriptions regarding movement ranged from students focusing on electron movement (as in the excerpt above) to atomic and molecular movements (see excerpts below and Figure 10).

K Why is the solid solid, a liquid liquid, and a gas a gas?
S Gases you can’t touch \textcolor{red}{[gases can’t be touched]}, liquids and solids you can touch, \textcolor{red}{[solids and liquids can be touched]} you can’t feel a gas. In solids the atoms are attached (draws) they don’t move they are attached (pointing at the round balls in the drawing). \textcolor{red}{[shifting to an atomic-level no movement in solid state] due to some form of attachment}. In gases they are more scattered and they move (draws) \textcolor{red}{[in gases particles’ are scattered and move]}

K And liquids?
S They are see through and they flow it is difficult to explain there are quite a few atoms and the move quite a lot (draws) \textcolor{red}{[liquids are see thru, they flow and move quite a lot]}

K What moves?
S The electrons and the atoms

K Could you draw a solid for me?
S Yes, they are stuck like this (drawing a solid)

K What solid is that?
S It is water or ice...

K So explain
S I don’t know a lot, here they are stuck they are closely packed \textcolor{red}{[particles in solid state are stuck and closely packed]}. If you boil it then they move…movement is heat \textcolor{red}{[increased movement as due to heating, defining heat as movements]}

K Who are they?
S The molecules \textcolor{red}{[particles in the solid are molecules]}

K How about movement here? (Pointing at the solid)
S No, they are to closely packed \textcolor{red}{[no movement to solids due to close packing]}

K Would you draw a molecule for me?
Let’s see ice…that’s one hydrogen and one hydrogen and one oxygen (drawing a water molecule)…there [describing atoms included in a water molecule].

Why is a solid solid, a liquid liquid and a gas a gas?

In the solid they are close like this… they are stuck together with some form of magnetism (draws) and in the liquid they are more loose…(draws) [in solid particles are close, stuck with some form of magnetism, in liquids particles’ are more loose comparative manner] and in the gas they run a way a bit… (draws) [Increased in distance between particles in liquid state]. It is the distance between atoms that is the difference [distance between atoms is the difference between s-l-g].

Why do they run away?

They move more and then the electrons get looser [particles move more and electrons get looser] and they move away.

Who are “they”?

The atoms [particles are atoms].

Since movement was such an integral part of student answers, movement was used as a category. As this category was emerging in all student answers it was further explored as interviews progressed.

Since students employed drawings in their descriptions of the states of matter and phase transitions, categories were created around visualisations. Thus the initial category “descriptions” was complemented with two additional categories: movement and interaction.
Interview session three was focused on chemical reactions and the results from the discussion regarding states within this interview session were very similar to those obtained in the second interview session. For example, some students presented in drawings of the three states of matter in principle identical to those presented in the earlier interview. Student descriptions from this interview session again involved movement. The category “interactions” was expanded upon during this interview session, as chemical reactions had at this point been addressed in the course. The student explanations for chemical reactivity phenomena were mainly based on electron configuration, in particular using the octet rule and most were anthropomorphic in nature, e.g. “wanting a full shell”, “need eight electrons”, “I don’t know they just do this”. Examples of excerpts deriving from the third interview sessions are presented below.

K If you were to assume states, solid liquid or gaseous state to the substances included in this reaction what would you assume?
S This is difficult but I would assume that these are liquid (sodium ions) and these are solids (chloride ions).
K Why would you assume that?
S Because they do not bond.
K What is a bond then?
S They attach since they want a full shell [bonding due want a full shell]…or may be they already have a full shell and then they can’t be in the same state [no bonding due to difference in state].
K OK, so assume a state.
S Now I will say liquid and solid
K OK, can you describe the solid state for me?
S It is a lot of atoms organised in a pattern [solid state as atoms organized in pattern].
K Why are they organised?
S They are attached somehow.
K What kind of attachment would that be?
S Some force [attachment due to some force]. I don’ know.

Here thirteen out of eighteen had no movement in the solid state. Ten of the eighteen students described liquids as an atomic state. Six of the students did not appreciate the difference between atoms and molecules and two saw liquids as small groups of atoms.

K If you were to assume solid, liquid or gaseous state to the substances in this reaction, what states would you assume?
S I don’t know, this may be a liquid [pointing at the dissolved sodium atom]
K Could you describe your liquid for me?
S The atoms they are in small groups but they are not structured in the liquid...in the solid they are [liquids are not structured]...in the liquid the atoms are quite far apart. [In liquids atoms are far apart].
K Anything else?
S The move more in the liquid [more particle movement in liquids].

The gaseous state was seen as an atomic state by ten of the students. This excerpt is derived from a student who assumed that reactions mainly occur in gaseous state and therefore assumed that the reactants in the ionic precipitation were gaseous.

K Can you describe your gas for me?
S A gas looks like this (draws) a lot of atoms together...next to each other...and the electrons shift between them...and new substances' form...atoms disappear and more atoms show up because they all want to have full outer shells [describing the gaseous state as moving atoms wanting to fill their shells].
K How about a liquid?
S They move around too but not so much [describing movement in liquids in a comparative manner].
K What are these round balls?
S They are atoms [identifying the round balls in the drawing as atoms].
K And the solid?
S Nothing happens in solids, they are stuck... they cant move [describing the solid state as having little movement since the particles are stuck].

Due to the focus on electron movement in many students’ answers, attention was directed towards the models in the textbook (Andersson et al., 2003). An analysis, Figure 11, of the textbook’s references to movement showed that particle movement was mentioned once in the first introductory chapter/class. Focus then turned towards electron movement during the introduction to the atom, and was maintained as a focal point throughout the first four chapters (for the classes studied here, this corresponded to more than two months of study, August-October). One student explicitly touched on this topic when she expressed her doubts about acidic-reactions "so far electrons have been moving, but I don't know... now they say that protons can move too".
Axial coding is the next part of the process, where links between categories are discovered and “compared with existing theory” (Cohen et al., 2007, p493). Here, “existing theory” was a review of literature and interpretation of the content of the textbook. As coding progressed more categories were found and the focus of the analysis was turned towards the categories containing formally presented chemical models. The main connecting category that emerged from axial coding of the data was Movement. Movement was interpreted as the core category for data presented in Paper I.

Interview transcripts derived from this first study were analysed in the manner described above and categories were developed. Common themes were identified and used to construct a model that represents common features derived from students expressed models. Three common topics that were found and designated: descriptions, interactions and movement. The categories *descriptions and movement* were found to be interrelated in a very entwined manner as evidenced by the student responses throughout the study. *Movement* was used as the descriptive explanation for differentiating between the different states of matter. This was expressed both verbally, and through drawings where an increase in distance between round balls was presented. All 18 students used the teaching model of matter in the different states in their drawings, as well as in their descriptions.

Students expressed and illustrated their model of the atom, and for all 18 students their model included electron movement were for example: jumping, spinning, moving in shells and moving between shells. Further, some 15 students viewed the nucleus as stationary. These students’ expressed models coincided with the textbook model of the general atom, which did not address movement within the nucleus. Categorisations from this analysis were presented in Paper I and are in Table 3 marked in bold font.
When exploring an area with such diverse variables as a learning environment the focus of data collection is shifted as analysis progresses. Although *Interactions* were defined as a category, the focus of this first data collection did not further explore the *development* of this category. This first study became a platform for a second study with focus on students’ developing models for chemical bonding. Therefore, a second longitudinal interview study with a new group of informants was initiated. This time with a higher focus on interactions instead of descriptions. Interview questions for the second part of the study were further developed (see below). Interviews were recorded, transcribed and translated in the same manner as in the first study.

Table 3. General categorisations derived from the first data collection.

<table>
<thead>
<tr>
<th>Atomic</th>
<th>Describing model</th>
<th>Movement</th>
<th>Restricted movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleus, protons and neutrons</td>
<td>Visualized, immobile nucleus, electrons in shells, round balls</td>
<td>Pulled, repelled, force, attraction, balance, neutralizing, fusing, strengthening, stabilizing</td>
<td>Moving electrons, jump or spin, in shells, in-between shells, between substances</td>
</tr>
<tr>
<td>Matter</td>
<td>Visualized system of round balls, packed, empty space, close, overlapping</td>
<td>Visualized irregular system of round balls, water</td>
<td>Visualized non-structured round balls, large distances between</td>
</tr>
<tr>
<td>Interactions</td>
<td>Interactions</td>
<td>Lack of interactions, increased movement, comparative manner, wants more room</td>
<td>Free movement, disperse, large distance between, reactions</td>
</tr>
<tr>
<td>Effects of heating</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Data analysis in Paper II**

Eleven students from one student group volunteered to participate in the second study. Interview transcripts were also for this study analysed line-by-line and interpretations continuously compared as the data collection
progressed. Word meaning was explored and data were analysed from both longitudinal and individual perspectives. The focus of this data collection was based in students’ increasing repertoire of models and explanations concerning the previously defined category of interactions. Some excerpts from the first interview session and accompanying line-by-line analysis are provided below (K=interviewer, S= student).

K … now you mentioned a copper atom if it is a solid how would you picture it?
S Well there would be many atoms. (Draws a picture of a solid)
K You add energy -what happens?
S Since there is a shell on the atom [the atom has a shell] and the electrons move more [electrons move more when energy increases] then they crash into the same surface a lot then the atom starts to vibrate [atomic vibration due to electron movement].
K Can you draw a liquid?
S Well the molecules are connected [in liquid as molecules are connected] in the same way as in the solid.
K What is a molecule then?
S It is atoms that are stuck together [a molecule is atoms stuck together].
K … you mentioned a copper atom, if it is a solid how would you picture that?
S Well there would be many atoms [draws the next picture of a solid].
K Would there be a difference in the gas then?
S No, although there is something released when they transform at least some substances [something is released during phase transition for some substances] and then some substances do not contain two oxygen atoms. If it moves over to gaseous then maybe they loose one oxygen atom or something [oxygen may be lost during phase transition].
K Why would they transform?
S If they feel that they do not get the space they need or something [phase transition due to particles feeling that they need space] … in gaseous state they get more surfaces to move in than the liquid. They should get it since it is in the air. There is much more room in the air then in the liquid. [there is more room in air].
K … so why are the atoms connected in a molecule?
Well that is why it is a substance. If there would only be one atom then it would be an element. A molecule can be another substance than the elements since there are several atoms connected. And they can be connected to different places.

[**Molecules** have several **atoms connected**]

K But why do they attach?

S They feel that they need each other, [**atoms attach since they feel they need** each other], they see that the other atoms have something that they want [**atoms see** the other atom as having something they want].

K What would that be?

S It could be an electron or a proton or a neutron or something. [**atoms want electrons, protons or neutrons**] I don’t know if energy has anything to do with it [**energy may be of importance**]. They are used for different things in different places and then the one who is most interested to have it merges with the other atom and they might feel that [**atoms can be interested, merge and feel**] I would much rather be in this place.

K Let’s say that one atom needs another electron or a proton or a neutron. How does the other one know this?

S If they feel that together they will have these qualities then the other one might feel this to [**atoms feel**]. It might also be aiming towards the same direction. If they are not aiming towards the same direction then it is not they who get stuck together later on. Then it moves in the other direction.

The above excerpt is derived from the first interview session of the second study. The causal explanation for interactions is comprised of mainly anthropomorphic formulations. Two more interview excerpts from this initial interview session are provided below to illustrate the more common student responses.

**Student 2**

K … but how does a liquid look?

S They release from each other… the atoms that make it more liquid [**In liquids atoms release**]

K Anything else?

S Well there could be differences in how they bond and different properties. They get different properties like ice and then water and then water vapour. But it cannot be anything else than movement since then they would react and you would get a
different substance [movement is what separates' the different states of matter; reactions change the substance]

K
Why would they react?
S
They want full shells, or balance [reactions due to wanting full shell or balance].

K
What is a full shell then?
S
That depends the inner needs only two and then there is eight and then it moves on eight or eighteen I think it is. The electrons want to be even [full shell depends on inner needs, electrons want to be even].

K
So what is the balance?
S
Everything in nature is in balance, balance between different charges. [balance is between charges] Like if one electron is missing then of course it wants one, and then it will take one from another. Another one might want to let one go [if electrons are missing the particle wants one]. The balance is between electrons protons and neutrons. [balance between sub-atomic particles] If it takes one electron then it becomes minus and if it gives one then it becomes positive. Then it is not like the original one that has equal numbers of protons and electrons [taking and giving electrons gives the particle charge; the original particle has equal numbers of protons and neutrons].

Student 3:
K
It is 22 degrees at constant pressure, why is this one solid and this one liquid and this one a gas?
S
That is because... before this one for example... oxygen needs probably 100 degrees minus and this one, the metal, needs to be exposed to an incredibly high temperature to melt.

K
But why is there such a difference?
S
It has to do with the different properties of the atoms. That is what decides how high temperatures they can be exposed to [differences in melting point, boiling point between substances are due to different properties].

K
What is it in the properties of the atoms that could affect that?
S
It could be the number of electron shells or the number of valence electrons... that causes them to react more easily with other substances [number of electron shells or valence electrons cause reactions] But it is the difference in the
atoms that affect at what temperature the substance melts.

[**differences in the atom affect mp**].

K

What is a valence electron?

S

It is the outer electrons so for example in hydrogen there is only one valence electron. Then this electron can jump over to another one and form a new substance [**electrons can jump** and form new substances].

K

Why?

I don’t know if that is one of those mysteries...that scientists do not know why ... since they have less electrons then it wants to take up more electrons or let go of one if they think [**why electrons move is a mystery, particles want to take electrons**]

The explanations for chemical interactions were in many cases demonstrated similar traits; most noticeable was the fact that eight (out of eleven) students employed anthropomorphic and teleological causes to some extent. The cases above provide examples of strong and weak anthropomorphism. Two of the remaining students offered no explanation, and the final student suggested an interlocking mechanism for chemical bonding, the basis for Paper III.

As the focus in the second study was on interactions, it was commonalities with regard to particle interactions that were conceptualised and categorised. Three in vitro labelled sub-categories were assigned: **weak and strong anthropomorphism**. Explanations such as “wants, needs, think, happy, feel and interested” were used for amongst other things to explain movement. As in the first data collection, commonalities in student use of models turned focus towards target teaching models. Results are presented per individual in chronological order in Paper II. A subsequent analysis of teaching models (see Table 2, page 7, Paper II) demonstrated a high degree of similarity between teaching models and students' expressed models.

**Data analysis in Paper III**

Results presented in Paper III are derived from a case study of one student. Results from this student were also in part included in the results presentation for Paper II. After the line-by-line analysis, concept maps (Novak, 1990) were constructed for each interview session as a way to visualise the development of Jesper's models. Analyses were performed in the same manner as in Paper II, but significantly more detail is provided to the reader since results are presented in the form of a case study.
Analysis of the first interview session with Jesper resulted in the identification of two categories, small particles (possibly quarks) and gravity. That Jesper used as a basis for his explanations. Some short excerpts and concept maps from the first and last interview sessions are provided here (J = Jesper, K = interviewer). For a more complete account of the results see Paper III.

**Interview session 1**

K Could you draw a solid for me?

J Well in the solid state the atoms are really close to each other, they are held together that’s how I think…[solid atoms are close, held together]

K How about the liquid then?

J Then I think of them as… or think this is how I have learnt it, they are more scattered like this (draws) they have gathered together but they have some distance between them anyway or they attract one another still. [liquid as particles being further apart but still attracted]

K Why are they attracted to each other?

J It is the gravitation from each atom or magnetism. So they attract one another. They can still be scattered but…[attraction = gravitation or magnetism]

K What is gravitation then?

J I think of gravitation as a form of magnetism sort of…[gravitation is a form of magnetism]

K What is magnetism then?

J Well magnetism there are metals that sort of attract… gravitation and magnetism, gravitation is between something really big compared to something else it is attracted since it has larger it is hard to explain [gravitation concerns difference in size. magnetism occurs between metals]

Gravity/magnetism and smaller particles (smaller then electrons, possibly quarks) were the basis for Jesper’s reasoning in interview session 1, Figure 12. As the interview excerpt and concept map derived, Figure 13, from the final interview session of the year demonstrate, Jesper had incorporated the majority of teaching models introduced to fit into his view. Excerpts derived from the last interview session of the year are presented below.
Interview session 4

K Would you draw a liquid for me?
J I would do this… if it were a gas then it goes in all directions but since it is a liquid then it like this they are affected by the others by gravitational …like this there is enough energy for them to hold together [particles in the liquid are affected by some form of gravity].

K Why would they hold together?
J I think that it could be like gravitational forces, these are really small things, but they affect each other in one way or the other and since there are so many of them then they hold together as one, a form of mass but if you pour it out then… (sound) [holding together could be due to gravitational forces]

K What is this round thing?
J Molecule…
K Would you draw an atom for me?
J Water I think it is like it is surrounded by … let say how many water is there in H₂O? Here is the oxygen molecule and here is
the oxygen and it has a cloud around it with electrons or what
ever it is particles and then the atom it self may be like a kind
of cloud of things [oxygen has a cloud of electrons or
particles’ around it; the atom may be a cloud of
things].

K  What things?

J  Some form of particles… [things = particles].

K  What kind?

J  A kind of particles that kind of… yes… that some how defines
its properties and that are affected a lot more by energy and
stuff like that and… if you say that this is an atom then you
have electrons around it that may affect it…[smaller
particles’ in the atom defines properties and are more
affected by energy]

K  What is this?

J  It is like little particles… hmmm… not like charged particles
or maybe it is like charged particles that are affected by each
other and it is their bonding forces to each other are so much
greater then to other so that…[little particles are affected
by each other; they have bonding forces that are much
greater].

K  What kind of bonding forces?

J  It is like ions were minus is drawn to plus it may be the same
but they are so much smaller If you have the electrons… I
think that an electron is a collection of other small particles
that move around like this in a shell and yes …[bonding
forces like ions but much smaller; electrons are a
collection of smaller particles]

K  What is an electron shell?

J  It could be how… it is a bit strange… I think it is like this the
further in… like very little thing and then here we have an
electron shell that really is a lot of small particles that are
crowded so that they cant get any closer and then if more is
added then it cant get any closer and adds outwards [The
electron shell is composed of smaller particles. There are
so many that they can’t get closer. If more particles are
added then the particles add outwards ]
The concept map from the final interview session year illustrates how Jesper readily incorporated most of the teaching models included in formal teaching into his own way of thinking. Jesper’s ideas cannot be dismissed as fragmentary and arbitrary, rather these were the type of thoughts Jesper “thinks about when trying to fall asleep at night.” Moreover, these were what Jesper brought to chemistry to make sense of teaching, and through which he came to from an alternative understanding of the key concept areas such as states of matter, changes of state, solubility, chemical reactions and chemical bonding.
SUMMARY OF RESULTS AND GENERAL DISCUSSION

The two studies underlying the results presented in this thesis help shed light on the nature of the relationships between some of the models used for the teaching of chemistry and those expressed by students.

Results derived from the first study (Paper I) show how visual images were an integral part of students’ descriptions of the basic models, such as the atom, and matter in the different states. Students’ drawings of atoms strongly resembled the images presented in textbooks, including the distortion in the size of the nucleus found in textbook images describing both nucleus and electron configuration.

The students’ use of images appeared to hold a high degree of similarity to the everyday use of maps. Although these students were, in the formal school environment, only exposed to images derived from textbooks, their use of images highlights the importance of visualisations as tools for the process of learning chemistry. The movement of and the distance between particles in the different states of matter are commonly used to provide initial descriptive explanations for categorisation of the solid, liquid and gaseous states. At the introductory level no explanation was provided as to what the round balls/particles were meant to symbolise. This choice was possibly made since only atoms, and not ions or molecules, had been addressed so far. The model was not revisited after the introduction of non-atomic particles.

Both teachers in the first study addressed phase transitions as something that could be induced by an increase in temperature. The effect of this increased temperature would be manifest as an increase in distance and movement, something that was easily adopted and expressed by all 18 students. Unfortunately, the emphasis on electrons and electron movement in several
teaching models (electron configuration, similarities in reactivity within groups in the periodic table, ion formation, the octet rule and inter-molecular bonding) resulted in electron movement being used as the basis for the majority of student explanations. Although students’ conceptions matched appropriate target knowledge to a large extent, their explicit focus on electron movement in combination with visualisations made it possible for students to explain phase transition without invoking chemical bonding.

Results from the second study highlighted student use of anthropomorphic frameworks for describing chemical phenomena (Paper II). Anthropomorphic language can become habitual since it fills an “explanatory vacuum” (Taber & Kind, 2005). The explanatory vacuum in this case is the substantial amount of time elapsed between the introduction of the particulate nature of matter (of basic particles: atoms, ions and molecules) and the presentation of chemical bonding (using electrostatic interactions) as an explanatory principle for particulate interactions. The anthropomorphic frameworks developed as teaching progressed and became more frequent in students answers towards the end of the year. Analysis of teaching models in the textbooks identified the use of anthropomorphic frameworks even there, e.g. the driving force behind chemical reactions where the atoms strive to achieve noble gas structure. It was not possible for the students included in this study to build a coherent framework for chemical bonding as electrostatic interactions were only vaguely addressed and no consistent model for deriving molecular geometry was offered.

A particularly interesting case was identified in the second study, and subjected to a more comprehensive analysis (Paper III). This case highlighted the way in which a student's alternative conceptions can interact with formal instruction. Here the student retained his initial intuitive ideas throughout the course, and incorporated the majority of teaching models into his alternative framework.
CONCLUSION

Possible consequences for chemistry teaching

The results presented within this thesis represent a snapshot picture of the Swedish national chemistry curricula in action. From a teaching perspective, the findings illustrate some of the practical consequences of the unspecific nature of the Swedish chemistry curricula.

General variability in compulsory school chemistry education

The unspecific nature of the Swedish curricula gives rise to variations in the time allocated for chemistry, and at which level chemistry is introduced to students at the compulsory level. It has previously been argued that initial categorisations and their descriptive explanations are important for the introduction of chemical frameworks. Students included within this study displayed substantial variation in their ability to categorise basic particles. On their initial interview sessions, student answers ranged from students who were unable to separate between atom and molecules, to students categorising atoms, molecules and even classes of substances, such as hydrocarbons. This variation suggests that some students had received more exposure to chemistry and/or an earlier introduction to chemistry at compulsory level, while others stated that “we did not have a lot of chemistry at my school”. Not being able to define what teaching models students had encountered at compulsory level caused teachers to reintroduce the basics, such as the general atom. This approach can on one hand be beneficial; it provided students with a repetition of basic models, or introduced models to students that had less contact with chemistry in compulsory school. An unfortunate consequence of reintroductions is the reduction in the amount of time that could be used for introducing and engaging students in work with new models.

Anthropomorphism and visualisation in compulsory school

The alternative conceptual frameworks used by students when entering upper
high school chemistry made extensive use of the *states of matter* model, as derived in Paper I. Similarly the anthropomorphic language focused on in Paper II was also common to the students in the first study upon entering high school. Students’ common use of anthropomorphism and the states of matter in their frameworks suggest that both have been presented as canonical scientific ideas in compulsory school. Another difficult issue for compulsory school level chemistry is that chemical models and theories are abstract and complex, “whereas the phenomena themselves are often readily observable and accessible. This is certainly the case in terms of the states of matter, and such changes as dissolving and evaporation.” (Paper II). When introducing chemistry at the compulsory school level, it is a common intention of teachers and textbook writers to draw upon a student’s own prior experience. The different states of matter are one way to begin the theoretical categorisations of matter. Encouraging experience-based chemistry at the compulsory school level can contribute to the challenges identified here, and even described by others (Novik & Nussbaum, 1981; Andersson, 1990; Renström, Andersson & Marton, 1990). In summary, student explanations derived from prior learning at the compulsory school level are commonly anthropomorphic in nature, which hinders student incorporation of more advanced teaching models into their chemical frameworks.

**Implications for the Swedish upper secondary school chemistry curriculum**

Common to both studies was the observed reliance teachers placed on the use of textbooks for defining course content. Results included in this thesis indicate that the curriculum in use at the time (The Swedish national agency for education, 2001) did not provide sufficient support for the teachers in their daily work. Instead teachers relied heavily upon interpretations offered by textbooks (Paper I), an outcome that is in contradiction with individual-based focus of interpretations by student and teacher that was the stated intention of the curriculum. Despite the intentions of the national curriculum, the possibility for delivering individual focused education is in practice limited by e.g. the constraints of time and student group size. A direct consequence of the vagueness of the curriculum is the resultant (extensive) devotion of time to the reintroduction of basic chemical models, rather than the introduction of new models aimed to contribute to student progression in chemistry.

The teaching models used were derived directly from textbooks and the teachers’ presentations were structured in the same manner as in the textbook. Accordingly, the structure of the textbook influenced directly upon the creation of an explanatory vacuum regarding chemical bonding, in particular due to the late introduction of inter-molecular bonding. The results also showed that electrostatic interactions were not significantly represented in
either teaching models or student explanations of chemical bonding. This reflected the limited use of electrostatic interactions, in conjunction with the presentation of chemical bonding in the textbook.

Implications for the teaching of chemical bonding

The students in this study were formally introduced to what has been referred to as the “traditional approach” (Levy Nahum et al., 2008) to chemical bonding. When contrasting the teaching models used in this “traditional approach” with the students’ use of the models, it becomes evident that the current framework and the timing of model introduced do not support students in building a coherent framework. Not only was there a strong tendency to explain reactions in terms of atoms “needing” or “wanting” to fill their outer electron shells, we also found that this form of explanation was even more prevalent after teaching about chemical bonding at upper secondary level than before teaching. Students in our sample were explicitly told that reactions occur because atoms strive to achieve noble gas configuration (see: Table 2 in Paper II). It was noted that electrostatic interactions were not emphasized as an explanatory principle and no means for determining molecular geometry was offered to the students. Both electrostatic interactions and molecular geometry are essential for understanding inter-molecular bonding, which is critical for understanding phenomena such as changes of state, solubility and molecular recognition. The incorporation of VSEPR-theory into the curriculum and chemical bonding framework may help improve student progression in upper high school chemistry. To provide the reader with an example of the importance of one of these concepts, an ISI Web of Science search (2012-01-16) using the term molecular recognition identifies over 17 000 papers using this term as a key word.

The results indicate that the chemical bonding framework used is incomplete, in particular with regard to inter-molecular bonding, suggesting the need for a revision of the teaching models employed at the upper secondary school level.

In closing

In conclusion, the results presented within this thesis show that focus needs to be placed on the content taught and teaching models used at all levels. According to the constructivist theory, “learners’ existing ideas have consequence for the learning of science” (Taber, 2009b). This perspective strongly suggests that more focus needs to be place on learners’ existing ideas before further formal content is introduced; this conclusion is also emphasised by the results derived from Paper III.
The students included in this study took their chemistry course over a two-year period. Although the science programme at upper secondary school is a three-year programme, the choice was made to postpone physics to years two and three, while only chemistry, biology and mathematics were presented in years one and two. This choice was made so that students would have received more mathematics before attending physics. In light of the results presented by Johnson (1998), the transition between the experienced world and the particulate nature of matter can take years for students to accomplish. Accordingly, a better progression in learning might be achieved if the chemistry course were extended over the full three years.

It is hoped that the conclusions drawn from this work will provide a basis for improving the repertoire of models and frameworks used by teachers in order to facilitate a more coherent relationship between their use in teaching and their impact on those expressed by students.
FUTURE OUTLOOK

Research often raises more questions then it provides answers to – as is the case here. The results underpinning this thesis and the findings derived therefrom have led to the identification of a number of issues that can influence student progression in chemistry during student tenure in Swedish upper high school chemistry classes.

More specifically, the results presented in this thesis shall hopefully contribute to the future teaching of chemistry by being of use:
- to policy makers and those involved in the revision of national curricula
- to textbook authors
- to teachers
- to fellow researchers in the field of chemistry didactics, and in particular those studying the role of the particulate nature of matter in chemistry teaching.
- to students of chemistry in Swedish and other education systems through impact upon the above.

The findings presented in this thesis highlight the need for further study of the teaching models of chemistry. One possibility for further research could be identifying “optimal” levels of simplification for the various teaching models, in order to construct a more coherent framework for school chemistry, so as to better support teachers and students of chemistry.
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