

Redox models in chemistry textbooks for the upper secondary school: friend or foe?

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Received 21st September 2009, Accepted 19th May 2010

DOI: 10.1039/C005467B

We have investigated how chemistry textbooks use models of redox reactions in different subject areas, how they change models between and within the topics, and how they deal with specific learning difficulties identified in the literature. The textbooks examined were published for use in the natural science programme in Swedish upper secondary schools and in the UK A-level course. As a starting point, the defined redox models found in the literature were used to investigate the textbooks. The results show that all redox models are used with the addition of alternative representations. Authors exclusively use the electron and the oxidation number models in inorganic chemistry. In organic chemistry, the oxygen and hydrogen model are used, and in biochemistry mainly hydrogen and alternative representations. There is no guide to changes of models between the subject areas. However, within the inorganic chemistry, authors guide model change which was not identified in either organic or biochemistry. Regarding the learning difficulties, the authors dealt with just a few of them.

Keywords: textbook analysis, chemistry, oxidation, reduction, redox, model, learning difficulties

Introduction

The world we live in can be explained, to a large degree, by chemical reactions. Redox (reduction and oxidation) reactions are perhaps the most important of all chemical processes (Silberberg, 2000). They explain the vital process of photosynthesis, energy-producing reactions such as the burning of fossil fuels, the production of ATP in our bodies and the corrosion of metals.

Many of the reactions noted above are included in the syllabus for the study of chemistry in the natural science programmes offered by upper secondary schools in Sweden and the UK. Even though these reactions are covered in a number of subject areas within chemistry, research has shown that these reactions are difficult both to teach and to learn (de Jong and Treagust, 2002).

Textbooks are often central to teaching (Weiss, 1993). The textbook is used by the teacher in many cases to define and present the content of the course syllabus. In this way, the textbook determines both the content of what is taught and the way it is taught. The textbook is also significant in that homework is often set from it (Nelson, 2006).

Despite the importance of the textbook in teaching, few of those used in the teaching of chemistry have been subjected to analysis. Östman (1995) and Drechsler and Schmidt (2005) are examples from the Swedish context. Östman's text analysis is based on chosen extracts from 11 textbooks in chemistry intended for use in the lower secondary school.

These texts were analysed from the perspectives of the natural science's subject focus, emphasis on knowledge and language. Drechsler and Schmidt carried out an exploratory study of four textbooks at upper secondary level, with the aim of – amongst other things – investigating how models are used in acid-base reactions. The texts were analysed partly using specific concepts concerning acid-base reactions, and partly by investigating how the reactions are related to various models. The result shows that the books neither clarify nor describe the differences between the acid-base models that are used, or what it is that characterises these models.

This study aims to investigate how textbooks use redox models to explain redox reactions in different areas of chemistry, how they change models between and within the subjects, and how they address various learning difficulties about redox processes identified in the literature.

Background

Models and concepts

Models are important tools used in the explanation of abstract theories (Gilbert, 1998). In the field of chemistry, models at the sub-microscopic level are used to explain macroscopic qualities (Oversby, 2000). Concepts are related to scientific models (Schmidt, 1997). According to Schmidt (2000), concepts have both a name and a meaning. Over time, the meaning of the concept may change, but the name remains the same through the processes of scientific development. This applies to the concepts of oxidation and reduction, where the names have remained unchanged while their meanings have changed over time.

Ringnes (1995) also described these concept changes in relation to different redox models (Table 1). All four models are used in current chemistry education, and are recognized

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Table 1 Four redox models according to Ringnes (1995)

Model	Reduction	Oxidation
1. Oxygen model	Loss of oxygen	Gain of oxygen
2. Hydrogen model	Gain of hydrogen	Loss of hydrogen
3. Electron model	Gain of electrons	Loss of electrons
4. Oxidation number model	Decrease of oxidation number	Increase of oxidation number

and accepted within the various sub-disciplines of chemistry. These models are referred to below as the oxygen model, the hydrogen model, the electron model and the oxidation number model.

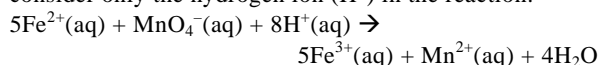
Students seldom have a full understanding when they use models in their explanations of a phenomenon (Boutler and Buckley, 2000). Carr (1984) explained that the understanding of the use of models can be further hindered if they are changed without giving the reason for doing so. Using acid-base models as an example, he described how the move between different models that describe the same phenomenon must be explained. It should be made clear when the new model is introduced in what way it differs from the earlier model, and why this model functions better. Boutler and Buckley (2000) suggested model-based teaching for promoting learning. The students should develop their understanding of the models that represent a specific phenomenon, and how these models are similar to each other in various contexts. By finding common qualities in the models, it can be determined what facilitates or hinders learning.

Learning and redox reactions

As mentioned above, redox reactions are perceived to be one of the most difficult areas both to learn (de Jong and Treagust, 2002) and to teach (de Jong *et al.*, 1995). Three important difficulties that students have are: 1) difficulties in comprehending oxidation and reduction as complementary reactions (de Jong and Treagust, 2002); 2) difficulties in identifying oxidizing and reducing agents (imprecise terminology and complex language use) (de Jong and Treagust, 2002); 3) the comprehension that a redox reaction is defined as a loss and a gain of oxygen (Garnett and Treagust, 1992; Schmidt 1997; Österlund and Ekborg, 2009).

Gilbert (2006) described a list of problems that challenge the teaching of chemistry. Amongst these are the students' difficulties with solving problems where the same concept is used but in different contexts. Soudani *et al.* (2000) showed in their study that university students have problems in the use of associated redox concepts in everyday contexts. Anselme (1997) suggested that university students have problems understanding organic redox reactions, because oxidation and reduction are described in a different manner from that in inorganic chemistry.

As the concepts oxidation and reduction are found in various redox models, this can sometimes lead to mistaken interpretations of what is oxidized and reduced. Let us consider only the hydrogen ion (H^+) in the reaction:



According to the oxygen model hydrogen ions have been oxidised by taking up oxygen and forming water. According to the electron model, hydrogen ions have been reduced by taking up electrons from oxide ions, forming water. According to the oxidation number model, neither oxidation nor reduction has taken place as the oxidation number of hydrogen is +1 both before and after the reaction (Davies, 1991).

Aim of the study

The aim of this study was to analyze how chemistry textbooks use redox models within various subject areas, and to study if – and if so, in what way – the authors explain why models are changed within and between subject areas.

The following research questions were posed:

1. In what subject areas and to what extent are redox reactions treated by these textbooks?
2. Which models are used to explain redox reactions and to what extent are they used in the various subject areas?
3. How do the textbooks explain the models and the related concepts of oxidation and reduction?
4. How do the textbooks treat the known difficulties that students have with redox reactions?

Method

As all the authors work with science education in Sweden, it was of interest to investigate all Swedish chemistry textbooks intended for the natural science program. For an example of how other textbooks use redox models at the corresponding level but from another country, an English textbook was chosen.

The syllabus

The chemistry course for the natural science programme at upper secondary school in Sweden is divided into two courses, an A and a B course. The objective in the syllabus for electrochemistry in the A course states that students should “*be able to use the concept of oxidation and reduction, and describe applications in industrial and everyday contexts*”. In the B course; organic chemistry students should “[...] *be able to discuss the principles of some simple organic reaction mechanisms*” and in biochemistry “[...] *describe the main biochemical features of the cell's metabolism [...]*” (Skolverket, 2000). The syllabus is goal-driven and not very detailed, stating what pupils should learn but leaving the teachers free to choose content and teaching methods as long as their students reach the goals.

In the corresponding English curriculum for upper secondary schools, redox reactions are specifically included. Students should be taught about oxidation and reduction as electron transfer, oxidation states and their calculations and electrode potentials and their applications. In organic chemistry, students are to learn oxidation and reduction reactions and organic synthesis including e.g. alcohols, aldehydes, ketones, carboxylic acids and esters. In contrast to the Swedish curriculum, biochemistry is included in the curriculum for Biology, not Chemistry. (QCDA, 2006).

Selection and description of textbooks

In Sweden, four publishers issue five different textbooks in chemistry for upper secondary school (divided into textbooks for courses A and B). To investigate if our findings are unique for Sweden or if similar results can be found elsewhere, we chose an English textbook for the corresponding school level, A-level. One reason for choosing an English book was practical – we understand the language. Another was that many students, not only in the UK, use English textbooks. The chosen book consists of two separate volumes aimed at A-level chemistry - one volume for the first year and one for the second year – and is written by separate authors, Nicholls and Harwood. In this study, however, these volumes are examined as one textbook.

These six textbooks became the basis of this study (Appendix 1). No supplementary materials for teachers have been analyzed, as this study focuses on the text that the students meet when they use a textbook. The Swedish textbooks will be referred to below as Andersson, Borén, Engström, Henriksson and Pilström, *i.e.* the name of the first-named author, and the English textbook as Nicholls and Harwood.

Andersson, Borén, Henriksson and Pilström are traditional textbooks. This means that they have a structure with a theoretical chapter as a starting-point, with short summaries in the margin, explanatory examples and subsequent suggested exercises. The structure of Engström is, according to the authors, inspired by the English material, Salter's A-level Chemistry. Salter's is written for a context-based teaching of chemistry (Bennett and Lubben, 2006). The chapters in the thematic section are related to everyday life. These common phenomena are connected to a theory section which gives the chemical explanation of the theme under study. Exercises are provided continuously throughout both the thematic and theory sections. The books of Nicholls and Harwood differ from the Swedish traditional textbooks. Each chapter is introduced by a section on how the science treated in that chapter is applied in real life. The chapters contain consecutive factual text with more chemistry content than the Swedish textbooks, in-depth text on how the science is applied, quiz sections and concluding questions.

The order in which the subject areas are presented in the books follows the general order: inorganic chemistry, organic chemistry and biochemistry.

Analysis

Two analyses were carried out. In the first one we identified in the textbooks all the passages that describe redox reactions. In the second one we studied what redox models were used, and how and to what extent they were used. In this analysis we also investigated if the authors dealt with a number of previously identified difficulties that students have in learning about redox reactions.

Passages that describe oxidation, reduction and redox in textbook material

To answer research question (1) 'In what subject areas and to

what extent are redox reactions treated by these textbooks?' all the relevant text in each book was analyzed. The term 'text' means captions, body text and summarizing factual text. The analysis aimed to identify text where spontaneous – *i.e.* not electrochemistry – oxidation and reduction was described, regardless whether specific words such as oxidation reduction *etc.* were used or not. Text sections covering redox were totalled and then expressed as a percentage of the total number of pages of 'text' in each book, giving an estimate of the proportion of text where redox reactions were described. The 'redox' pages were categorised into subject areas, *i.e.* inorganic, organic *etc.* The number of pages within each category was calculated. Redox could be attributed to three main subject areas: inorganic chemistry, organic chemistry and biochemistry. Redox was also found in physical chemistry, but consisted only of a few pages. These pages were attributed to the subject area inorganic chemistry. This formed the limits in the text material for the continued analysis.

Analysis of redox models and the specific difficulties experienced by students

In order to answer research question 2, 'Which models are used to explain redox reactions and to what extent are they used in the various subject areas?' the models used in the textbooks were first identified. The analysis had its basis in the four redox models found in the literature (Table 1), which gave rise to the four categories, but as we found text passages that described redox reactions and that could not be attributed to any of these categories, these were assigned to a fifth category called 'alternative representations' (see description, next paragraph).

In order to identify which models were used in the textbooks, the texts themselves were interpreted using the context the model was presented in. An example is when the authors describe a reaction where oxygen reacts with another substance – oxidation according to the oxygen model – but the reaction is described from the perspective of the electrons that are lost or gained. In such a case, the text has been interpreted as one using the electron model. Where the authors do not use concepts such as oxidation, reduction or redox, texts have been consigned to the 'alternative representations' category. An example of this is "*split water into oxygen and hydrogen*" (Henriksson, 2002, p. 205). The textbooks' use of the models, as well as to the extent they are used within the various subject areas, is presented in Figure 1. The quantitative part of the analysis was carried out by estimating the frequency of the use of models and their descriptions.

In order to answer research questions 3, 'How do the textbooks explain the models and the related concepts of oxidation and reduction?' and 4, 'How do the textbooks treat the known difficulties that students have with redox reactions?' the analysis focused on how the models are used and explained in the texts. 'Use of the models' in this context is which model is used and in what way the concepts of oxidation, reduction and redox are used and explained in the model. The analysis also included an investigation of the ways in which a number of previously identified and reported

Table 2 The space devoted to redox reactions, estimated in 'text' pages and as the proportion of the total 'text' in the books

Book	Inorganic chemistry	Organic chemistry	Biochemistry	Total no of 'text' pages	Percentage of 'text' pages
Andersson	63	9	9	340	~24%
Borén	42	5	9	250	~22%
Engström	48	2	7	264	~22%
Henriksson	39	6	4	299	~16%
Pilström	41	5	11	305	~17%
Nicholls and Harwood	39	6	---	201	~22%

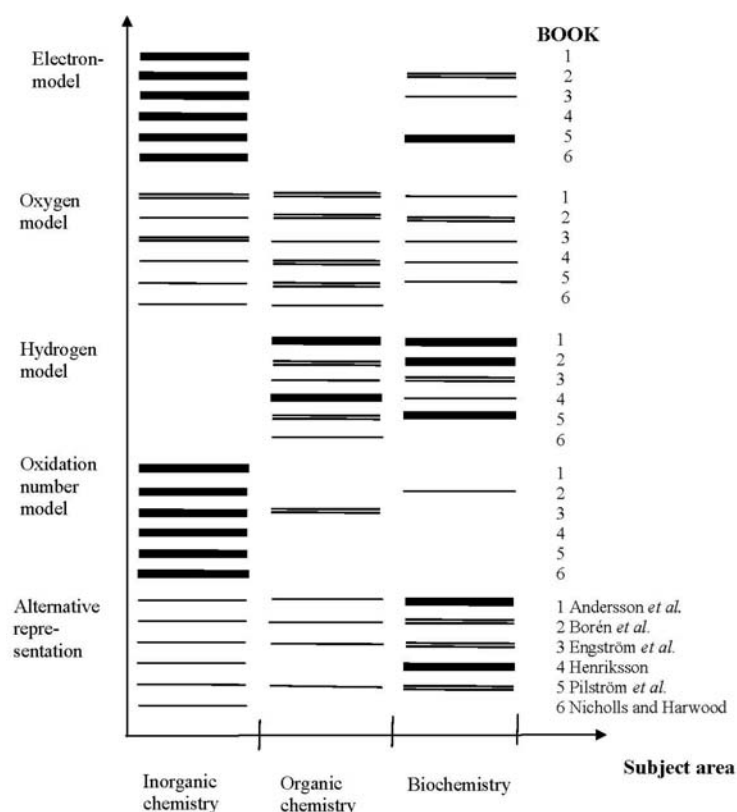


Fig. 1 Redox models and other representations used to explain redox reactions in textbooks within the various subject areas, as well as an estimate of the amount of their use. The subject area of biochemistry is found only in the Swedish chemistry books. Their use is denoted in the following ways:

* Not included

* Rarely included

* Included a number of times

* Included many times

difficulties that students have with understanding redox reactions are treated in the texts. The difficulties chosen for study in all subject areas were: oxidation and reduction as complementary reactions, problems in the identification of oxidizing and reducing agents, and the belief that in all redox reactions oxygen has to take part.

Results and discussion

The results are presented and discussed in three sections; first the text related to redox and the use of redox models, then the subject areas (inorganic, organic and biochemistry) and last the textbooks' treatment of known learning difficulties. Finally, how redox is treated in textbooks as a whole and

implications for teaching are discussed.

Texts that describe oxidation, reduction and redox in textbook material

The total space devoted to the description of redox reactions in all the books is relatively large: 16-24% of the textbooks analyzed (Table 2). This suggests that redox is regarded as important, and as the role of the textbook in teaching is central (Weiss, 1993, Nelson, 2006) this would indicate students have a great deal of contact with these reactions.

Another indicator that redox reactions are important is that they recur in many subject areas such as inorganic, organic, physical, environmental and biochemistry in the Swedish

textbooks. The English book uses them in inorganic, organic and physical chemistry.

Redox reactions are also used as examples in chemical calculations, the writing of reaction formulae and equations. Great emphasis is laid on redox reactions in inorganic chemistry where redox reactions take up twice as much space as in organic and biochemistry. The reason for this may be that redox reactions in inorganic chemistry are a clearly-identified goal in the Swedish as well as in the English curriculum (Skolverket, 2000; QCDA, 2006).

The use of redox models

Fig. 1 shows which model is used in each respective subject area and textbook, as well as an estimate of to what extent the model is used.

As the figure shows, all the redox models are represented in all textbooks, which are very similar in their use of the models within inorganic and organic chemistry. Within inorganic chemistry, the models most often used are the electron and oxidation number models, while the oxygen model is used only sparingly. The hydrogen and oxygen models are used within organic chemistry, while use of the alternative representations is infrequent. Variation in the use of models is greater within biochemistry in the Swedish textbooks; the hydrogen model is used, and also some variety in the use of the oxygen and electron models. Alternative representations are often used in the field of biochemistry.

Inorganic chemistry All the textbooks show similarities in the use of redox models and the examples used in the area of inorganic chemistry. Most often, the books use three models: the oxygen model, the electron model and the oxidation number model. The authors explain why they substitute the oxygen model for the electron model, and justify the introduction of the oxidation number model. A detailed presentation of these results is found below.

All the books introduce oxidation and reduction using the oxygen model as a starting point. The oxygen model is consistently described as a historical model in the Swedish textbooks, which the English textbooks do not do. From a Swedish textbook:

“The reaction where a substance binds with oxygen, building an oxide, was called oxidation in former times. “Taking away oxygen” was called reduction”. (Henriksson, A-course, p. 111)

All the books introduce the electron model and define oxidation and reduction as reactions where electrons are lost and gained, and explain that a redox reaction can also occur by means of an incomplete transfer of electrons, justified by the electron model. All the books except Andersson use the incomplete transfer of electrons in order to introduce the oxidation number model. Engström supports the oxidation number model in this way:

“This means that the transfer of electrons is “incomplete”, as the electrons are now shared between the atoms. To determine which substance is oxidized and which is reduced, we need to broaden our definition of oxidation and reduction” (Engström, A-course, p. 175)

The books also define oxidation and reduction as an increase or decrease in the oxidation number, with rules for the calculation of an atom's oxidation number, the naming of chemical compounds, and the balancing of redox reactions when written as formulae.

As the results describe above, the textbooks in inorganic chemistry are to a large degree consistent in their explanations of the redox models that are used. They also explain and show why one redox model is replaced with another. Our interpretation of the textbook passages within this subject area is that they are written so that the students can understand redox reactions as complete or partial transfer of electrons.

Organic chemistry Within organic chemistry, the textbooks also show great similarity in their use of redox models and the examples that are used. Two models are mainly used; the oxygen model and the hydrogen model. Engström mentions the oxidation number model, but applies it only vaguely. The authors do not explain why they introduce the hydrogen model, nor do they justify their use of the oxygen model. A detailed presentation of the results is given below.

Combustion reactions are described in introductory passages in all the books, where the combustion of carbon, hydrocarbon or alcohol in air or in oxygen is used as an example. The books later explain combustion as an oxidation. Many of the combustion reactions in the Swedish books are complemented with a reaction formula where oxygen is presented as a reactant. This may give association to the older oxygen model, as the use of the oxygen model is not given any explanation in the text. The comprehension that a redox reaction is defined as a loss and a gain of oxygen (Garnett and Treagust, 1992; Schmidt 1997; Österlund and Ekborg, 2009) may be enhanced, see citation below.

“Alkanes do not react in air in room temperature but are oxidized at high temperatures to carbon dioxide and water in a combustion reaction. If the amount of air (oxygen) is limited, the combustion can be incomplete (...)” (Engström, A-course p. 186)

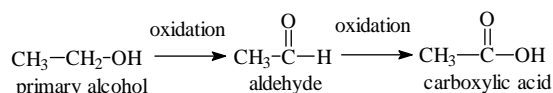
Even if the English textbook does not explain in detail the use of the oxygen and hydrogen models, the models are defined in an organic context:

“Combustion is one type of oxidation reaction. In organic chemistry, oxidation is regarded as the gain of an oxygen atom or the loss of two hydrogen atoms. Reduction is the opposite, and can be considered as the loss of an oxygen atom or the gain of two hydrogen atoms” (Nicholls and Harwood AS p. 266).

Andersson, Borén, Engström and Henriksson describe the oxidation of primary, secondary and tertiary alcohols to aldehydes, ketones and carboxylic acids. The redox models that are used to explain the oxidation of a primary alcohol to aldehyde and aldehyde to carboxylic acid, for example, are the oxygen and hydrogen models.

Primary, secondary and tertiary alcohols can be converted by oxidation into different products with different functional groups. A primary alcohol can be converted by careful oxidation into an aldehyde. The aldehyde is converted into a carboxylic acid by continued oxidation:

(Borén, A-course p. 275)



The authors refer the reader to the structural formulae that illustrate the reactions in order to be able to identify what is happening. By calculating the types of atoms that are included in the molecules that are participatory in the reaction, one can determine that in the case of the oxidation of a primary alcohol, hydrogen is lost (hydrogen model) and in the case of the oxidation of an aldehyde, oxygen is gained (oxygen model). The reaction shows only that an oxidation occurs. Andersson also introduces the concept of dehydrogenation in the step where the primary alcohol is converted into the aldehyde.

In the majority of the books, oxidation in the form of combustion is introduced after the section on inorganic redox reactions. As the examples described above, the oxygen model is reintroduced and the hydrogen model appears in this subject area, without justification. Anselme (1997) discusses from his classroom review precisely this problem that university students have when they are to work with redox reactions in organic chemistry: they have learned about redox reactions from the perspective of electron transfer. Anselme explains further that the students often have to learn other concepts that describe oxidation within organic chemistry – for example, dehydrogenation, and mixing concepts in an area which is already problematic creates even further problems in learning. The English book provides, unlike the Swedish ones, at least an explanation of how organic chemists regard oxidation and reduction reactions, and the complementarity of the redox reaction is considered (Nicholls and Harwood, AS p. 266).

Biochemistry The textbooks show great variation in the use of redox models in biochemistry. These differences apply both within the respective books, and between the books. In each individual book, all the models are represented to a greater or lesser extent. While the hydrogen model is used most often, it is not clearly explained in the books.

Because of the great variation in how the models are used in the books, we have looked at the molecules NAD^+ , NADH , FAD , FADH_2 , FMN (in metabolism), NADP^+ and NADPH (in photosynthesis) as markers for redox reactions in this context. We find this limitation to be representative for the model use in the biochemistry subject area. As we found that the authors use the models in a similar way both in the sections on metabolism and on photosynthesis, we present quotations from the metabolism section because in most of the books this section was introduced before the section on photosynthesis. A detailed presentation of the results is given below.

Pilström introduces the molecules NAD , NADP , FMN and FAD in the catabolism from the view of reduction of carbon atoms:

“In the catabolism energy is released and several of the reactions are oxidations of carbon atoms[...] anabolism [...] is a reduction of carbon atoms”. (Pilström B-course p. 187)

“As mentioned earlier, catabolism is oxidation and anabolism a reduction of carbon atoms. There must therefore be compounds in the cell which act as oxidants and reductants. The most common are NAD , NADP , FMN and FAD .” (Pilström B-course p. 189)

This method of explanation can be confusing for the reader, as the authors have earlier defined oxidation and reduction as a loss or gain of electrons (Pilström A-course p. 110).

Henriksson explains the involvement of NAD^+ in redox reactions with an alternative representation:

“A cell must avoid this uncontrolled burning and does so by using molecules called hydrogen carriers, which bind released hydrogen atoms and prevent them from reacting immediately with oxygen.” (Henriksson B-course p. 207)

In this quote it is difficult to recognise that the text describes redox reactions.

Andersson gives an explanation of oxidation and reduction with the hydrogen model:

“We can describe the reaction when NAD^+ removes two hydrogen atoms from a molecule XH_2 with the formula $\text{NAD}^+ + \text{XH}_2 \rightarrow \text{NADH} + \text{H}^+ + \text{X}$

The reaction has the result that XH_2 is oxidized to X .

NADH can then in turn, together with H^+ , transfer two hydrogen atoms to another molecule, Y , which is thus reduced to YH_2 :

$\text{NADH} + \text{H}^+ + \text{Y} \rightarrow \text{NAD}^+ + \text{YH}_2$ ” (Andersson p. 258)

This explanation can, however, be interpreted as if oxidation and reduction occur at different times in comparison with the earlier definition of oxidation and reduction as complementary reactions in inorganic chemistry.

When Andersson further describes a step in glycolysis, an ‘alternative representation’ is used in order to describe the reduction of NAD^+ .

“[...] NAD^+ molecules are charged with hydrogen atoms”. (Andersson, p. 259)

Most of the books explain NAD^+ as hydrogen carriers. When these carriers appear in the respiration chain, Pilström, Engström, Borén and Andersson use the electron model for the redox reactions occurring. Henriksson uses the oxygen model. Here is a quote from Engström:

“The enzymes involved in the respiratory chain are in the mitochondrial inner membrane. These enzymes are electron carriers that can be oxidized and reduced, for example, $\text{Fe}^{2+} / \text{Fe}^{3+}$. When NADH is oxidized to NAD^+ protons (H^+) and electrons (e^-) are lost”. (Engström B-course, Theory book p. 100)

Since the electron’s role in biochemical redox reactions is not mentioned when the hydrogen carriers are introduced, it may be difficult to understand where the electrons actually come from. Oxidation is in the biochemical field described as a loss of hydrogen. The quote above shows that an oxidation means that protons and electrons are formed.

These examples demonstrate that several redox models are mixed up in the texts and the authors use ‘alternative representations’ for describing redox. The hydrogen model is used, but we wonder if the students can understand that it is redox reactions that are described, and how it is possible to understand that the metabolism is a question of moving

electrons from nutrients to the final electron acceptor oxygen in the respiratory chain. Using ‘alternative representations’ might make the reading of the text easier, but can also carry with it the risk that the student loses the chemical meaning of the reaction described. It should be remembered that the students have so far only met a definition of oxidation and reduction according to the electron model and the oxidation number model where oxidation and reduction are complementary reactions.

The textbooks’ methods of treating students’ specific redox-related difficulties

The textbooks were analyzed from the perspective of a number of specific learning difficulties about redox reactions, *i.e.* the redox reaction’s complementarity, oxidizing and reducing agents and the belief that oxygen defines a redox reaction. The methods of treating these redox-related difficulties within the subject areas of inorganic, organic and biochemistry are described below.

Complementarity In inorganic chemistry, all the books introduce the concepts of oxidation and reduction as simultaneous, from the perspective of the electron model. The redox reaction is described in all the books either as a half reaction – Andersson, Borén, Pilström and Nicholls and Harwood – or as a single reaction formula with a complementing picture of electron transfer between the atoms – Engström and Henriksson. The complementarity of redox reactions is explicitly described in more than one way, and this difficulty is dealt with in the textbooks. The quotation below from Engström is representative of the other books’ descriptions of a redox reaction.

“As electrons can neither be lost nor be left over, oxidation and reduction always occur simultaneously and balance each other. The total reaction is called a redox reaction.” (Engström, A course p. 144)

In organic chemistry, none of the Swedish books explain the complementarity of redox reactions, but simply mention the concept of oxidation. A gradation in the oxidation of primary, secondary and tertiary alcohols is introduced in all the textbooks except Pilström, without explaining what this means. This can be problematic for the reader, as the textbook passages have not mentioned earlier any gradation of an oxidation. See the earlier citation by Borén, A-course p. 275.

The English book shows in some examples that both oxidation and reduction occurs.

“When primary, secondary and tertiary alcohols are oxidized using either acidified potassium dichromate(VI) solution or (...) the oxidizing agents are themselves reduced (...)”. (Nicholls and Harwood AS p. 268)

Borén introduces an ‘organic family tree’ illustrating oxidation and reduction. Figure 2 shows part of the tree. As oxidation and reduction have in inorganic chemistry been described as complementary reactions, this figure can be difficult to understand. The reader can interpret it to mean that when an alcohol is oxidized to an aldehyde, the aldehyde is reduced simultaneously to an alcohol.

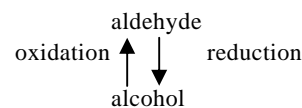


Fig. 2 Part of an ‘organic family tree’ from Borén. The tree shows connections between various functional groups: here how an alcohol can be oxidized to an aldehyde and how an aldehyde can be reduced to an alcohol.

In biochemistry, none of the books support the complementarity of redox reactions. Andersson defines, as previously described, oxidation and reduction in such a way that the use of the definition may lead to the misconception that oxidation and reduction are not complementary reactions. Borén only defines the oxidation reaction. Engström and Henriksson give no definition at all of oxidation and reduction.

The complementarity of the redox reaction is fundamental in inorganic chemistry in both the Swedish and English textbooks. Complementarity is then lost to sight in the Swedish textbooks. There is a risk that the reader will consider redox reactions in organic and biochemistry as any other chemical phenomena, because only oxidation reactions are considered and justified in the texts.

Oxidizing and reducing agents In inorganic chemistry, all the textbook authors describe oxidizing and reducing agents but with complicated language, which means that none of them explicitly deal with this difficulty. A quotation from Andersson:

“Substances which have a tendency to attract electrons from other particles are said to be oxidizing agents. Oxygen and chlorine are particularly strong oxidizing agents. Conversely, substances which have a tendency to donate electrons are reducing agents. Magnesium and carbon are examples of strong reducing agents.” (Andersson, A course p. 132)

In organic chemistry, most of the books mention oxidizing agents but give no examples of their participation in any reaction. No Swedish book mentions reducing agents. The English textbook defines both oxidizing and reducing agents in the organic context. Andersson and Borén grade their descriptions of oxidizing agents as mild, medium or strong.

“If we oxidize a secondary alcohol with a medium oxidizing agent the final product will be a ketone. Strong oxidation [...] will break the carbon chain in the ketone molecule” (Andersson, B course p. 145).

Why oxidizing agents are graded in different ways is not explained in the text. This way of describing oxidizing agents must appear inconsistent to the reader, as earlier definitions of oxidizing agents are “substances that have a tendency to attract electrons from other particles” (see citation above). The indication is that the authors have not confronted the difficulties that students are known to have with oxidizing and reducing agents.

In biochemistry, two books mention the concepts of oxidizing and reducing agents in this subject area: Borén and Pilström. The concepts are brought up in connection with the

description of the molecule NAD^+ and Borén presents them in this way:

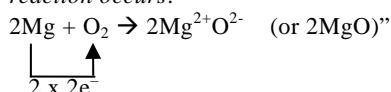
“Oxidation occurs with the help of enzymes that are rather mild oxidizing agents, dehydrogenases. NAD^+ is a co-enzyme in the case of a number of dehydrogenases.” (Borén, B course p. 184)

The introduction here of dehydrogenases can create difficulties in understanding the concept of oxidizing agents – what they are and how they work – even more difficult.

The definition of oxidizing and reducing agents is in itself difficult to understand. The books reflect this in their complex way of defining them. This gives rise to the risk of rote learning, but the question is, what can be done to increase the students’ understanding of the meaning of these concepts? As the Swedish textbooks only describe oxidations in organic chemistry, it is not surprising that only oxidising agents are considered in the texts. Regarding the gradation of the oxidizing agents, which is described in biochemistry as well, it is interesting to speculate what concept a term such as ‘mild oxidizing agent’ gives to the reader; that the reaction will occur slowly, that just a few molecules will be oxidized, or perhaps a molecule is just partly oxidized?

Oxygen defines redox reactions The first example in inorganic chemistry given of the electron model in all the textbooks is a reaction with oxygen. Many of the books continue to use oxygen as a reactant in describing redox reactions. The frequent use of oxygen at this introductory stage can be interpreted by the students as the use of the oxygen model in every redox reaction. An example is given below (Andersson, A course, p. 130):

“When magnesium combusts in oxygen (air), the following reaction occurs:



In organic chemistry, the perception that oxidation is the gain of oxygen is strengthened. Andersson, Borén and Pilstrom give further examples of the oxidation of primary alcohols as the oxidation of wine illustrated by a wine-bottle left open, with the wine in contact with air:

“If you let a little wine stand in an open bottle, after a few days you notice that the wine has soured. This is because oxygen in the air has oxidized the ethanol in the wine, forming acetic acid.” (Andersson, B course, p. 142)

In catabolism, the oxygen atom is the final electron acceptor in respiration, which results in the reduction of oxygen. It can be difficult not to point out the participation of oxygen in this reaction, and only two books, Borén and Pilstrom, explain this redox reaction using the electron model. The other books use the oxygen and hydrogen models or an ‘alternative representation’. For example Engstrom explains the final redox reaction in the respiratory chain with an ‘alternative representation’.

“The hydrogen atoms that the hydrogen transporters NAD^+ and FAD have taken care of will react with oxygen and build water [...]”. (Engstrom, B course, Theory p. 99)

The analysis of the students’ belief that a redox reaction can be recognized by the fact that oxidation is the gain of oxygen and reduction the loss of oxygen (Garnett and Treagust, 1992; Schmidt 1997), showed an interesting result. All the textbooks use the *same* experiment in the introduction to the area of redox reactions – that is to say, magnesium burning in air. When the authors of the Swedish textbooks rejected the oxygen model, due to its ‘historical’ aspect, it may be less confusing to introduce the electron model with another electron acceptor than just oxygen. Similarly, the authors use the ‘historic’ oxygen model in organic chemistry, without any justification of why they do so.

General discussion

We have identified that all the redox models (Ringnes, 1995) are used in the books with the addition of alternative representations. However, justification of model change could only be identified in inorganic chemistry. In organic and biochemistry the authors do not justify model change, neither between nor within the subject areas. The important criteria stated by Carr (1984) regarding model change are not met here. In general, the authors do not take the reported learning difficulties into consideration.

By considering the use of redox models in the studied subject areas, it seems that the authors use the models, in whole or in part, as they do in the corresponding established chemistry disciplines (*e.g.* Berg *et al.*, 2002; Zumdahl and Zumdahl, 2007; Solomons and Fryhle, 2008). As the models are used in the same way in the textbooks, it can be tempting to think that the authors have adopted the ways of using redox models employed in the scientific disciplines. The use of models in the books reflects how models are used by experts in the various fields of chemistry. An example of this could be a chemist in organic chemistry who wishes to produce a carbon skeleton with various functional groups. This goal is obtained through a number of synthetic steps where oxidations and reductions are often important. Focus is on the carbon skeleton and its modification: important concepts such as the oxidizing or reducing agent and the complementarity are not needed.

To sum up, this unjustified change of redox models and the associated concepts of oxidation and reduction can have consequences for the newcomer to the field – the student – who has not attained the same language competence as the expert. The same problems have been noted with acid-base models in textbooks, where neither the differences nor explanations of the models used have been given (Drechsler and Schmidt, 2005).

In order for students to learn, textbooks must be structured so that they can build up their knowledge. When one progresses further in courses in chemistry and meets the concepts of oxidation and reduction, one should expect to make use of the foundation knowledge one has acquired on redox reactions in inorganic chemistry. Authors must help students to move between the different redox models presented in the texts.

Implications

Redox reactions are touched on in many different subject areas. This study shows that the textbooks to a large extent did not provide any justification for the change of models within and between subject areas – why one model is exchanged for another and why this model functions better in a particular context. Greater effort is needed too to help the students with their difficulties with redox reactions. As students appear to have difficulties in applying knowledge about redox in various fields (Anselme, 1997; Soudani *et al.*, 2000) and feel that their knowledge is fragmentary (Gilbert, 2006), the authors of textbooks could show how the various redox models are connected, and in this way provide valuable links for clearer understanding.

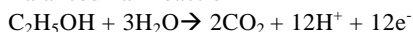
Other substances than oxygen can be used in introductory texts to show students that oxygen does not need to be present in a redox reaction – for example, chlorine used by Henriksson. To help students make necessary connections regarding redox reactions between different subject areas, greater focus on the participation of electrons can be used. Sisler and van der Werf (1980) and van der Werf *et al.* (1945) argue that the electron model is not useful in all redox reactions, but in the context of the chemistry course for the upper secondary school it is a matter of linking previously-used redox models to new models in order to learn and recognize redox processes.

The oxidation of ethanol forming carbon dioxide and water can be used as an example. One can use half reactions and electron transfer as a strategy for recognizing an oxidation or a reduction. Balance the half reaction by adding H₂O for oxygens and then H⁺ for hydrogens. Balance the charge of the half reaction by adding electrons to one side or the other (Brown, 2000). Electrons can be transferred with hydrogen atoms as a hydrogen atom consists of a proton, H⁺ and an electron, e⁻ (Nelson and Cox, 2005). This way of describing the redox reaction will indicate electron transfer even if the hydrogen model is used. In these examples, one does not have to take into account whether the reaction occurs in an acidic or basic solution.

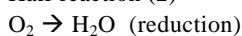
Half reaction (1)



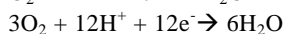
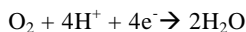
Balanced half reaction



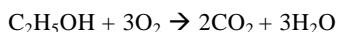
Half reaction (2)



Balanced half reaction



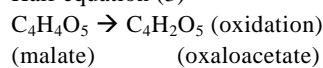
Overall reaction



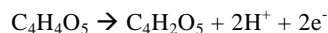
What can be commented on here is that there is a substance that is reduced: electrons can neither be lost or be left over, even if organic chemistry does not focus on the reduction in this reaction. The electron model can be used like this to show the oxidation of an alcohol to an aldehyde and further to a carboxylic acid, linking the electron model to hydrogen and oxygen models.

Biochemical redox reactions are often described by the hydrogen model. One can discuss the electrons' participation in these redox reactions as well by explaining that a hydrogen atom consists of a proton, H⁺ and an electron, e⁻. The oxidation of malate to oxaloacetate below can be used as an example. Both malate and oxaloacetate occurs as dianions at physiological pH. For a simplification we describe the molecules as neutral. The oxidation can be shown by half reaction with a balance of the reaction with hydrogen i.e. hydrogen ions and electrons.

Half equation (3)



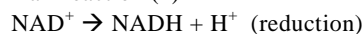
Balanced half reaction



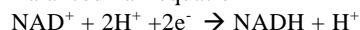
During the reduction the reaction $\text{NAD}^+ \rightarrow \text{NADH} + \text{H}^+$ occurs. This reduction reaction *will* occur when NAD^+ is the oxidizing agent. In this case it can be appropriate to tell the students that the material we have available in the reduction is two hydrogens (written as 2H^+ and 2e^-) released from the oxidation step. Recall that a reduction is a gain of electrons.

To show what happens, a half reaction can be written.

Half reaction (4)

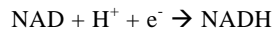
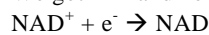


Balanced half equation



One way to describe the reaction is to illustrate the balanced half reaction in the following way:

We got 2H^+ and 2e^- from the oxidation



What is left is one H⁺ which NADH cannot gain. This proton will enter the surrounding solution (Nelson and Cox, 2005, p. 512).

Overall reaction:



From the examples given above, one can explain that various redox models are used to explain the same phenomenon, oxidation and reduction. However, it may be difficult for the novice to see the connection between the models. By highlighting the characteristics that unite the models, such as electrons as a participator in the reactions, these difficulties may be possible to overcome.

Appendix

Reference list and working titles for the books in the analysis

Working titles	Textbooks
Andersson	Andersson S., Sonesson A., Stålhandske B. and Tullberg A., (2000), <i>Upper secondary school chemistry A (Gymnasiekemi A)</i> , Stockholm: Liber.
	Andersson S., Sonesson A., Stålhandske B., Tullberg A., and Rydén L., (2000), <i>Upper secondary school chemistry B (Gymnasiekemi B)</i> , Stockholm: Liber.
Borén	Borén H., Boström A., Börner M., Larsson M., Lillieborg S. and Lindh B., (2005), <i>Chemistry book A – 100p: With laboratory work and exercises (Kemiboken A – 100p: Med laborationer och arbetsövningar)</i> , Stockholm: Liber.
	Borén H., Larsson M., Lif T., Lillieborg S. and Lindh B., (2001), <i>Chemistry book B – 100p: With laboratory work and exercises (Kemiboken B – 100p. Med laborationer och arbetsövningar)</i> , Stockholm: Liber.
Engström	Engström C., Backlund P., Berger R. and Grennberg H., (2005), <i>Chemistry A: Themes and Theory (Kemi A: Tema och Teori)</i> , Stockholm: Bonniers.
	Engström C., Backlund P., Berger R. and Grennberg H., (2001), <i>Chemistry B: Theme book (Kemi B: Temaboken)</i> , Stockholm: Bonniers.
	Engström C., Backlund P., Berger R. and Grennberg H., (2001), <i>Chemistry B: Theory book (Kemi B: Teoriboken)</i> , Stockholm: Bonniers.
Henriksson	Henriksson A., (2000), <i>Chemistry Course A (Kemi Kurs A)</i> , Malmö: Gleerup.
	Henriksson A., (2002), <i>Chemistry Course B (Kemi Kurs B)</i> , Malmö: Gleerup.
Pilström	Pilström, H., Wahlström, E., Luning, B., and Viklund, G., (2000), <i>Model and reality A - Chemistry for the upper secondary school (Modell och verklighet A – Kemi för gymnasieskolan)</i> , Stockholm: Natur och Kultur.
	Pilström, H., Nordlund, S. Luning, B., and Wahlström, E., (2001), <i>Model and reality B - Chemistry for the upper secondary school (Modell och verklighet B – Kemi för gymnasieskolan)</i> , Stockholm: Natur och Kultur.
Nicholls and Harwood	Nicholls, L., (2008), <i>AS Chemistry for AQA</i> , in J. Perkins (Ed.). London: Harper Collins Publishers.
	Harwood, P., (2008), <i>A2 Chemistry for AQA</i> , In J. Perkins (Ed.). London: Harper Collins Publishers.

References

- Anselme J-P., (1997), Understanding oxidation-reduction in organic chemistry, *J. Chem. Educ.*, **74**, 69-72.
- Bennett J. and Lubben F., (2006), Context-based chemistry: the Salters approach, *Int. J. Sci. Educ.*, **28**, 999-1015.
- Berg, J. M., Tymoczko, J. L., and Stryer, L., (2002), *Biochemistry*, New York: W. H. Freeman
- Boulter C. J., and Buckley B. C., (2000), Constructing a typology of models for science education. In J.K. Gilbert and C.J. Boulter eds., *Developing models in science education*, Dordrecht: Kluwer Academic Publishers, pp. 41-57.
- Brown H. B., (2000), *Introduction to organic chemistry*, Fort Worth: Saunders Collage Publishing.
- Carr M., (1984), Model confusion in chemistry, *Res. Sci. Educ.*, **14**, 97-103.
- Davies A. J., (1991), A model approach to teaching redox, *Educ. Chem.*, Sep, 135-37.
- de Jong O., Acampo J. and Verdonk A., (1995), Problems in teaching the topic of redox reactions: actions and conceptions of chemistry teachers, *J. Res. Sci. Teach.*, **32**, 1097-1110.
- de Jong O. and Treagust D., (2002), The teaching and learning of electrochemistry, in J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust and J. H. van Driel, eds., *Chemical education: towards research-based practice*, Dordrecht: Kluwer, pp. 317-337
- Drechsler M. and Schmidt H-J., (2005), Textbooks' and teachers' understanding of acid-base models used in chemistry teaching, *Chem. Educ. Res. Pract.*, **6**, 19-35.
- Garnett P. J. and Treagust D.F., (1992), Conceptual difficulties experienced by senior high school students of electrochemistry: electric circuits and oxidation-reduction equations, *J. Res. Sci. Teach.*, **29**, 121-142.
- Gilbert J. K., (1998), Models in explanations, Part I: horses for courses? *Int. J. Sci. Educ.*, **20**, 83-97.
- Gilbert J. K., (2006), On the nature of "context" in chemical education, *Int. J. Sci. Educ.*, **28**, 957-976.
- Nelson D. L. and Cox M. M., (2005), *Lehninger principles of biochemistry*, New York: W.H. Freeman
- Nelson J., (2006), How are textbooks used by teachers and pupils? (Hur används läroboken av lärare och elever?), *NorDiNa*, **4**, 16-27.
- Österlund L-L. and Ekborg M., (2009), Students' understanding of redox reactions in three situations, *Nordina*, **5**, 115-127.
- Östman L., (1995), *Socialization and meaning: science education as a political and moral environment problem*. (Socialisation och mening: No-utbildning som politiskt och miljömoraliskt problem), Diss. Uppsala: Univ.
- Oversby J., (2000), Models in explanations in chemistry: the case of acidity, in J. K. Gilbert and C. J. Boulter eds., *Developing models in science education*, Dordrecht: Kluwer Academic Publishers, pp. 227-251.
- Ringnes V., (1995), Oxidation-reduction – learning difficulties and choice of redox models. *Sch. Sci. Rev.*, **77**(279), 74-78.
- Schmidt H-J., (1997), Students' misconceptions – looking for a pattern. *Sci. Educ.*, **81**, 123-135.
- Schmidt H-J., (2000), Should chemistry lessons be more intellectually challenging? *Chem. Educ. Res. Pract.*, **1**, 17-26.
- Silberberg M. S., (2000), *Chemistry: the molecular nature of matter and change*, Boston, Mass: McGraw-Hill Companies.
- Sisler H. H. and van derWerf C. A., (1980), Oxidation-reduction. An example of chemical sophistry, *J. Chem. Educ.*, **57**, 42-44.

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- Skolverket, (2000), *Natural science programme. Programme goal, structure and syllabuses*, http://www3.skolverket.se/ki/eng/nv_eng.pdf, (accessed 01-02-2010).
- Solomons T. W. Graham and Fryhle C. B., (2008), *Organic chemistry*, Hoboken: Wiley.
- Soudani M., Sivade A., Cros D. and Médimagh M. S., (2000), Transferring knowledge from the classroom to the real world: redox concepts, *Sch. Sci. Rev.*, **82**(298), 65-72.
- Qualifications and Curriculum Development Agency (QCDA), (2006), *GCE AS and A level subject criteria for science*, http://www.ofqual.gov.uk/files/qca-06-2864_science.pdf, (accessed 01-03-2010).
- van der Werf C. A., Davidson A. W. and Sisler H. H., (1945), Oxidation-reduction: a re-evaluation, *J. Chem. Educ.*, **22**, 450-456.
- Weiss I. R., (1993), Science teachers rely on the textbook, in R. E. Yager ed., *What research says to the science teacher, volume seven: The science, technology, society movement*, Washington, D.C.: National Science Teachers Association, pp. 35-41.
- Zumdahl S. S. and Zumdahl S. A., (2007), *Chemistry*, Boston, Mass: Houghton Mifflin Co.