Redox models in chemistry

A depiction of the conceptions held by secondary school students of redox reactions

Lise-Lotte Österlund
To my family
Abstract

According to previous research, students show difficulties in learning redox reactions. By the historical development different redox models exist to explain redox reactions, the oxygen model, the hydrogen model, the electron model and the oxidation number model. This thesis reports about three studies concerning conceptions held by secondary school students of redox reactions. A textbook analysis is also included in the thesis.

The first study was an investigation of the students’ use of redox models in inorganic contexts, their use of the activity series of metals, and the students’ ability to transfer redox knowledge. Then the students’ work with an open-ended biochemical task, where the students had access of the textbook was studied. The students talk about redox reactions, the questions raised by the students, what resources used to answer the questions and what kind of talk developed were investigated. A textbook analysis based on chemistry books from Sweden and one book from England was performed. The redox models used as well as the dealing with redox related learning difficulties was studied. Finally, the students’ conceptions about redox in inorganic, organic and biochemistry after completed chemistry courses were studied.

The results show that the students were able to use the electron model as a tool to explain inorganic redox reactions and the mutuality of oxidation and reduction was fundamental. The activity series of metals became a tool for the prediction of reducing agent in some reactions. Most of the students rejected that oxygen is a prerequisite for a redox reaction. In the biochemical task the resource most used to answer the raised questions were the students’ consultation of the textbook – together or individually. Most questions resulted in short answers and the majority of these questions were answered. Questions concerning redox were analysed by the students and integrated into a chemical context but they could neither identify the substances oxidised or reduced nor couple the concepts to transfer of hydrogen atoms. The majority of these redox questions became unanswered. The textbook helped the students to structure a poster as well as to answer basic chemistry questions. For questions about organic and biochemical redox, the book was of no help. The textbook analysis showed that all historical redox models are used. Different models are used in inorganic, organic and biochemistry. The mutuality of oxidation and reduction is treated differently in subject areas. The textbooks did not help the reader linking the different redox models that were used. Few redox-related learning difficulties are addressed in the books. After completed chemistry courses the students had major problems to justify a redox reaction explained by transfer of hydrogen atoms both in the organic and biochemistry examples.


# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preface</strong></td>
<td>8</td>
</tr>
<tr>
<td><strong>List of papers</strong></td>
<td>10</td>
</tr>
<tr>
<td><strong>1. Introduction</strong></td>
<td>11</td>
</tr>
<tr>
<td><strong>2. Theoretical background</strong></td>
<td>13</td>
</tr>
<tr>
<td>2.1 Redox models</td>
<td>13</td>
</tr>
<tr>
<td>2.1.1 Historical development</td>
<td>13</td>
</tr>
<tr>
<td>2.1.2 Redox models in different disciplines of chemistry</td>
<td>15</td>
</tr>
<tr>
<td>2.2 To teach and learn redox reactions</td>
<td>17</td>
</tr>
<tr>
<td>2.2.1 Constructivism</td>
<td>17</td>
</tr>
<tr>
<td>2.2.2 Models in science and models in science education</td>
<td>18</td>
</tr>
<tr>
<td>2.2.3 Specific teaching and learning problems related to redox</td>
<td>20</td>
</tr>
<tr>
<td>2.2.4 Textbooks</td>
<td>22</td>
</tr>
<tr>
<td><strong>3. Aim and rationale of the studies</strong></td>
<td>24</td>
</tr>
<tr>
<td><strong>4. Methodology</strong></td>
<td>26</td>
</tr>
<tr>
<td>4.1 Methodological considerations</td>
<td>26</td>
</tr>
<tr>
<td>4.2 Data collection methods and analysis</td>
<td>28</td>
</tr>
<tr>
<td>4.2.1 Interviews</td>
<td>29</td>
</tr>
<tr>
<td>4.2.2 Video observation</td>
<td>30</td>
</tr>
<tr>
<td>4.2.3 Textbook analysis</td>
<td>31</td>
</tr>
<tr>
<td>4.3 Credibility</td>
<td>32</td>
</tr>
<tr>
<td>4.4 Ethical principles</td>
<td>33</td>
</tr>
<tr>
<td><strong>5. Summary of the articles</strong></td>
<td>34</td>
</tr>
<tr>
<td>5.1. Article I: Students’ understanding of redox reactions in three situations</td>
<td>34</td>
</tr>
<tr>
<td>5.2. Article II: Questions, reasoning and redox reactions: the work of upper secondary school students on an open-ended biochemistry task</td>
<td>35</td>
</tr>
<tr>
<td>5.3. Article III: Redox models in chemistry textbooks for the upper secondary school: friend or foe?</td>
<td>36</td>
</tr>
<tr>
<td>5.4. Article IV: The conceptions held by upper secondary school students of redox reactions in inorganic, organic and biochemistry</td>
<td>37</td>
</tr>
<tr>
<td>5.5. Summary of main findings</td>
<td>39</td>
</tr>
<tr>
<td><strong>6. Discussion</strong></td>
<td>41</td>
</tr>
<tr>
<td>6.1 Students’ conceptions about redox reactions</td>
<td>41</td>
</tr>
<tr>
<td>6.2 The textbooks’ contribution to the students' conceptions about redox</td>
<td>44</td>
</tr>
<tr>
<td>6.3 Implications</td>
<td>45</td>
</tr>
<tr>
<td><strong>Acknowledgement</strong></td>
<td>51</td>
</tr>
<tr>
<td><strong>References</strong></td>
<td>52</td>
</tr>
</tbody>
</table>
Preface

My interest in chemistry began very early, while I was still in lower secondary school. I remember that before Christmas, a catalogue from the local toy store arrived at our home, showing a huge variety of things to tempt a girl aged 10. However, what caught my eye and what was put at the very top of my Christmas “wish list” was a chemistry set.

Finally, on Christmas Eve, it was time to open my presents. A large, rectangular box was put into my lap and I tore the paper off: there it was, Chemistry Set Number 2.

This set really caught my interest. The instructions for one of my favourite experiments, Number 20, were as follows: “Dip a clean iron nail for two minutes in a solution of copper sulphate (two measures in a small test tube, half-filled with water). Remove and inspect it!” The explanation of the experiment was expressed: “Experiments 20 – 22 are examples of reactions where the immersing of a metal A into a solution containing a metal B, causes a displacement of B when A takes its place in solution – for example iron + copper sulphate \(\rightarrow\) iron sulfate + copper. This is a shift equation. The solid brown substance is copper, and the solution contains ferrous sulphate.”

In retrospect, I know it was the experiment that fascinated me, and not the chemical explanation. The beautiful coloured crystals turned the water bright blue and, as if by magic, the nail was coated with a solid substance and the blue colour in the water almost disappeared. I remember that I did this experiment time and time again. If I had known at that time as an adult I would become a doctoral student learning about this kind of reaction, it would have sounded like a fairy-tale. Today, almost 35 years later, this is my reality. I found my chemistry set in my parents’ attic recently and when I opened it, even the nails were still in the box.

Chemistry in lower secondary school is something I have little memory of, but studying chemistry at upper secondary level in the Natural Science Programme is still very clear. Unfortunately, I found the chemistry we learned very difficult and compartmentalized both within and between the science subject areas. My interest in chemistry faded, while my interest in mathematics grew stronger. When it came time to apply for university courses, however, neither subject area felt completely ‘right’ and I settled for a course that would cover my interests in a more general way: qualification as a health inspector. The training included a variety of subjects, and eventually it was time for a 4-point course in chemistry. I rather dreaded this course because of the negative experience I had had in upper secondary school. However, it became something of an epiphany for me: we worked with real analysis of PCB levels in salmon and many of the pieces of the
confusing chemistry ‘puzzle’ fell into place. I decided to transfer to a course in teacher education, focusing on biology, chemistry and mathematics.

I graduated in 1987 and got a job as a teacher in the lower secondary school in Arvidsjaur in the north of Sweden. I stayed in Arvidsjaur for 10 years teaching my subjects. In the autumn of 1997, I moved to Piteå, where I worked for four years at a natural resource school, again teaching mathematics, chemistry and computer science. My continued and increasing interest in biochemistry led me to decide in 2004 to continue my studies in this subject: I was awarded my Master’s degree in the autumn of 2005 and then enrolled in my doctoral studies in chemistry education research.
List of papers

This thesis is based on the following articles. In the text they will be referred to using the following Roman numerals:


IV. Österlund, L-L. The conceptions held by upper secondary school students of redox reactions in inorganic, organic and biochemistry. *Submitted, 2010, to RISE (Research in Science Education)*.

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1. Introduction

“The true voyage of discovery consists not in seeking new lands, but in seeing with new eyes”

- Marcel Proust

Redox reactions are part of the world around us and important components of the processes that sustain life, so important that they have been called the driving force of the biosphere (Anonymous, 1978). I believe that knowledge about redox reactions is important, not only for the chemical disciplines themselves but also for people in general. Redox reactions are common chemical reactions in everyday life. Knowledge about this issue provides to the means of understanding and participating in many debates, such as sustainable development. Redox reactions have a significant impact on, for example, the model for global warming where redox reactions explain the production of greenhouse gases: amongst others, the carbon dioxide production by the combustion of carbon compounds, the formation of nitrous oxide by oxidation of ammonia, and methane production such as in anaerobic decomposition of biomass. (Solomons & Fryhle, 2008; Zumdahl & Zumdahl, 2010).

In this thesis, I present my studies of the conceptions held by upper secondary students enrolled in the Natural Science Programme about redox reactions in different subject areas. With conception I mean students’ ideas about redox reactions which they express in their explanations. There were several reasons for my choice of study. Firstly, these reactions are considered difficult to learn (e.g., de Jong & Treagust, 2002). Secondly, in my own schooling, I experienced compartmentalisation of the teaching of science – not least in the teaching of redox reactions in chemistry and biology subjects. Another reason to study students’ conceptions of redox reactions is that most studies in the field were conducted in the 1990s – thus rather old – and mainly carried out in inorganic chemistry. As far as I know, research on students’ conceptions of redox in organic and biochemistry has not been undertaken. On the other hand, Anselme (1997) reports from his own classroom experiences university students problems in understanding organic redox reactions because different redox models are used in inorganic and organic chemistry.

Upper secondary school students enrolled in the Natural Science Programme became the target group for my study. I chose this group of students because they meet redox in several contexts and subject areas
according to the course objectives in chemistry (Skolverket, The Swedish Agency for Education, 2000).

The research summarised in this thesis is in the field of chemistry education. It can be viewed as a bridge anchored in both the disciplines of chemistry and pedagogy. Depending on the focus of the research, the disciplines meet somewhere on the “bridge” (Sjøberg, 2005). Figure 1, modified after Sjøberg, illustrates that bridging process.

![Figure 1](image)

*Figure 1.* Chemistry education research viewed as a research field underpinned by both chemistry and pedagogy.

The conceptions held by students of redox reactions is the main focus of this thesis. As the theories for redox reactions have developed over time, different redox models have also developed to explain these reactions. These historically scientific models are accepted redox models in different chemistry disciplines, for example inorganic, organic and biochemistry. Scientific models such as the redox models are as well used in chemistry education to explain redox reactions. In education the textbooks are teaching aids, written with the intention of supporting the students’ learning. According to the constructivist theory of learning, learning occurs when an individual constructs their own knowledge, for example on the issue of redox reactions. In the literature, however, both redox-related teaching and learning problems are identified (e.g., de Jong, Acampo & Verdonk, 1995; Garnett & Treagust, 1992).

The theory and research framing this study can be set to the following areas; redox models (historical development and the models in a number of chemistry disciplines), to teach and to learn redox (constructivism, models in science and science education, specific redox-related teaching and learning difficulties and textbooks.) These areas will comprise the major part of the next section, Theoretical background.
2. Theoretical background

2.1 Redox models

This section begins with a historical review of the development of theories describing redox reactions and thus the development of different redox models. How redox models are applied in today’s chemistry disciplines of inorganic, organic and biochemistry at the university level will also be presented.

2.1.1 Historical development

The historical development of the concepts of oxidation and reduction has subsequently given rise to various redox models; the oxygen model, hydrogen model, electron model and oxidation number model. These four models are all central in this thesis because they are all used in today’s chemistry education. I will therefore give a historical overview of the concepts of oxidation and reduction and the development of related redox models.

Human beings have managed to extract metals from their oxide ores since ancient times. In the extraction process, charcoal was combusted. The charcoal acted both as fuel by providing heat and as a reducing agent, and the metal was reduced from the metal oxide, (re-(lat.) = back and ducere (lat.) = before) (Ringnes & Hannisdal, 2000, p. 154).

The philosophical idea of Aristotle (384–322 BC) that everything was built of the four elements of fire, air, water and earth survived into the 1600s. However, by the time of the scientific revolution, this theory was insufficient to explain combustion: a scientific explanation was needed. Stahl’s theory, the “phlogiston theory”, made its entrance in the early 1700s and its explanation of the combustion process reigned supreme for almost 100 years (Asimov, 1966, p.18, 46). Stahl explained that all combustible materials contained phlogiston. Ash, for example, was left without phlogiston and therefore could not burn. With a similar approach, a change of metal ore into free metal could also be explained. Phlogiston-poor oxide ores are heated with phlogiston-rich charcoal. Phlogiston moves from the charcoal to the oxide ores. The charcoal is then phlogiston-poor and the oxide ore forms a phlogiston-rich metal (ibid., p. 46).

Lavoisier, who was a supporter of the phlogiston theory, also studied the combustion process in the late 1770s. A contemporary scientist named Priestley had discovered a kind of air, "phlogiston-free air", which made a glowing wooden stick flare up when it came into contact with the “air”. By making quantitative combustion experiments, Lavoisier perceived that air
was a mixture of two gases: the “phlogiston-free air”, to which he gave the name oxygène and “azote”, no life. Lavoisier called reactions with oxygène oxidations (Asimov, 1966 p. 59; Ringnes & Hannisdal, 2000, p. 154). An example is the combustion of carbon by the formation of carbon dioxide, as seen below:

\[ C(s) + O_2(g) \rightarrow CO_2(g) \]

Later, during the 1830s, Liebig explained oxidation as a hydrogen loss. He had observed that organic compounds could, through reaction with hydrogen, be reduced. By losing hydrogen, an organic compound could also be oxidized. A primary alcohol could be oxidized to an aldehyde by losing two hydrogen atoms as in the example below (Ringnes & Hannisdal, 2000, p. 155-156).

\[ CH_3CH_2OH \rightarrow CH_3CHO + 2H \]

Faraday worked during the same decade as Liebig, the 1830s, but in the area of electrochemistry. He discovered that a solution could lead electric current. He called the solution an electrolyte and the cells carrying the electrical current ions. Ions moved in the solution, anions to the anode and cations to the cathode (Asimov, 1966, p. 138). By 1884, oxidation had been explained both as an oxygen gain and as a hydrogen loss when Arrhenius adopted Faraday’s concept of ions. For example, when sodium chloride (NaCl) is dissolved in water, it breaks down forming ions carrying a positive or negative charge. Another explanation was presented by the oxidation. Arrhenius called a reaction where the ion charge increases an oxidation, and a decrease in ion charge a reduction, see the example below (Asimov, 1966, p. 140; Ringnes & Hannisdal, 2000, p. 156).

**Oxidation:** \( Fe \rightarrow Fe^{2+} \rightarrow Fe^{3+} \)

**Reduction:** \( Fe^{3+} \rightarrow Fe^{2+} \rightarrow Fe \)

In 1897, Joseph John Thomson, established that cathode rays consist of negatively charged particles, electrons (Asimov, 1966, p.173). With this discovery, a theory of the atomic structure was developed. He suggested a model of the atom as a positive substance where electrons are positioned by electrostatic forces, (ibid., p. 173-174, 176). In 1902, Lewis postulated that sodium chloride could be formed by a complete electron transfer from sodium atoms to chlorine atoms. Through electron transfer, both sodium and chloride atoms get eight electrons, filled a valence shell. The fourth
definition of oxidation was presented as a loss of electrons. Reduction was defined as a gain of electrons (Ringnes & Hannisdal, 2000, p.156).

\[ \text{Oxidation: } 2\text{Na} \rightarrow 2\text{Na}^+ + 2\text{e}^- \]

\[ \text{Reduction: } \text{Cl}_2 + 2\text{e}^- \rightarrow 2\text{Cl}^- \]

According to Lewis, atoms forming a molecule can share pairs of electrons involved in covalent bonds. Atoms have different electronegativity and Linus Pauling developed during the 1930s a method to determine the values of electronegativity. Thus oxidation and reduction could also involve reactions with incomplete electron transfer. Such a reaction can be illustrated between hydrogen and chlorine gas, forming a molecule of hydrogen chloride. The electron density is lesser around the hydrogen atom in the hydrogen chloride molecule than in the hydrogen molecule and hydrogen is oxidised. Chlorine is at the same time reduced (Asimov, 1966, p. 190; Ringnes & Hannisdal, 2000, p. 157):

\[ \delta_+ - \delta^- \]

\[ \text{H}_2 + \text{Cl}_2 \rightarrow 2\text{HCl} \]

By imagining that the electrons would have been completely transferred to the most electronegative atom in the molecule (in this case the chlorine atom) and then calculating the charge of the participating atoms, an oxidation number is determined (ibid.).

\[ \text{H}_2 + \text{Cl}_2 \rightarrow 2\text{HCl} \]

This shows that according to the oxidation number model, hydrogen has increased its number from 0 to +I, i.e. an oxidation – and chlorine has decreased its oxidation number from 0 to –I, a reduction (Ringnes & Hannisdahl, 2000, p. 158-159; Zumdahl & Zumdahl, 2010, p. 162-163).

### 2.1.2 Redox models in different disciplines of chemistry

I will present below how redox models are applied today in inorganic chemistry, organic chemistry and biochemistry at university level, to give an insight into how redox models are used in more advanced chemistry. The presentation is based on three books – Nelson and Cox (2004), Solomons and Fryhle (2008), Zumdahl and Zumdahl (2010) – aimed for studies at university level showing the way different disciplines of chemistry deal with redox. The selected books are used in chemistry education at Umeå University according to teachers working in these disciplines (T. Hedlund,
Inorganic chemistry is the study of the elements and their compound chemistry. All chemical compounds are inorganic, except those containing carbon and hydrogen, which belong to organic chemistry. In inorganic chemistry, redox reactions are defined as reactions where one or more electrons are transferred. It can occur either as a complete or partial transfer of electrons, i.e. the electron model is used. Two methods are used to balance oxidation and reduction reactions; the oxidation number model and half-reaction. The oxidation number model is used as a way to track electrons, especially in redox reactions forming covalent bonds. For more complicated redox reactions, such as reactions occurring in aqueous solutions, half reactions are often used to identify the oxidation and reduction reactions. At this level of chemistry, there is a need to consider if the reactions occur in basic or acidic solution as the half-reaction method differs slightly, depending on these environmental factors. The mutuality of a redox reaction is not explicitly addressed (Zumdahl & Zumdahl, 2010, p. 161-162, 817).

Organic chemistry is the science of carbon compounds. Organic compounds always contain carbon and hydrogen, but often other elements as well. Common atoms included are oxygen, nitrogen, halogens, and sometimes sulphur or phosphorus. In organic chemistry redox reactions are most often explained using the hydrogen and the oxygen model. A reduction is usually defined on the basis of an organic molecule that increases its hydrogen content or decreases its oxygen content. One example is the conversion of carboxylic acid to an aldehyde: a reduction as the oxygen content decreases. The conversion of an aldehyde to an alcohol is a reduction as well, because the hydrogen content increases. Oxidation is defined as the opposite, an increase of the oxygen content or the decrease of hydrogen content in an organic molecule. The oxidation number model is also used to determine oxidation and reduction. The assignment of the oxidation number is based on “the groups attached to the carbon (or carbons) whose oxidation state undergoes change in the reaction we are considering” (Solomons & Fryhle, 2008, p. 516). The mutuality of the redox reaction is also defined in that when a compound is reduced a reducing agent must be oxidized, and when a compound is oxidized an oxidizing agent is reduced (ibid., p. 515-516).

Biochemistry is the science of the molecules and chemical processes occurring in living organisms. Nelson and Cox (2004, p. 508, 509, 512) describe biochemical redox reactions with the hydrogen model, i.e. an oxidation is a loss of hydrogen and a reduction is a gain of hydrogen. The concept dehydrogenation is used synonymously with oxidation. Even if the redox reaction is described by hydrogen transfer, the participation of the
electrons in the reaction are identified as the driving force for biological work. A biological redox reaction is explained by when a substrate gives up two hydrogen atoms. Depending on the redox reactions, molecules such as NAD+, NADP+, FMN or FAD gains electrons and undergoes a reduction. FAD can serve example when it is fully reduced in the reaction below:

\[ \text{FAD} + 2e^- + 2H^+ \rightarrow \text{FADH}_2 \]

The mutuality of the redox reaction is also underscored by the explanation that the molecules listed above undergo reversible oxidation and reduction reactions by participating in many of the electron transfer reactions of the metabolism (ibid., p.512).

### 2.2 To teach and learn redox reactions

In this section, first an overview of constructivism as a learning theory will be presented. Secondly, a description of models in science and models in science education, ending with a description of redox models. Finally specific teaching and learning problems related to redox will be presented. To conclude, the role of the textbook in teaching will be reported and a discussion of some analysis of chemistry textbooks.

#### 2.2.1 Constructivism

This thesis is based on a constructivist tradition. One of the most important contributions to the theory of constructivism was developed by Jean Piaget (1896-1980) and has to do how individuals construct knowledge. One basic assumption of the theory is that individuals construct knowledge for themselves, even if social interaction is important for the acquisition and refinement of skills and knowledge (Schunk, 2004; Driver & Leach, 1993). The cognitive function of individuals, i.e. the intellectual processes that have to do with insight, sense and knowledge – is, according to Piaget, organised in schemes. The individual’s interaction with the environment will change the schemes, which implies that the cognitive structures will gradually change by the processes of adaption, assimilation and accommodation. New information will be more easily understood and learned if the information fits an existing scheme. These schemes will be confirmed and consolidated from that information. Information which does not fit into existing schemes will create a cognitive conflict; an imbalance with that already consolidated. An accommodation of the scheme must be made to achieve a new equilibrium. Piaget defined this process of adjustment as learning. New information which is anchored in previously-existing schemes will therefore be easier to learn than new information not
anchored to any or less-established schemes, leading to compartmentalized or rote learning (Cakir, 2008; Sjøberg, 1998).

The research conducted in this study focuses on students’ conceptions about redox reactions in different contexts. Students enrolled in the Natural Science Programme learn about these reactions throughout the chemistry course in upper secondary school. From a constructivist view, the individual student constructs knowledge about redox through teaching and social interaction. The taught message is either anchored to an existing scheme, a less-established scheme or no scheme at all. If the message is assimilated into an existing scheme the scheme has to accommodate the new information until equilibrium has been reached and learning takes place. Since different redox models are used in chemistry education depending on context, the student’s scheme must accommodate every new model introduced to reach equilibrium. It is easier for the student to learn redox in the different contexts if the information about a new model can be anchored to a previously-existing scheme; otherwise there is the risk that students only achieve rote learning.

In this study, I have used the students’ explanations as expressions for their thoughts and as qualitative measurements of the students’ conceptions of redox reactions and use of redox models in different contexts. The research reported in this thesis is not considered to belong to the conceptual change field of research. Conceptual change research works with identifying misconceptions or alternative frameworks to understand the persistence of certain concepts and how to get students to abandon less-developed ideas in favour of concepts that are more in line with scientifically-established theories. Conceptual change in learning can be viewed from the words *assimilation* – which here means when a student uses existing ideas to explain a new phenomenon – and *accommodation*, when a student uses inadequate current conceptions to explain a new phenomenon, thus needing to reorganise and replace current conceptions (Posner, Strike, Hewson & Gertzog, 1982).

This research aims at studying students’ conceptions about redox reactions in different situations and subject areas, and thus to identify the redox models that students use when they explain various phenomena. The study concerns conceptions held by students of several different redox models, and does not investigate the replacement of current ideas in the process of learning.

### 2.2.2 Models in science and models in science education

Since redox models are scientific models, I will give a brief description of the role of scientific models in science and in science education.
A scientific model is a human construction used to explain parts of our experienced life-world (Gilbert, Boulter & Elmer, 2000). Scientific models differ in appearance. According to van Driel and Verloop (1999) many attempts have been made to categorise scientific models on the basis of their differences, for example, as physical models – such as an atom – or descriptive models, which show for example the planets moving in orbits in our solar system.

However, scientific models also share many common features. For example, a model is always related to a target; the issue that we want the model to represent. This issue can be a scientific phenomenon, an object or a process. A scientific model can also represent an abstract target that is not visible or measured directly, such as the atomic model or a model of the black hole (ibid.). Models are also very important in the scientific research process. Gilbert and Boulter (1998) summarise functions of scientific models as important tools for interpreting results, generating predictions and developing scientific knowledge. However, depending on the specific research interest, models are simplified and certain aspects of the models are excluded. Thus scientific models can appear in many different forms in their representation of scientific phenomena.

As scientific models segregate our experienced life-world into smaller parts, scientific models are also important for teaching and learning (Harrison, 2000; Harrison & Treagust, 1998). The intention of using models in science education is to make science understandable (Justi & Gilbert, 2002). Teachers argue that without models it is almost impossible to teach non-observable entities such as electron flow, or chemical processes (Harrison, 2000; Harrison & Treagust, 1998). On the other hand, students seldom have a full understanding of how to use models in their explanations of phenomena (Boulter & Buckley, 2000). The nature of the models in science classes is seldom discussed, and the models are presented rather as facts to be learned, thus undermining constructivist teaching and learning strategies (van Driel & Verloop, 1999). Often, neither the function of the model nor how the model is connected to the studied phenomenon is explained. Consequently, the students cannot imagine the different ways in which models are connected to each other (Boulter & Buckley, 2000). Understanding models becomes a further obstacle if the models are changed without giving the reason for doing so. It should therefore be made clear when a new model is introduced in what way it differs from the previous model, and why this model functions better Carr (1984).

Concepts contain scientific information and scientific models are designed on the basis of concepts (Gericke, 2009; Gilbert et al., 2000; Novak, 1996; Schmidt, 1997). A concept is, like a model, a human construct which is ‘a package of meaning’ describing a pattern or a definition (Novak, 1996). A concept can also be seen as a carrier of a label, where each label corresponds
to a meaning, an explanation of a phenomenon; a model. Since scientific
theories and models in some cases develop over time, a certain concept can
be related to different theories. The meaning of the concept may change, but
the label remains (Schmidt, 2000). An example of this is the concept
oxidation which can be explained by a gain of oxygen, a loss of hydrogen, a
loss of electrons or an increase in the oxidation number. The same applies to
the concept of reduction, which has a label and can be explained as a loss of
oxygen, a gain of hydrogen, a gain of electrons or a decrease in oxidation
number. Ringnes (1995) has made a summary of the models to which the
concepts oxidation and reduction are related (Table 1). Three of the models,
– the hydrogen, the electron and the oxidation number model – also explain
the mutuality of a redox reaction; an oxidation and a reduction always occur
simultaneously (Nelson & Cox, 2004; Solomons & Fryhle, 2008; Zumdahl &
Zumdahl, 2010).

Table 1
Four redox models according to Ringnes (1995)

<table>
<thead>
<tr>
<th>Model</th>
<th>Reduction</th>
<th>Oxidation</th>
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<tr>
<td>1. Oxygen model</td>
<td>Loss of oxygen</td>
<td>Gain of oxygen</td>
</tr>
<tr>
<td>2. Hydrogen model</td>
<td>Gain of hydrogen</td>
<td>Loss of hydrogen</td>
</tr>
<tr>
<td>3. Electron model</td>
<td>Gain of electrons</td>
<td>Loss of electrons</td>
</tr>
<tr>
<td>4. Oxidation number model</td>
<td>Decrease of oxidation number</td>
<td>Increase of oxidation number</td>
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2.2.3 Specific teaching and learning problems related to redox
This section will provide the reader with insight into redox-related
teaching and learning difficulties found in the literature.

How to teach oxidation and reduction has been an issue of discussion for a
long time among chemistry educators. In the 1940s, it was discussed which
model was most advantageous to use in teaching. VanderWerf, Davidson and
Sisler (1945) argue for the oxidation number model over the established and
generally-accepted electron model, because the former includes complete
electron transfer and partial electron transfer as well. The oxidation number
model facilitates the balancing of redox reactions independently of complete
or partial electron transfer. Davies (1991) explains that the established redox
models (Table 1) are incompatible. In an educational context, a rote
application of the models may lead to confusion. He illustrates the incompatibility with the following example:

$$5\text{Fe}^{2+}(aq) + \text{MnO}_4^-(aq) + 8\text{H}^+(aq) \rightarrow 5\text{Fe}^{3+}(aq) + \text{Mn}^{2+}(aq) + 4\text{H}_2\text{O}$$

If only the hydrogen ion (H+) in the reaction is considered, then according to the *oxygen model*, an oxidation has occurred by gaining oxygen and a water molecule is formed. According to the *electron model*, hydrogen ions have been reduced by the taking up of electrons from the oxide ions, and a water molecule is formed. Neither oxidation nor reduction has taken place according to the *oxidation number model*. The oxidation number is +1 both before and after the reaction. Davies writes further that it easy for the teacher to underestimate the confusion that may be created when different models are used for a scientific explanation, particularly as students may not have a full understanding of the use of models.

The literature shows that teachers perceive redox as one of the most difficult topics to teach. According to de Jong et al. (1995), teachers experience difficulties in making the students adopt the electron model over the oxygen model. The students feel the electron model is superfluous since the oxygen model reports the same product in the given reaction. Ringnes (1995) on the other hand reports that most students define an oxidation as a loss of electrons, while few are able to demonstrate the electron transfer in equations.

In a study by Garnett and Treagust (1992), students were asked to explain which inorganic equations represented oxidation-reduction reactions. Many students explained the reaction in which oxygen was a participator as a redox reaction. Schmidt (1997) states that students identify oxidation as an addition of oxygen, and reduction as the removal of oxygen and suggest that this could be due to the syllable “ox” in redox.

The students’ use and understanding of the oxidation number model has been investigated (de Jong et al., 1995; de Jong & Treagust, 2002; Garnett & Treagust, 1992). Garnett and Treagust (1992) show that students believe that oxidation numbers can be assigned by changes in charges in polyatomic species instead of changes in the oxidation numbers of individual atoms. de Jong et al. (1995) maintain that students assign oxidation numbers according to the charges of ions. de Jong and Treagust (2002) summarise that students describe the oxidation number as ‘the number of oxidized substances’ and ‘how many times a substance can be oxidized’. Ringnes (1995) on the other hand shows that most students could produce an acceptable redox equation and explain what substance was oxidized by assigning the oxidation number.

Soudani, Sivade, Cros and Médimagh (2000) explain that university students relate the words oxidation and reduction to electron transfer. The
students fail to use theoretical redox knowledge in everyday situations such as the combustion of petroleum.

2.2.4 Textbooks

The textbooks intended for the Natural Science Programme are a part of this study. In this section, therefore, I will present from reviewed literature the role of textbooks in teaching and some analysis of textbooks. I will in particular present one analysis performed on acid and base models in chemistry textbooks, which is similar to the textbook analysis performed in this thesis.

Textbooks are widely used as a teaching aid and play a vital role for teachers in shaping the course content. The teachers use the textbook as a tool in organising their teaching and the textbook often replace the course curricula (Barros, Losada, Vega & Mondelo, 2001; Budiansky, 2001; Nelson, 2006; Weiss, 1993). The teachers consider the textbook to be important to the students as well, because the textbook contains important information which is collected in one place and homework can easily be based on it (Abimbola & Baba, 1996; Nelson, 2006). For the student, the textbook is a resource for learning (Cunningham, Duffy & Knuth, 1993; Smith & Jacobs, 2003). Science teachers are satisfied with the textbooks’ explanations of concepts and from their point of view textbooks are structured and clearly written (Weiss, 1993). However, some textbook analyses indicate that science textbooks often contain errors, misconceptions and oversimplifications. The authors use scientific information wrongly or the content can be too ‘simplified’ resulting in misleading information (Abimbola & Baba, 1996; King, 2010). The authors can also use a too-difficult language that it creates obstacles in learning (Pedrosa & Dias, 2000). Specifically in the area of electrochemistry, many simplifications and misleading statements are identified in textbooks, an additional source of misconceptions for the reader (Sanger & Greenbowe, 1999).

Besides the analysis of errors and misleading information in science textbooks, textbook analysis may be conducted using many different approaches. Notable examples are analyses of images in the books from different viewpoints. For example Han and Roth (2006) analysed the function and structure of chemical inscriptions in science textbooks, and Clément et al. (2008) analysed images of neuronal pathways in the human central nervous system. Others, such as Östman (1995) have analysed the use of language in chemistry textbooks and Harrison (1994) gives a review of textbook analogies for the scientific explanation of the refraction of light. In the field of acids and bases, Drechsler and Schmidt (2005) carried out a textbook analysis of four chemistry books intended for upper secondary schools in Sweden. The analysis was performed by identifying how the
textbook authors introduced and presented a number of acid-base concepts such as pH, salt and acid-base model. All acid-base equations were categorised according to different models, such as the Arrhenius and Brønsted models. None of the books promote the use of acid and base models as tools for understanding their properties, nor is any information given that different models are used in parallel. Only one textbook describes the history of the acid and base models, but in the text it is not clear which model is currently used.
3. Aim and rationale of the studies

The overall aim of research underlying this thesis is to describe students’ conceptions about redox reactions in different situations and subject areas. Upper secondary school students enrolled in the Natural Science Programme in Sweden, and chemistry textbooks intended for the programme’s chemistry course were used as the target for the study.

The following broad research questions were posed:

1. What conceptions do upper secondary school students have about redox reactions?
2. What contribution does the textbook make to the students’ conceptions about redox?

The questions were investigated empirically; the first question by an analysis and description of the students’ conceptions about redox reactions and their use of models in their explanations in different contexts. The second research question was addressed partly through a textbook analysis based on redox models used and the explanations of these, and partly by investigating the role of the textbook during students’ work with an open ended task. What follows below is a short rationale of the four studies comprising this thesis.

My research interest is students’ conceptions about redox reactions in different subject areas. Most of the previously-conducted research was carried out during the 1990s, mainly in the area of inorganic chemistry. Initially, I was interested in examining if the previously-identified redox-related learning problems still remained. The students’ conceptions in a number of inorganic redox reactions in different situations, both indoors and outdoors were studied. The students’ use of redox models was identified and problems related to their explanations of the reactions were investigated.

In the second study, I wanted to extend the students’ redox reasoning into a biochemical context. The students’ questions and their use of resources to answer their questions during a biochemical group task were studied. In this study, the students used the textbook as a support in their work.

The results from the previous studies motivated the next. The results indicated that the students showed both redox knowledge and some difficulties in the inorganic context (Study I). In the biochemistry context however, the students showed major understanding of redox difficulties, even when the students used the textbook (Study II). My overall question was; how do the textbook authors use and explain redox in various subject areas? My research continued with a textbook analysis of books intended for
the chemistry course. In each book I studied the use of redox models and the explanations of these in different subject areas.

The textbook analysis showed that the authors to a greater or lesser degree use all the established redox models in their texts. As the textbook is often important in teaching, I wanted to study the students’ conceptions of redox after completing their chemistry course. Since different redox models are traditionally used in inorganic, organic and biochemistry, I selected these subject areas for my study. I was interested to identify how the students explained redox on the basis of the models used and if the models became tools in their explanations.

All specific research questions can be found in the respective articles.
4. Methodology

4.1 Methodological considerations

In this section I will discuss the methods and theories I have chosen as appropriate to address the issues raised. Finally, the ethical principles that were employed are described.

In this thesis I have investigated students’ use of redox models and how redox models are described in textbooks. Ringnes (1995) definitions (Table 1) of the established redox models, with the extension of the mutuality of oxidation and reduction according to the hydrogen, electron and oxidation number model (Nelson & Cox, 2004; Solomon & Fryhle, 2008; Zumdahl & Zumdahl, 2010) have been used as analysing units. In the following, the mutuality will be ascribed to the definitions of these models. The reason for choosing these definitions was that they describe redox reactions in a scientific way at a sub-micro level i.e. atoms, molecules, ions and structures (Johnstone, 2000) which I found appropriate to address the problems. In the following sections I will address further considerations in each study.

In the first study, the purpose was to describe students’ reasoning about redox in three inorganic situations. The research questions concerned students’ model use, their reasoning about redox reactions, the activity series as a tool in their reasoning and the students’ abilities to transfer redox knowledge between situations. According to Oxford Advanced Learner’s Dictionary is reasoning is defined as “the process of thinking about things in a logical way; opinions and ideas that are based on logical thinking” (Reasoning, n.d). Logic is “a way of thinking and explaining something” (Logic, n.d) and thinking “ideas or opinions about something” (Thinking, n.d). Reasoning in this study concerns the students’ thinking and explanations of redox reactions, what conceptions students have about these reactions and how they explain the processes. The research questions were aimed at investigating the students’ explanations at a sub-micro level and thus their use of redox models and the activity series of metals as a tool in their explanations. I chose interviews as a data collection method because this method provides opportunities to ask supplementary questions such as "Can you tell me more about this reaction?" or "Can you describe what happens at the atomic level?".

The reason for using the activity series of metals as an analytical tool was to be able to identify if and how the series was used as a resource in the students’ explanations of what substance that was oxidized in a redox reaction.

In this study, I was also interested in investigating the students’ capabilities in transferring knowledge from a school situation to an outdoor
situation. To identify knowledge transfer, I used Bransford, Brown & Cocking’s (2000, p. 51) definition: “the ability to extend what have been learned in one context to new contexts”. I compared two different contexts by organizing two situations with similar chemical phenomena, one situation indoors and a similar situation outdoors.

I used individual interviews indoors and two individual and four two-group interviews outdoors. The reason for the shift from individual to group interviews was to increase the possibility of gathering data. According to Robson (2002, p. 283) interviews in groups may become flexible and effective as the interview is characterized as a discussion and group interactions can be utilized.

In the second study the overall aim was to investigate students’ own chemistry questions, their discussions and their use of resources to answer their questions while working in groups with a biochemistry task. According to Plowman (1998), video recordings capture many angles and provide rich data. The data collection method also gives the researchers the opportunity to repeatedly inspect the activities carried out at the time of the data collection (Heat, Hindmarsh & Luff, 2010, p.2). Therefore video observations were made in this study. However, obtaining high-quality video can be a challenge. The researcher is limited to what activities you actually can see and what you can hear (Barron, 2007).

The emphasis of the investigation was the students’ questions and talk about redox. As many young people are engaged in gym activities, the task was taken from this context to invite the students to talk and discuss redox. Since I was interested in the students' questions and discussion, I wanted to see to what extent complex discussion developed from the questions asked. Parts of the SOLO-taxonomy (Structure of the Observed Learning Outcome (Biggs & Collis, 1982) were therefore appropriate for use as the taxonomy defines, on the basis of a learner’s understanding of an issue, levels of complexity in mastering the issue.

In the third study, an analysis of textbooks, the research questions focused on the authors’ use and explanations of redox models and on how they handle a number of redox-related learning difficulties identified in the literature. I thought it was important to study if, and if so how textbook writers respond to the results of earlier research in the field of learning difficulties and redox. Based on the literature (e.g., de Jong & Treagust, 2002; Garnett & Treagust 1992; Schmidt 1997) three redox-related learning problems were selected in the analysis. The problems chosen for study in all subject areas were: oxidation and reduction as mutual reactions, problems in the identification of oxidizing and reducing agents, and the conception that in all redox reactions oxygen has to take part. I selected these since I considered them possible to analyze in the text and because these problems are associated with basic knowledge of redox.
The research questions in the fourth study focused on the students’ use of redox models in different subject areas. The research design was created to collect data about the students’ conceptions about redox both with little stimuli and with further stimuli in the form of material of a guiding nature, to pave the way for the students to discuss redox. I assumed that if the students could give explanations of redox with little stimulus, this would represent well-founded knowledge. If they had guiding material it would give the students something to talk about and reason around, encouraging them to express thoughts and explanations about the reactions even if they had less well-founded redox knowledge. I used group discussions which, according to Robson (2002), make the interviews flexible and the group interaction can encourage the students to talk and discuss with each other. I carefully selected examples of redox reactions in three subject areas; inorganic, organic and biochemistry to use during the interview. These areas were chosen because different redox models are traditionally used to describe and explain redox reactions in these areas. The degree of difficulty varied among the examples. In biochemistry it was difficult to find an appropriate example that could be implemented in the short time that the interview admitted. The students had, however, met all the examples during the chemistry course.

For a more elaborated description of the methods, I refer to Article I-IV.

4.2 Data collection methods and analysis

This thesis is mainly based on qualitative methods to address the research questions. Golafshani (2003) summarises, in qualitative research you seek to understand and produce findings on phenomena in the real-world by illumination and understanding. I have used this naturalistic approach to search for answers to the questions and produce findings which illuminate students’ conceptions about redox reactions. For this I have used different methods. Over time, I have developed the methods in addition to developing my knowledge and experience as a researcher.

Table 2 shows the samples, the schools and the data collection method for each study. I chose two different schools, A and B, in two different places in the northern Sweden. School A is located in a smaller town (~22 600 inhabitants) and school B in a small municipality (~6 700 inhabitants). All participating students volunteered for the study. All data collection was performed in groups or individual interviews. In study I, the teacher formed the groups while in Study II and IV the students formed the groups themselves. Altogether, 37 students participated, 20 students in school A and 17 students in school B. Three different data collection methods were used;
interviews, video observation and a textbook analysis. In the articles are excerpts. All are translated by myself.

### Table 2
*The samples, the age of the students, the chosen schools denoted by letters, and the data collection method for each study.*

<table>
<thead>
<tr>
<th>Study</th>
<th>Sample</th>
<th>Age (years)</th>
<th>School</th>
<th>Data collection method</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>10 students</td>
<td>17</td>
<td>A</td>
<td>Interview</td>
</tr>
<tr>
<td>II</td>
<td>10 students</td>
<td>17</td>
<td>A</td>
<td>Video observation</td>
</tr>
<tr>
<td>III</td>
<td>6 books</td>
<td>---</td>
<td>---</td>
<td>Textbook analysis</td>
</tr>
<tr>
<td>IV</td>
<td>17 students</td>
<td>18</td>
<td>B</td>
<td>Interview</td>
</tr>
</tbody>
</table>

#### 4.2.1 Interviews

Studies I and IV were conducted by semi-structured interviews. According to Kvale (1997), a semi-structured interview covers a range of themes and issues with the possibility to change the order and the form of the questions to follow up the respondents’ answers. The content of the interview guide in these studies consisted of an overview of chemistry areas that would be covered during the interviews, along with relevant questions. The guide was also open for the students’ spontaneous remarks where I could ask follow-up questions to check anything revealing and interesting. All interviews were centred around objects of varying natures, for example an experiment, a picture, images or formulas in the textbook or an object outdoors. I carefully selected all the objects, on the basis of my teaching experience. I considered it to be very important to choose items that showed commitment to the students, and made them feel relaxed. For example in Study IV, I was influenced by the Concept Cartoons (Keogh & Naylor, 1999) as a possible way to encourage students to talk about redox. I developed pictures along those lines, illustrating three students of the age of the respondents expressing opinions of the same examples of redox reactions as demonstrated during the interview. The respondents were then encouraged to talk about these opinions. Questions were also asked around pictures and text sections from the textbook. These objects facilitated the interview situation since they became both objects of enquiry and of reasoning for the students. For a more elaborated description of the objects used, I refer to Article I and Article IV.

All interviews were recorded. In the first study, the interview was recorded digitally on a mini-disc and in study number VI digitally on camcorder. The camcorder was primarily used to ensure the audio recording with the benefit that I could go back to the video if the audio provided insufficient
information about what students meant, for example talking about issues in
the book or pointing at something while they were talking - which otherwise
would have been difficult to interpret. The paper and pen notes from the
students’ chemical explanations and drawings were also used as a data
source.

All interviews were transcribed verbatim. The attention of the analysis in
the studies described above was directed to the students’ use of redox models
and how these models were used to explain redox reactions. I applied
Ringnes (1995) definitions (Table 1) as analysis units and put the definitions
in a grid for the identification of the students’ model use. Study VI showed,
however, that all explanations at the sub-micro level could not be covered by
Ringnes’ framework. An additional analytical unit was developed as the
students in some cases explained redox without using any redox model, for
example, giving explanations at the macroscopic level.

In Study I, attention was also directed to the students’ use of the activity
series of metals as a tool in their explanations of the reactions. By comparing
the students’ explanations of certain redox reactions with the activity series
of metals, it was possible to identify if the series became a tool or not in their
explanations.

An investigation of the students’ ability to transfer redox knowledge
between situations was also performed. The definition of transfer of learning
(Bransford et al., 2000, p.51) was used in the analysis by comparing
students’ explanations of a redox phenomenon in a school situation with a
similar phenomenon outdoors, and identify if, and if so what, redox
knowledge was transferred.

The written notes were used in the analysis to get deeper information
about certain passages in the interview.

4.2.2 Video observation

In Study III, video recordings were used to document the student groups’
reasoning and their work and to see clearly what the students were actually
doing (activities) as well as their discussion.

A digital camcorder was used for the video recordings. In all cases, the
camera was placed in front of the student group on a camera tripod. The
camera’s placement was checked carefully before the start of the group work
so it would be possible to identify the students’ activities. Initially, the
students may have been influenced by the presence of the camera. However,
according to Plowman (1998), students seem to forget the camera quickly. In
this study, it was of utmost importance in the analysis to identify for
example, which pages in the book the students consulted and their work with
the poster: hence the camera’s close proximity to the students. The posters
were collected from each group and were used as a data source.
The video observations were transcribed verbatim. The attention of the analysis was directed to the students’ chemical questions, the talk that developed from the questions raised, their use of redox models and use of resources available to get answers to their questions. Categorisation was performed to answer the research questions. Ringnes (1995) definitions were used as a grid to identify the redox models in the students’ explanations. All raised questions were identified and counted. The resources the students used to answer their questions were categorised. These were the students in the group, and the textbook. The students’ talk, which developed from the raised questions, was categorised. The SOLO-taxonomy (Biggs & Collis, 1982) was used as a starting point to analyse the talk. The taxonomy describes five levels of complexity which a learner displays in a given task. The levels are the prestructural, unistructural, multistructural, relational and extended abstract level. Certain characteristics are ascribed to each level. For example, at the prestructural level the student reports bits of information that is unconnected while at the extended abstract level the student can make generalizations from several aspects, analyse and relate information, and is able to make connections beyond the subject area (ibid.). In the evaluation of the students’ talk, the unistructural, multistructural and the relational levels were used. The group was considered as a unit during the analysis, not the individual students.

The groups’ posters were compared with each other in terms of structure, the concepts that were included and the manner in which the poster explained catabolism.

4.2.3 Textbook analysis

A textbook analysis was performed to assess the textbook authors’ use and explanations of redox models and how the authors handle redox-related learning difficulties identified in the literature (de Jong & Treagust, 2002; Garnett & Treagust, 1992; Schmidt, 1997).

The data was collected from upper secondary level chemistry textbooks, intended for the chemistry course in the Natural Science Programme, grade 10 to 12. The most used Swedish textbooks (2007) were analysed and these were: Andersson, Sonesson, Stålhandske, and Tullberg (2000), Andersson, Sonesson, Stålhandske, Tullberg and Rydén (2000), Borén, Larsson, Lif, Lillieborg and Lindh (2001), Borén et. al. (2005), Engström, Backlund, Berger and Grennberg (2001a, 2001b, 2005), Henriksson (2000, 2002), Pilström, Wahlström, Luning, and Viklund, (2000), Pilström, Nordlund, Luning, and Wahlström (2001). These books were examined as five books (N=5). An English textbook for the corresponding level, A and A2 level, was also chosen as a part of the investigation. These books were Nicholls (2008) and Harwood (2008) and were examined as one book (N=1). This book was
chosen to study if the findings in the Swedish textbooks are unique or if there are similarities elsewhere. To select an English textbook was partly practical as I can read English, but also because many students - not only those in the UK - read English textbooks.

In this analysis, the data consisted of text: captions, body text and summarizing factual explanations of redox reactions. These “redox” pages could be categorised into three main subject areas: inorganic chemistry, organic chemistry and biochemistry. It showed that much of the inorganic, the organic as well as biochemistry describes and explains spontaneous redox. I therefore chose to limit the material to concern spontaneous redox reactions in these three subject areas – i.e. not electrochemistry. Another reason to exclude electrochemistry is that other definitions are introduced to explain oxidation and reduction – for example, emf (electromotive force).

The focus of the analysis was the authors’ use of redox models and their explanations. Ringnes (1995) definitions (Table 1) were used for the categorisation of the models used in the text. To frame all representations of redox, the category “alternative representations” was developed as the authors used other ways to explain redox than the established definitions given by Ringnes. The analysis also dealt with the authors’ responses to redox-related learning difficulties identified in the literature. I selected a number of these learning difficulties. The text passages explaining these redox reactions in the text were identified. The text passages were classified as to whether the authors responded to the difficulty or not.

4.3 Credibility

This study was conducted by using qualitative methods. In contrast to quantitative researchers who seek predictions, causations and generalisations of findings, qualitative researchers seek to illuminate and understand situations that are similar to one another. Regardless of the methods used, the credibility of the studies has to be demonstrated. In quantitative research, credibility often depends on the construction of the instrument, whereas credibility in qualitative research depends on the researchers’ abilities and efforts. Credibility in quantitative research is referred to as its validity and reliability, while the terminology in qualitative research can be expressed differently (Golafshani, 2003).

To ensure the credibility of this study, I have used some of the criteria established by Larsson (1994): the discourse criterion, heuristic value, empirical anchorage and pragmatic criterion.

From the perspective of the discourse criterion, discussions of a research group have been used to determine the credibility of interpretations and created categories in the various studies. The discussions continued until consensus was reached. The partners in the research group have been
persons with great experience in chemistry teaching, science education research and chemistry research. Considering the contribution of knowledge that studies have led to, the design of the analysis was important to demonstrate the conceptions the students have of redox in different settings and create a heuristic value to the reader.

An empirical anchorage is about a line between interpretation and reality. This criterion requires a consistency between what describes the phenomenon (the student, the text in textbooks) and how the phenomenon was interpreted by the researcher. During the interviews, I have asked the respondent many interpretive or clarifying questions, or by reformulating a response such as “so you mean that...” or “do I understand you right when you are saying ....” to ensure that the interpretation was consistent with what the respondent actually meant. In the reports of the studies many direct quotes from students and textbook texts have been reproduced to give the reader a description showing clearly the interpretations of phenomena. The interpretations have been deemed reasonable by teachers because the results have given a feeling of recognition. To ensure the interpretation I have experiences of chemistry and chemistry teaching.

From the pragmatic criteria, I suggest that my contribution to knowledge can be used in the classroom, primarily in chemistry education in the upper secondary school, but also in chemistry education at university level.

The preface describes some of my experiences, which may have affected the interpretation of the data that I have made. During the writing I have tried to be as transparent as possible.

4.4 Ethical principles

In all studies in which students participated (Study I, II and IV) the four main requirements for the basic protection of integrity were presented to the informants (Vetenskapsrådet, 2006). All the informants were informed about their role in the project, that their participation was voluntary and that they could withdraw if they wished. All informants gave their consent to participation in the separate studies. Furthermore, they were informed that all data would only be used for research purposes, and handled in a confidential manner. In cases where data has been used for publishing, the identity of individuals has been disguised.
5. Summary of the articles

5.1. Article I: Students’ understanding of redox reactions in three situations

In this study we explored how students attending the Natural Science Programme in upper secondary school explain redox reactions in different situations. We also investigated how students use the activity series of metals in these situations and whether any redox knowledge was transferred between two of the situations, an indoor situation and an outdoor situation.

The analysis was based on 10 interviews conducted around inorganic redox reactions, two indoor experiments (situation 1 and situation 2) and a sculpture outdoors (situation 3). The experiment in situation 1 consisted of iron nails combined with other metals. Each iron-metal combination was immersed in water. In situation 2, zinc was immersed in copper sulphate solution. The sculpture, situation 3, was made of copper resting on a rusty iron stand.

For categorisation of the students’ model use, Ringnes (1995) definitions were used as analysing units. The activity series of metals was used as an instrument to evaluate the students’ use of the series as a tool. The result indicated that the students explain redox reactions mainly by using electron transfer, i.e. the electron model, in all situations. Some students suggested that oxygen could be involved in all redox reactions. Most students argued for the mutuality of redox reactions.

The activity series of metals is a tool to compare the reducing power of different metals. The students seemed to have the ability to use the series to predict both oxidizing and reducing agent in the situation where zinc was immersed in copper sulphate solution. On the other hand, when the students identified a non-metal as oxidizing agent - for example in the situation where iron was combined with copper surrounded by water - it seemed in some cases that the series became an obstacle. This can be due to the fact that the students were dealing with two solid metals and not a metal and metal ion. The students had difficulties in identifying what substance became the oxidizing agent. This was shown in the situations where the students were explaining corrosion. However, students seemed to be familiar with the formation of copper oxide in air. The majority of the students could identify oxygen as the oxidant in this case.

The students were also able to predict some of the products formed in the redox reactions in the different situations, although the reaction mechanism did not seem to be completely understood. Their explanations indicated transfer of certain basic redox knowledge between the indoor and the outdoor situations, such as the use of the electron model, mutuality of redox
reactions and identification of the reducing agent, where the activity series of metals was suitable.

5.2. Article II: Questions, reasoning and redox reactions: the work of upper secondary school students on an open-ended biochemistry task

In Study II, the investigation continued with a study of students’ conceptions of redox but in a biochemical context. Students’ group work with an open-ended task on catabolism was studied, where the students were supported by the textbook. The study also focused on students’ questions during work, the discussion that developed and what resources the students used to answer their questions.

The analysis was based on 10 students of the entire class of 21, who volunteered to be video-recorded. These were high achievement students. The ten were divided into three groups: two groups with three students and one group with four students. The main task was that the students were to play the role of a personal instructor at a gym, and produce a poster an educational purpose. The poster should explain, at cellular and molecular levels, how energy is extracted from a meal. The analysis was performed by using categorisation to answer the research questions.

The results show that the groups worked purposefully with the task and each group created a poster. The students used the available resources in three ways to find answers to their questions: I) one student silently read the textbook and found an answer to the question, which was then spoken aloud; II) one student in the group answered the question without consulting the textbook; and III) the group members consulted the textbook together. Altogether, 93 questions were raised in the three groups. 19 of these were clearly related to redox reactions. The students consulted the textbook – together or individually – to answer most questions.

The questions which were raised entailed discussion of different complexity in the groups. Approximately half of the questions produced shorter discussion, such as a short answer to a posed question. Approximately one third of the questions produced discussion that focused on a very limited chemistry area, but involved chemical issues from more than one aspect. About a quarter of the questions stimulated discussion in which the students analyzed and related information which was then incorporated and integrated into a context. Most of these questions concerned redox reactions. The analysis indicated that biochemical redox reactions, described by hydrogen transfer, were difficult to grasp and understand. The students could neither see similarities nor differences between inorganic and biochemical redox; rather, they were confused over in which way the electrons participated in the reaction.
There were differences between the groups’ use of resources, the complexity of the discussion that developed and how many questions were answered or unanswered. However, the posters – the concrete result handed over to the teacher – did not differ much in terms of structure or the concepts used.

5.3. Article III: Redox models in chemistry textbooks for the upper secondary school: friend or foe?

Based on previous studies, we had an interest in studying the Swedish chemistry textbooks’ use of redox models and explanations of redox reactions in different subject areas, which became an aim of this study. Since multiple redox models are in use, the aim was also to study whether, and if so how, the authors explain the substitution of redox models within and between subject areas. As the literature indicates redox-related learning difficulties (e.g. de Jong & Treagust, 2002; Garnett & Treagust, 1992; Schmidt, 1997), we also studied how the authors deal with a number of these difficulties in the textbooks.

Chemistry textbooks from Sweden (N=5) intended for the upper secondary school Natural Science Programme and one textbook from England (N=1) were analysed. The analysis was carried out in two steps. In the first step, all text where oxidation, reduction or redox was described - regardless if these concepts are used or not - was identified. The number of these pages was estimated.

In the second step of the analysis, on the basis of Ringnes (1995) definitions of redox models (Table 1), text passages where the redox models were used were identified. Four categories of model use were formed. There was also text describing redox that could not be attributed to any of these categories. These were assigned to a fifth category called ‘alternative representations’, such as “split water into oxygen and hydrogen” (Henriksson, 2002, p. 205).

How the concepts of oxidation, reduction and redox were used was studied by searching for the concepts in the text in relation to the identified use of redox models in the texts. The quantitative part of the analysis was carried out by estimating the frequency of the use of models and their explanations.

From the learning difficulties identified in the literature, three difficulties were selected. These concerned oxidation and reduction as mutual reactions, identification of oxidizing and reducing agents and that oxygen takes part in all redox reactions. The textbooks were searched to reveal in which way the authors explain these issues. The results show that redox reactions are described with great detail in inorganic chemistry, both in Swedish and English textbooks. Redox reactions are described in other subject areas as
well, such as organic and biochemistry, but to a lesser extent. However, redox reactions are also frequently used to illustrate other chemical phenomena than redox; for example, equilibrium reactions and thermodynamics. A total occupies redox reactions a space of 16-24% of the total text pages in the books.

All redox models are represented in the textbooks. The authors mainly use the electron and oxidation number model in inorganic chemistry; oxygen and hydrogen model in organic chemistry; and most often the hydrogen model and "alternative representations" in biochemistry.

In inorganic chemistry, all authors justify the substitution of redox models by explaining why the oxidation number model may be used instead of the electron model. On the other hand, when substitution of redox models occurs across subject areas, such as between inorganic and organic chemistry, the authors provide no justification or explanation of why the current model is replaced, what is the difference between the 'the old' and 'the new' model and why the 'new' model works better.

Regarding the studied learning difficulties, the authors addressed the students’ difficulties in perceiving oxidation and reduction as mutual reactions only in inorganic chemistry, by explicitly declaring that oxidation is a loss of electrons and reduction is a gain of electrons. The other investigated learning difficulties were not considered in texts.

5.4. Article IV: The conceptions held by upper secondary school students of redox reactions in inorganic, organic and biochemistry

The previous articles report on students’ conceptions of redox reactions in inorganic and biochemical contexts, and the use chemistry textbooks make of redox models and explanations of redox in different subject areas. By the end of upper secondary school, students have met different redox models in both the Chemistry A-course and Chemistry B. Therefore, the aim of Study IV was to investigate students’ conceptions of redox reactions after having completed their chemistry courses, by using examples of redox phenomena from the subject areas inorganic, organic and biochemistry. I also wanted to identify in what ways the models became tools the students used in their explanations.

The entire class of 17 students volunteered to be interviewed in groups. The students were encouraged to form the groups themselves so that they would feel comfortable with their group mates during the interview. Seven pairs of students and one three-student group were formed.

The basic idea for the data collection was to begin the interview with open questions and later give more stimuli, hints, focused on redox reactions. The interviews were conducted around examples of redox phenomena, in
inorganic chemistry, organic chemistry and biochemistry. In each respective subject area the examples were: a magnesium strip burning in air, a wine bottle containing ethanol oxidized into acetic acid and a photo of two persons pedalling bicycles. Further stimuli were added, such as pictures illustrating students giving explanations of redox phenomena. Finally, some selected formulas or text sections from the students’ textbook were presented to the students (Andersson et al. 2000a; Andersson et al. 2000b).

For each example, starting with the inorganic example, the interview followed the order: 1) the students talked about their expectations of the example; 2) the researcher demonstrated the redox reaction (for example the students were allowed to smell the oxidized ethanol); 3) the researcher showed the picture; 4) the researcher showed sections from the textbook.

The data from the students’ spontaneous explanations of redox and the students’ explanations with material of a guiding nature was analysed. For categorisation of the students model use, Ringnes (1995) definitions were applied as analysing units. Explanations that concerned redox but could not be attributed to Ringnes’ definitions have been categorized as “no model” was used. A model was classified as a tool the students use when they used the model to explain a redox reaction. On the other hand, the model was not classified as a tool if it was used in an inconsistent scientific way or if the students indicated incomprehension such as “how can it be like this?”

The results show that initially the students’ expressed themselves in a macroscopic way such as “magnesium will form crumbs”, i.e. using no redox model. When they were guided into chemical explanations, the students mainly used the electron model in the inorganic example, where the model thus became a tool. The majority of the students rejected the suggestion that oxygen has to take part in all redox reactions.

In the organic example, half the groups used the electron model, but the model was not classified a tool because the model was used in an inconsistent scientific way. Half the groups used the oxygen model. The model was used in an additive way (de Jong & Taber, 2007) to explain the reaction and it is difficult to say if the model could be classified a tool. Even with guidance, in the organic example, the students had difficulties in utilizing the hydrogen model as a model to explain a redox reaction. The hydrogen model was therefore not used as tool in their explanations.

In the biochemical example, the students either got stuck or used a mix of the electron and the hydrogen models in their explanations, where the models could not be classified as tools as they were used in an inconstant way. The way the students justified the use of the hydrogen model was by highlighting the importance of NAD⁺ and FAD as ‘hydrogen carriers’. Further, just a few considered NAD⁺ and FAD as carriers of electrons. Some students assumed that the electrons entering the respiratory chain were located in a ‘pool’ nearby the chain.
The students seemed to consider oxidation and reduction as mutual reactions in all subject areas, although some students expressed some uncertainty in the organic example.

5.5. Summary of main findings

The overall aim of this thesis was to describe students’ conceptions about redox reactions in different situations and subject areas. I will summarise below the results from the different studies and answer the research questions.

The electron model seemed to be a reinforced tool in the students’ explanations of inorganic redox reactions. They were able to use the electron model with minor stimuli from basic examples of inorganic redox such as magnesium burning in air. The activity series of metals seemed to be a tool for prediction of redox reactions between a metal and a metal ion in solution. The students in this study seemed not to have the conception that oxygen is a prerequisite for a redox reaction.

As stated above, the electron model seemed to be a tool for explaining basic inorganic redox reactions. Many students continue to use the electron model when explaining redox reactions from examples in organic and biochemical contexts as well. The use of the electron model in these contexts seemed to become very confusing for the students, because they could not understand in what way the electrons participated. Regarding the organic redox reactions, the students could not justify use of the hydrogen model and when they used the oxygen model it was used in an additive way; i.e. from the reactants and the product they put substances together to form the product with the right elements.

Neither in biochemical redox reactions could the students justify the use of the hydrogen model. In cases where NAD$^+$ is reduced to NADH, the students considered the reaction rather as a hydrogen loss where NAD$^+$ acts as a hydrogen carrier. They seemed unaware of NADH as a carrier of electrons. For example, some students suggested that the electrons, which are delivered by NADH to the electron transport chain, were lying in an ‘electron pool’ nearby the chain.

The students considered oxidation and reduction as mutual reactions in all the studied chemical areas, although there was some doubt about this issue in organic redox reactions. Few students made attempts to use the oxidation number model.

The textbooks use all established redox models according to Ringnes (1995) with an addition of alternative representations where redox is explained but could not be referred to the models described by Ringnes. The authors used the models in quite similar ways in inorganic chemistry and organic chemistry, while the variation was larger in biochemistry. In
In inorganic chemistry the oxygen model is used but justified as a historical model. Instead oxidation and reduction are introduced according to the electron model. The model is well-defined as are oxidation and reduction as mutual reactions. The introduction of the oxidation number model is justified by partial electron transfer.

In organic chemistry, neither the reintroduced oxygen model nor the newly introduced hydrogen model are justified as models explaining redox instead of the previous used electron model. The mutuality of a redox reaction is not clear because only the concept of oxidation is used.

In biochemistry a mix of redox models are used for the explanation of redox. The hydrogen model which was introduced in organic chemistry is used in biochemistry as well but is not clearly explained in the books. Other expressions for oxidation and reduction for are used; a reduction is often described as a gain of hydrogen by a ‘hydrogen carrier’ such as NAD+, or “NAD+ is loaded with hydrogen”. None of the books support the mutuality of redox reactions.

Of the learning difficulties studied only one was considered in the text: the students’ difficulties in viewing oxidation and reduction as mutual reactions. On the other hand, this difficulty was only considered in inorganic redox reactions where the mutuality was clearly described.

The textbooks seemed to be of limited help to the students when they searched for answers to questions during group work. The book seemed to be a tool for the students when they structured their posters and needed answers to questions of a simpler nature. When it came to questions of a more complex nature such as redox reactions, the textbook was not of any help. The students’ redox questions remained unanswered.
6. Discussion

The overall aim of the work underlying this thesis was to investigate and describe students' conceptions about redox reactions in different situations and subject areas. In this section, I will discuss the results presented in this thesis. The first subsection addresses the first research question “What conceptions do upper secondary school students have about redox reactions?” and the second subsection the second research question “What contribution does the textbook make to the students' conceptions about redox?” Thereafter, the implications for teaching and learning redox will be addressed. Finally, suggestions for future research will be made.

6.1 Students’ conceptions about redox reactions

Over the course of history of modern chemistry, four redox models have developed which all are used in the chemistry education of today. To learn and to use these models for explaining redox seems to be a challenging task for students, since the outcome of this study shows varied results regarding the students' general conceptions and knowledge about redox reactions.

The students showed good redox knowledge when they were explaining inorganic redox reactions of a basic nature; such as a magnesium strip burning in air or zinc immersed in copper sulphate solution. They were also able to explain oxide formation in an everyday context from viewing a galvanic cell formed by the elements on a sculpture outdoors. They used the electron model in an appropriately scientific way in their explanations and the model seemed to be well-grounded. From the perspective of this study, it seems as if the students’ inorganic redox knowledge corresponds well to parts of the inorganic objectives for Chemistry A, which states that students should know and apply the concepts oxidation and reduction in an industrial and an everyday context (Skolverket, The Swedish National Agency for Education, 2000). This result is not in line with de Jong et al. (1995) who report that teachers experience difficulties in encouraging students to substitute the concept of oxidation as a gain of oxygen, with an electron loss according to the electron model. de Jong et al. report further that the students continue to use the oxygen model to explain oxidation because they believe there is no need to change model. However, Ringnes (1995) shows on the other hand that most students define an oxidation as a loss of electrons, but have problems in showing the transfer of electrons in equations. Most of the students in this study did not believe oxygen is a substance taking part in all redox reactions, while Garnett and Treagust (1992) state that students suggest that oxidation is an addition of oxygen. Other studies, such as Schmidt (1997) explain that students assume that the syllable ‘ox’ in redox is
an abbreviation of oxygen. The reason for the results in this study may be due to the well-grounded usefulness of the electron model and the students’ view of oxygen as any other substance, able to gain electrons. There is the possibility that the students did not relate the syllable “ox” in redox to oxygen due to the Swedish language, in which the Swedish word for oxygen is ‘syre’. Rather, these students may consider the abbreviation ‘ox’ to denote ‘oxidation’.

The result of this study mainly contributes to knowledge about students' conceptions about redox reactions in organic and biochemical contexts. The results do not give encouraging indications. In organic chemistry, it is difficult to say if the oxygen model was used as a tool for the students in their explanations, since they explained the reaction in an additive way. On the other hand, the students found the hydrogen model difficult to justify and use both in the organic and the biochemical contexts. This was true even if the examples were redox phenomena the students had met during the chemistry course, such as the oxidation of alcohol and redox reactions along the catabolic pathway. Anselme (1997) writes from his own teaching experiences about similar problems for university students, who have difficulties in understanding organic redox reactions. Anselme explains the problem as having to do with the differences in the models used in the different subject areas, and the introduction of new concepts such as dehydrogenation. This study shows that many of the students tried to use the electron model in their explanations of organic and biochemical redox reactions. It may be that the electron model is well-established in their chemistry knowledge and the explanation of oxidation and reduction is associated to electron transfer even in organic and biochemical contexts. If so, the result is in line with Soudani et al. (2000) who show in a word association test that students associate oxidation and reduction to inorganic redox reactions and not to biochemical, everyday redox phenomena such as respiration and photosynthesis. It may be the case that students have too little knowledge of the existence of multiple models to explain redox reactions. There is a further risk that knowledge of redox reactions in other disciplines remains fragmented and disconnected. For example, as one student said when reasoning about an ethanol forming acetic acid; "why is there an oxidation when removing hydrogen? [...] because if a hydrogen atom is removed, then it's not just one electron. It's both an electron and a proton. [...] that's what oxidation means, a removal of electrons.” This excerpt shows that it seems that the student lacks knowledge about the hydrogen model to explain a redox reaction and associate redox to electron transfer. Boulter and Buckley (2000) summarise that often students do not know there are different ways to think about a phenomenon, i.e. that different models are used, or students are in fact unaware that they are using models to explain phenomenon. As the excerpt above also shows, it seems as
though redox knowledge is not linked between the areas. One can wonder if the students in some cases were fully aware that they were dealing with redox reactions. For example, in the biochemical redox reaction when NAD$^+$ is reduced to NADH, most of the students viewed NAD$^+$ solely as a hydrogen carrier and not as a participator in redox reactions where electrons too are transferred. If students only consider NAD$^+$ as molecule carrying hydrogen, it is perhaps not surprising that the students may think the electrons transported in the electron transport chain as stored in an electron pool because it must be impossible to understand how the electrons originate in the chain. This resembles Boutler and Buckley (2000) claim that models in science education are often disconnected to the studied phenomena and that students are not able to understand how models are connected to each other.

van Driel and Verloop, (1999) argue that the nature of the models used in science classes is seldom discussed: rather, they are presented as facts. As in the case of the students’ use of the term ‘hydrogen carrier’, it is possible that the students consider hydrogen transport in the catabolic pathway as a ‘fact’ and do not consider that hydrogen transport is a series of redox reactions where different redox models could be used to explain the reaction.

It seemed that the students generally had the conception that a redox reaction is a mutual oxidation and reduction, independently of the studied subject area. Some students stressed, however, the problem with mixing the concepts of oxidation and reduction from the view of a loss and a gain of electrons. If the conception of mutuality depended on the students’ well-established knowledge about loss and gain of electrons according to the electron model and applied that conception in other contexts, or if the knowledge that oxidation and reduction are mutual reactions independent of the redox model used, is difficult to say. The result shows in any case contradictions to Garnett and Treagust (1992) reports that students have the conception that, in inorganic redox, oxidation and reduction can occur independently.

The studies performed in the 1990s indicate that the students had difficulties in adopting the electron model (de Jong et al., 1995) whereas Ringnes (1995) shows that most students define an oxidation as a loss of electrons, but have problems in showing the transfer of electrons in equations. According to Garnett and Treagust (1992) and Schmidt (1997) students suppose that oxygen is a pre-requisite for a redox reaction. This study shows the opposite, the students have adopted the electron model and the model is well-established. In general, students do not have the conception that oxygen is a pre-requisite for a redox reaction. The students seem to have the conception that a redox reaction is a mutual oxidation and reduction whereas Garnett and Treagust (1992) report from inorganic redox, that students have the conception that oxidation and reduction can occur independently.
Few students in this study used the oxidation number model to explain a redox reaction. When the model was used, the explanation often failed. Previous studies (Garnett & Treagust, 1992; de Jong et al., 1995; de Jong & Treagust, 2002) show that students have problems with the assignment of the oxidation number. In the Dutch chemistry curricula, the oxidation number model has been removed (de Jong et al., 1995).

6.2 The textbooks’ contribution to the students' conceptions about redox

The textbooks analyzed in this study showed that all the established redox models are used. From the analyzed subject areas in the books, the model use seems to correspond in general to the models used in each respective advanced chemistry discipline; that is to say, the electron and the oxidation number model in inorganic chemistry, and the oxygen and hydrogen model in organic chemistry. In biochemistry however, the textbooks use a mix of models while advanced chemistry mainly uses the hydrogen and the electron model.

It also seems as if the redox models used in the textbooks mirror the students’ redox knowledge in many ways. For example, inorganic redox reactions are well-defined in the books and most of the reactions are explained by the electron model. These reactions are assigned a large space in the books and many examples are given. The students also showed well-established redox knowledge in this area and the electron model seemed well-grounded. The organic redox reactions, on the other hand, are assigned little space in the books. Neither the oxygen model nor the hydrogen model is justified as the redox model used, or the mutuality of a redox reaction. The students also showed poor redox knowledge regarding organic redox reactions and could not justify the models used and were in some cases also doubtful about the mutuality of a redox reaction.

Biochemical redox reactions are explained with a mix of models in the textbooks. Few authors made an attempt to justify the hydrogen model used for the explanation of biochemical redox reactions. In addition, the textbooks use alternative representations for the explanation of oxidation and reduction. These kinds of explanations do not stress explicitly that it is a redox reaction occurring, since the concepts oxidation and reduction are left out. This must cause problems for the reader to understand the reaction mechanism actually happening. The hydrogen model in a biochemistry context seemed to be a threshold for the students. Although they read the textbook, they could neither understand biochemical redox reactions nor make any use of what they learnt about inorganic redox reactions.

In an attempt to understand the reason for this I would suggest that the students do not have sufficient knowledge to understand what is written in
the books, or that books are written in such a way that students do not understand what the books want to describe. van Boxtel, van der Linden and Kanselaar (2000) made a study of students’ knowledge acquisition with and without textbooks. The result shows that students working with the textbook found useful information on only half the occasions they consulted it.

It seems that the textbooks do not sufficiently help the students to build knowledge about redox reactions. The authors do not provide the information to bridge the redox models used in the different subject areas, or to view redox reactions as the same chemical phenomena independently of subject area. Since teachers often use the textbook as the curriculum and for shaping the course content (Budiansky, 2001; Nelson, 2006; Weiss, 1993) and they believe that textbooks are well-structured and clearly written (Weiss, 1993) it is very likely that redox reactions in various subject areas will be taught as they are described in the book. That is to say, each redox model will be taught separately, without any attempt to linking the models together. Justi and Gilbert (2002) summarise this situation by saying that due to the fact that multiple models are used to explain redox reactions, this is both challenging and confusing for students. To help students to construct knowledge, Carr (1984) describes three important demands to be met in changing models describing the same chemical phenomena. The students should be informed when a new model is introduced, how the model differs from the previously-used model and why this newly introduced model it is better. I would say that the textbooks authors do not meet these demands regarding the change of redox models between subject areas. For a reader of the textbooks, redox knowledge must become fragmentary and compartmentalized, and paving the way for rote-learning only.

To revisit the beginning of this section, there appears to be a risk for the students - even in advanced chemistry - to be faced with compartmentalised redox reactions, as the use of redox models in the analysed textbooks reflected in many ways the use of redox models in advanced chemistry.

6.3 Implications

One can ask how important redox reactions are for upper secondary school students to learn and understand. From a chemistry aspect, redox reactions are described as one of three (precipitation, acid-base and oxidation-reduction) most common reaction processes and perhaps the most important of these three, because redox reactions explain an amazing variety of chemical reactions. Redox not only explains important inorganic reactions such as the reduction of ores to obtain metals, the production of fertilizers or production of electrochemical cells. Redox reactions also explain vital biochemical processes such as photosynthesis and metabolism, or the organic combustion reactions (Silberberg, 2000). Thus, the redox reactions
continually taking place are a large part of us and our surroundings. From this I believe it follows that it is of great importance that students have the opportunity to learn about these reactions, helping them to understand our world both from a sub-micro level and as a whole.

It was found in Study I, II and VI that Swedish upper secondary school students attending the Natural Science Programme have the ability to use and apply the electron model in different inorganic examples and situations of redox phenomena. Their use of the oxygen model was not obvious in organic chemistry and they seemed to lack the ability to use and apply the hydrogen model in both organic and biochemistry. In Study III, the textbook analysis, all the redox models were to be found but used as isolated islands without connections to each other in the studied subject areas. This reflects to a large extent the students’ ability to use and apply the redox models, i.e. the students’ ability to use the models seems to be mirrored by the books descriptions. In any educational context, such as in the teaching of chemistry and redox reactions, we are dealing with individuals with different experiences and ideas. However, it seems as if the electron model and the mutuality of oxidation and reduction are well-grounded in students. It would be possible to use this well-established knowledge of redox as a tool to challenge the students’ ideas about these reactions in other contexts, such as organic and biochemistry. Electron transfer could, therefore, be an attribute linking the redox models together.

When the students are to study organic redox, the teacher can start with a review of inorganic redox with a focus on the electron model, for example the oxidation of sodium and the reduction of chlorine by the electron model and half reactions (Table 3, row A). The teacher then shows the oxidation step when, for example, ethanol is oxidized to ethanal (Table 3, row B, a) where ethanol loses two hydrogen atoms. The students can be confronted with the question of how this can be an oxidation when oxidation has been defined as an electron loss. This can be a rather challenging question for the students, because the electrons are not directly visible in the reaction. By looking closer at the hydrogen atom and its components, (Table 3, row B, b) may be written. The electrons are now visible in the equation and the reaction can be linked to the previously-learned electron model. The teacher can then question the mutuality of a redox reaction and show the reduction step (Table 3, row B, c).

The formation of acetic acid from ethanal can be demonstrated in a similar way by using the electron model.
<table>
<thead>
<tr>
<th>Subject area, ox and red reactions</th>
<th>Half equation</th>
<th>Balanced half equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  oxidation</td>
<td>Na → Na⁺ + e⁻</td>
<td>Na → Na⁺ + e⁻</td>
</tr>
<tr>
<td>Inorganic example</td>
<td></td>
<td></td>
</tr>
<tr>
<td>reduction</td>
<td>½ Cl₂ + e⁻ → Cl⁻</td>
<td>½ Cl₂ + e⁻ → Cl⁻</td>
</tr>
<tr>
<td>Redox reaction</td>
<td>Na + ½ Cl₂ → Na⁺ + Cl⁻</td>
<td></td>
</tr>
<tr>
<td>B  oxidation</td>
<td>CH₃CH₂OH → CH₃CHO</td>
<td>a) CH₃CH₂OH → CH₃CHO + 2H</td>
</tr>
<tr>
<td>Organic example</td>
<td></td>
<td>b) CH₃CH₂OH → CH₃CHO + 2H⁺ + 2e⁻</td>
</tr>
<tr>
<td>reduction</td>
<td>½ O₂ → H₂O</td>
<td>c) ½ O₂ + 2H⁺ + 2e⁻ → H₂O</td>
</tr>
<tr>
<td>Redox reaction</td>
<td>CH₃CH₂OH + ½ O₂ → CH₃CHO + H₂O</td>
<td></td>
</tr>
<tr>
<td>C  oxidation</td>
<td>C₄H₄O₅ → C₄H₂O₅</td>
<td>d) C₄H₄O₅ → C₄H₂O₅ + 2H</td>
</tr>
<tr>
<td>Biochemical example</td>
<td></td>
<td>e) C₄H₄O₅ → C₄H₂O₅ + 2H⁺ + 2e⁻</td>
</tr>
<tr>
<td>reduction</td>
<td>NAD⁺ + 2H → NADH + H⁺</td>
<td>NAD⁺ + 2H⁺ + 2e⁻ → NADH + H⁺</td>
</tr>
<tr>
<td>Redox reaction</td>
<td>C₄H₄O₅ + NAD⁺ → C₄H₂O₅ + NADH + H⁺</td>
<td></td>
</tr>
</tbody>
</table>
Biochemical redox reactions often involve NAD\(^+\) as the oxidizing agent. From a substrate, which is oxidized, the electrons are transferred to NAD\(^+\) as a hydride ion. The students may find it difficult to understand the hydride ion: the redox reaction can instead be shown by half reactions. The formation of oxaloacetate from malate can serve as an example of an oxidation. The oxidation involves a loss of two hydrogens from malate (Table 3, row C, d). The participation of the electrons can also be visualized here by the components of the hydrogen atom, a proton and an electron (Table 3, row C, e). The mutuality of redox reactions in this biochemical context can be questioned. The electrons need, as previously taught, to be gained by a substance. The message that the reaction \(\text{NAD}^+ + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{NADH} + \text{H}^+\) will occur must be explained to the students. The number of electrons can, however, be visualized in the balanced equation. The reduction can be explained in the following way: We got 2H\(^+\) and 2e\(^-\) from the oxidation of malate. The gain of one electron by NAD\(^+\) cancels the charge forming NAD (1. below). The gain of one electron and a proton, i.e. a hydrogen atom, forms NADH (2. below). What is left is one H\(^+\) which NADH cannot gain. This proton will enter the surrounding solution (Nelson and Cox, 2004, p. 512).

(1) \(\text{NAD}^+ + \text{e}^- \rightarrow \text{NAD}\)
(2) \(\text{NAD} + \text{H}^+ + \text{e}^- \rightarrow \text{NADH}\)

By having a focus on the electrons participating in biochemical redox reactions it may be easier for students to understand how the electrons take part in the electron transport chain. The transport of the electrons through the chain, which occurs by a series of redox reactions between electron carriers in specific protein complexes (I-IV), could be compared to elements in the activity series of metals. The theories why the series is structured in this way can be repeated from the view of an element’s reducing ability. The possibility for the electrons to be transported through the electron transport chain by the complexes can then be discussed from a redox perspective. For example, the electron transport occurs because the electron carrier in complex I is a stronger reducing agent than the electron carrier in complex II. At the end of the chain is oxygen, the weakest reducing agent, but a strong oxidizing agent, which is reduced under the formation of water.

By explaining redox in this way using electron transfer, the students may be able to build knowledge about redox with the use of the electrons as an attribute linking the different redox models together. I am not advocating that the established redox model should be abandoned in the teaching of redox. This way of explaining redox as described above should be used to illustrate that the electrons are always involved in redox. Then the different models used in various chemical disciplines could be introduced. To get students interested in talking about redox and electrons, we must try to
arouse their interest with good examples. One proposal is the task we used in Study II, where the students were asked to act as a coach at a gym. They were given the task in groups, to create a poster for educational purposes in order to explain to beginners what happens chemically in the catabolic pathway when we have eaten. What happens as we get chemical energy to practice at the gym? It seems, however, that explicit questions about redox is required in order to initiate a conversation about the reactions is required. To follow up the work, the importance of the transfer of electrons by a series of redox reactions from, for example, the reduced glucose molecule can be focused on. Finally, how these electrons enter the electron transport chain (see description above) and that the transfer of electrons even here occurs by redox reactions to the final electron acceptor, the oxygen.

The textbook analysis, Study III, showed compartmentalized redox information, since the redox models are neither linked nor justified where different redox models are used. Since the textbook often is used as the basis of teaching and teachers often use the textbook to structure the content of the lessons (Nelson, 2006), there is a risk that the that the students learn redox as it is explained in the books, with the result that the redox knowledge will become fragmented and compartmentalized. Therefore I also suggest that textbook authors should reconsider the way redox reactions are presented in the textbooks by justifying changes of redox models and by linking the models together.

It might be the case that chemistry teachers in school are unfamiliar with the kind of compartmentalized or unrelated knowledge students acquire about redox during the chemistry course. The problem can be addressed in teacher education, raising awareness amongst prospective teachers about students' difficulties in understanding and using redox models in different contexts. If textbooks authors do not change their approach to using and explaining redox in different contexts, the teacher must critically review the textbooks and help the students to bridge the different redox models.

Research is needed to better understand the role of the redox models in teaching. As this research does not include teachers, it would be important to study their conceptions of redox models, their use of these models in teaching and if, and if so how, the teachers justify the models in different subject areas. It would be important to investigate how authors consider their writing about redox models in textbooks and their presentation of redox phenomena in their books. It would also be interesting to investigate textbooks in other countries and their use of redox models, since only one textbook from England was investigated. In Study VI, a short teaching sequence was carried out on teaching redox in different subject areas by linking redox reactions using the electron as an attribute connecting redox reactions in different subject areas, as described above. My suggestion is to
make a study where this model of teaching is used, and to study the learning outcome of redox in different subject areas.
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