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Students' Understanding of Redox Reactions in Three Situations

Abstract
Redox models that explain electrochemical issues have been found to be difficult to teach and to learn. The aim of this study was to investigate students' reasoning about redox reactions in three situations, how they used the activity series of metals and if they transferred knowledge between domains. Semi-structured interviews were carried out with ten students on two different occasions and dealt with three situations 1) a laboratory practical on corrosion; 2) a demonstration of zinc and copper sulphate solution; and 3) a corroded sculpture. The results indicated that the electron model was fundamental and reinforced. The identification of the reducing agent in the situations was unproblematic. The students' conceptions regarding the oxidizing agent varied and diverged from the scientific model in some situations. Depending on the situation, the activity series of metal became a tool as well as an obstacle. Some transfer of knowledge between the classroom and the outdoor situation was indicated.

Introduction
Gerhard Ertl was awarded the Nobel Prize in Chemistry in 2007 for his studies on chemical processes on solid surfaces. One such process is rust formation. This is one of the electrochemical processes which are studied in chemistry in upper secondary school. Although many of these processes are familiar to most people in their daily lives, the electrochemical redox models that explain these phenomena has been found to be difficult to teach and to learn according to studies reported in De Jong and Treagust (2002). From a constructivist position (e.g. Duit & Treagust, 1998) this paper presents a descriptive study into how students in upper secondary school reason about oxidation and reduction reactions, often described as redox, in three situations: 1) laboratory practical on corrosion 2) a demonstration experiment of zinc and copper sulphate solution and 3) a corroded sculpture.

Background

Redox reactions
Ringnes (1995) describes how the conceptualisation of the reactions oxidation and reduction has evolved over time. Four different redox models are commonly used in chemistry education today. These are the oxygen model, the hydrogen model, the electron model and the oxidation number model (Table 1).

Table 1. Four oxidation-reduction models

Model	Reduction	Oxidation
Oxygen model	loss of O	gain of O
Hydrogen model	gain of H	loss of H
Electron model	gain of electrons	loss of electrons
Oxidation number model	decrease in oxidation number	increase in oxidation number

The Activity Series of Metals (ASOM), arranges metals according to their ability to act as a reducing agent. The series also includes the non-metal hydrogen (H). Depending of the metal's reducing ability it can displace hydrogen gas from water, steam or acid (Silberberg, 2000). Metals which displace hydrogen are called ignoble metals and those which not are called noble metals. The ASOM is often used in textbooks as an introduction of teaching redox reactions (e.g Andersson, Sonesson, Stålhandske & Tullberg, 2000).

Redox reactions such as iron- and copper corrosion are everyday phenomena that are presented in the chemistry course during the secondary school natural science programme. Corrosion of iron is a very complex electrochemical process where rust is formed. One possible reaction pathway is the three step (a-c) reaction illustrated in Table 2 (Cornell & Schwertma, 2003). The corrosion of copper is simple in comparison to rust formation. Copper will oxide in the air in two steps according to the reaction (a) and (b) in Table 3. Depending on pollutants in the air such as sulphur oxides, green verdigris is formed on copper surfaces (e.g. Hägg, 1979).

Table 2: A scientific model of the corrosion of iron

a)	$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$
	$O_2(g) \rightarrow O_2(aq)$ (oxygen from air dissolves in the water)
	$O_2(aq) + 2H_2O + 4e^- \rightarrow 4OH^-(aq)$
	Total reaction: $2Fe(s) + O_2(g) + 2H_2O \rightarrow 2Fe^{2+}(aq) + 4OH^-(aq)$
b)	$Fe^{2+}(aq) + 2OH^-(aq) \rightarrow Fe(OH)_2(s)$
c)	$4Fe(OH)_2(s) + O_2(g) \rightarrow 4FeO(OH)(s) + 2H_2O$

Table 3: A scientific model of the corrosion of copper

a)	$2\,Cu(s) \rightarrow 2\,Cu^+(aq) + 2e^-$
	$\frac{1}{2}\,O_2(g)$ or $(aq) + 2e^- \rightarrow O^{2-}$
	Total reaction: $2\,Cu(s) + \frac{1}{2}\,O_2(g) \rightarrow Cu_2O(s)$
b)	$Cu_2O(s) + \frac{1}{2}\,O_2(g) \rightarrow 2\,CuO(s)$

Previous research

Teachers perceive redox as one of the most difficult topics to teach (De Jong, Acampo & Verdonk, 1995) and research has shown that school students have difficulties in conceptualising redox reactions (De Jong & Treagust, 2002). One of the problems noted by the teachers, and reported in De Jong et al. (1995) is how to explain the transfer of electrons in such a way as to enable students to adopt the electron model correctly. De Jong and Treagust (2002) suggested that students regard oxidation and reduction as independent reactions; they have problems with the meaning and assignment of oxidation numbers and the identification of reactants as oxidizing or reducing agents.

There are a number of explanations to the difficulties in conceptualising redox reactions. Schmidt (1997) found that many students believe that oxygen always takes part in all redox reactions and that oxygen is a pre-requisite for a redox reaction. Schmidt suggests that this could be due to the syllable "ox" in "redOX". Others, such as Anselme (1997) and Soudani, Sivade, Cros and Médimagh (2000) viewed the problem as to do with concept transfer between domains (Bransford, Brown & Cocking, 2000, p. 51). Anselme (1997) discussed the difficulties student have with transferring knowledge about redox between chemistry topics (from, for example, inorganic to organic), and Soudani et al. (2000) found that students have difficulties in using a theoretical knowledge of redox to interpret everyday phenomena. One explanation they gave is that teaching is dominated by solving algorithmic problems and that students find this too abstract. Another explanation could be that the students do not understand the ASOM correctly. However, as far as we know, there is no published literature that considers student conceptions and use of ASOM.

Aim of the study

The aim of this study was to investigate how students in natural science programme of the upper secondary school reason about redox reactions in three situations: how they use the activity series of metals in their reasoning and if they transfer knowledge to an outdoor situation.

To do this the following research questions were posed:

1. which redox models do the students use?
2. how do the students use redox models to explain the reactions with reactants and products?
3. how and in which situations do the students use the activity series of metals?
4. are the students capable to apply their redox knowledge to a daily life outdoor situation?

Method

Interviews

In order to get detailed data and be able to pose follow-up questions semi structured interviews were chosen as data collection method (Kvale, 1997). All the interviews were performed around artefacts. Vosniadou, Skopeliti, and Ikospentaki (2005), argue that the presence of an artefact helps - at least older children - to develop an "internal consistent scientific model" of the issue discussed.

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 goals in the syllabus for electrochemistry in the A-course state that students should "be able to use the concept of oxidisation and reduction, and describe applications in industrial and everyday contexts" (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 pupils reach the goals.

Description of the students and previous teaching

This study was conducted in a middle-sized upper secondary school in northern Sweden. The group consisted of 21 students in the second year (17 yrs) of the natural science programme. These students had worked in their first year (the A-course) with both electrochemistry and with chemical bonding. A textbook - Pilström, Wahlström, Luning, and Viklund (2000) -constituted the basis of the teaching. Regarding the area of electrochemistry, the teacher taught the electron model but often used oxygen in the air as example of oxidation. Also the oxidation number model was taught. ASOM was used for the illustration of different metals' reducing ability and redox reactions. In the topic chemical bonding, one issue was ion bonding. Ion charge of the transition metals and the formation of black and red copper oxide was one part.

Teaching sequence

During lesson 1, the teacher revised the topic redox reactions and gave a brief overview of the corrosion of iron. The lesson lasted about 45 minutes and included a lecture, a demonstration of zinc in copper sulphate solution and a dialogue with the students. A work sheet with lab instructions with ASOM included was distributed to the students to prepare as homework. During lesson 2 - the laboratory practical - the aim was to examine how iron in isolation was affected by water and how iron in contact with other metals was affected by water. The lab instruction followed a recipe model with clear statements of execution. The students worked in pairs during laboratory practical which included iron nails and thin sheets of metal; zinc, copper and aluminium. Each one of the three metals was put into contact with an iron nail. One iron nail was left without a metal sheet. The nails were put into separate dishes containing tap water. Questions were asked in the lab instructions about what would happen in each dish. By using their knowledge of the activity series of metals and their chemistry knowledge, students were asked to reason about oxidation and reduction in order to explain the redox phenomena of corrosion of iron. The third lesson was a sum-up of the laboratory practical with questions and discussion. The lessons were completed within a two-week period. The primary author attended the lessons as a passive observer.

Sample

The entire group of 21 students was asked to participate in the study. Five female and five male volunteered for the interviews. Eight of them had worked in pairs in the laboratory practical. The ten students were above average in academic achievement.

Data collection

The first interview series started two weeks after the last lesson was completed. These interviews were performed during a two-week period. The second interview period took place outdoors beside a sculpture, five weeks after the last lesson and was completed within a week.

The primary author conducted all the interviews. A semi-structured guide was used and the questions were related to different artefacts in three situations (described in the section below). After some general opening questions, the questions became more probing and specific. In order to get deeper information the informants were also given a pen and paper and were asked to write down chemical explanations and make drawings to illustrate their chemical reasoning during the interviews. These drawings were used in the analysis.

As described previously, interviews were performed on two different occasions and dealt with three situations: 1) the performed laboratory practical on corrosion completed by the students 2) the performed demonstration experiment of zinc and copper sulphate solution made by the teacher and 3) a corroded sculpture (Table 4).

The first interview occasion was individual and was carried out in a small group room, lasting for 30-40 minutes. Each interview concerned redox reactions in both situation 1 and situation 2. Regarding situation 1, the laboratory experiment on corrosion was used as an artefact and the students had access to the laboratory guide that they had used during their laboratory work. All the different combinations of iron and metals were set as a starting point for the interview. However, questions concerning dish A and/or B later became a focus of the interview as these metals reappeared at the sculpture, situation 3.

Concerning situation 2, the researcher performed the demo-experiment and dissolved solid copper sulphate in water and a zinc plate was placed in a beaker. The demo-experiment was used as an artefact during the interview.

During the second series of interviews, four pairs and two individual interviews were conducted outdoors using a copper sculpture as an artefact, situation 3. The interviews lasted for about 15 minutes. The sculpture was situated in the neighbourhood of the school and was made of copper with an outer layer of black copper oxide and verdigris. The sculpture rested on a rusty iron stand. The students were encouraged to move around the sculpture freely. They made observations: for example, the colours of the metals' oxides for identification of the metals of which the sculpture consisted. The interview was carried out while moving around the sculpture. All interviews were audio recorded and transcribed verbatim.

Ethical issues

One month before the study started, an information letter about the study was sent to all the students' parents. Before each individual interview the informant was informed about the purpose of the study, that all information would be confidential and that they could withdraw from the study if they wished.

Analysis

The analysis of the students' reasoning has been conducted in steps. In the first step the students' reasoning was analysed as to how they explained the reactions with regard to reactants, products and their use of the activity series of metals (ASOM). From that analysis, the students' use of redox models could be identified. The next step of the analysis was to identify if the students transferred knowledge between domains. The analysis mainly focused on transfer between situation 1, the laboratory practical on corrosion and situation 3, the sculpture - but also on transfer of prior knowledge applied in situation 3.

Analysis of the students' use of redox models, ASOM and students' explanations

All three situations consisted of redox reactions occurring. A summary of the situations under consideration and the reactions are summarised in Table 4.

Table 4. The studied situations and reactions

Situation	Description	Reaction	Setting
Situation 1	The laboratory practical on corrosion	A B	Iron in water Iron in combination with copper in water
Situation 2	The demonstration experiment	C	Zinc and copper sulphate solution
Situation 3	The sculpture	D1 D2 D3	Copper in a natural environment Iron in a natural environment Iron and copper in contact in a natural environment

From the view of the research questions, the students' reasoning has been analysed in each situation. The analysis started with the students identification of the reducing- and the oxidizing agent and how they explained the redox reaction. The analysis proceeded in identifying the product of the reaction in the students' explanations. During this analysis the students' use of ASOM as a tool and their use of redox models were identified. As a complement, the students' drawings were used during the analysis. A colour coding scheme was developed to structure the outcome of the analysis.

An analysis of if the students transferred knowledge between domains was made by comparing the outcome from the analyses of the reactions in situation 1 and situation 3. Also, analysis of other statements made by the students indicated the transfer of knowledge applied into situation 3.

Results

Redox models

All students used the electron model in all the situations. All students but one seemed to understand that oxidation and a reduction are mutual reactions in accordance with the scientific model. The excerpt below from Sune (S), reasoning on reaction C, illustrates the group's common conception of electron transfer. It also illustrates the majority of the students' conception of the mutuality of redox reactions.

> S: […] zinc, it will be a redox reaction between those two, with the copper […] Cu two plus
> S: […] zinc wants to give off its electrons, in comparison to the copper. Therefore, the zinc gives off two electrons and the copper gains them. […]

The researcher asked an explicit question regarding the participation of oxygen in reaction A and B. Four students added that oxygen takes part in a redox reaction. Grethel's (G) statement is an example of this.

> Int: […]. In these redox reactions, does oxygen always participate in the reaction?
> G: It's always like that.

Reducing agent and ASOM in the reactions

Seven students chose to explain reaction A, iron and water, and eight explained reaction B, iron in combination with copper and water. In reaction C, all ten students wrote explanations. However, with regard to the sculpture, some students chose to talk about copper (D1) or iron (D2) or both. Some of them talked about the contact area of the metals (D3). That is why the numbers of students shown in the cells of Table 5 is not equal ten.
The presentations of the results start with the students' conceptions of the reducing agent and their use of ASOM in the reactions. To achieve a logical presentation, the results are presented in the order of reaction A, B, D1-D3 and C.

The students did not have difficulties in identifying the reducing agent in any of the reactions. In reaction A, with only iron in water, the students stated iron. In reaction D1, about the sculpture, almost all of the students identified copper as the reducing agent. In these two reactions the students did not use ASOM in their reasoning. In reaction B, D3 and C however, they used ASOM and reasoned in terms of noble and ignoble metals when they identified the reducing agent, which is shown by the excerpt from Agneta's (A) comments about reaction B.

> A: Em. Since copper is nobler …it should take a longer time for it to oxidize […] it (copper) is twisted around the iron nail and the iron nail is more ignoble than copper, so it should oxidize first since they are in contact with each other […]

Oxidizing agent and ASOM in the reactions

In reaction A, B and D1-D3, the students identified water or molecular oxygen acting as the oxidizing agent. Concerning reaction A, B and D3, the majority of the students identified the oxygen atom in the water molecule as the electron acceptor. However, in reaction D1 and D2 they identified molecular oxygen in the air (Table 5). None of the students used ASOM as a tool in their reasoning in any of the reactions.

An excerpt from Lars (L) follows below, thinking about reaction B, which illustrates his belief that the oxygen atom in the water molecule is the oxidizing agent.

L: Aha, it will be, or…? (Writes on the paper "If it is an oxidation, then $Fe \rightarrow Fe^{2+} + 2e^-$")
Int: What happens then?
L: It will end up with…it should be then (Writes on the paper "$H_2O + 2e^-$") and then, because it is so, well that's it would be.
[…]
Int: Ok, you have written down these electrons here in the reduction step with water. Do the electrons react with the oxygen or the hydrogen in the water molecule?
L: Eh, with the oxygen …its place in the periodic table is where it misses two electrons to get its atom shell full (Table 5)

In reaction D1 and D2, at the sculpture, the majority of the students identified oxygen in the air as the oxidizing agent, which just a few students did in reaction A and B. Here are William (W) and Sara's (S) comments about molecular oxygen as the electron acceptor in the oxidation of the copper in the sculpture (reaction D1):

> Int: […] can you explain chemically what happened with the metals?
> S: Oxygen in the air
> W: Yes, and the water, it needs moisture (draws a figure on the paper and writes "metal" and "oxygen")
> S: Yes
> W: It has reacted with copper and …oxidizes. […] copper ions two plus and oxide ions two minus.
> Int: How does it become two plus and two minus?
> […]
> S: The electrons jump (Table 5)

Regarding reaction C, seven of ten students identified copper or copper ions as the oxidizing agent. Even if there was linguistic mix-up between macroscopic (observable) and sub-microscopic (ions) expressions, we have interpreted these statements as an awareness of what substance is acting as electron acceptor. In this situation, ASOM seemed to be an aid in the identification of the oxidizing agent. As reaction C had another oxidizing agent than reaction A, B and D1-D3, it is not part of Table 5.

Product and ASOM in the reactions

In reactions A and B, all the students mentioned iron oxide as a product. Almost a third of the students stated an additional product as well - hydrogen- or oxygen gas. William (W) states that hydrogen gas forms during the corrosion process in situation B, which he motivates with ASOM.

> W: Here is H_2O (H two O) and here is the nail (writes Fe) and … copper too (writes Cu). Well.. eh.., the oxygen must move to the iron (draws oxygen atoms bringing electrons from water molecule to iron)…iron oxide (writes FeO) and this is rust […] And since the iron is to the left

> of hydrogen in the activity series of metals it will displace hydrogen. […] I think I almost saw from the experiment that bubbles formed on the nail too […].

In the reactions D1 – D3, all the students identified copper oxide iron and oxide respectively. In these reactions, only one student identified an additional product in the form of hydrogen gas by using ASOM.

In reaction C, zinc and copper sulphate solution, the majority of the students identified copper as a precipitate of the zinc plate and zinc ions, in accordance with the scientific model.

Table 5. Identified oxidizing agents in the reactions A, B, D1, D2 and D3. The numbers in the cells show how many students of the total number of students reasoning in each reaction and what oxidizing agent they suggested.

Oxidizing agent	Reaction A Iron in water	Reaction B Iron in combination with copper and water	Reaction D The sculpture
1. Water	(5/7)	(7/8)	D1. (3/10) - with Cu as reducing agent D2. (1/10) - with Fe as reducing agent D3. (6/10) – with Fe as reducing agent
2. Molecular oxygen	(2/7)	(1/8)	D1. (7/10) - with Cu as reducing agent D2. (6/10) - with Fe as reducing agent

Transfer of knowledge from the classroom to a daily life outdoor situation

To get information if the students transferred knowledge between domains, the students' reasoning about the reactions in situation 1 was compared with their reasoning about reactions in situation 3. Situation 2 was not used, as it was not comparable to these reactions.

All students used the electron model and they had no problem in identifying the reducing agent in any of these reactions. They used ASOM for the identification of the reducing agent in a similar way in reactions B and D3. Below, Jacob (J) questions the construction of the sculpture with reference to the ASOM.

> Int: Does it matter that these two metals are in contact with each other?
> J: Yes, It is a rather foolish thing to do, to have a copper sculpture on iron nails
> Int: Why?
> J: Because copper is noble and that is why iron will be oxidized before copper […] copper is on the right in the activity series of metals.

The students' identified oxides as a product in all the reactions. However, fewer students identified gas as a product in the reactions at the sculpture, compared to the reactions A and B. The conception of water as the oxidizing agent still remained in reaction D3 outdoors, where copper and iron were in contact. In contrast, when the students were reasoning about the oxide formation of copper only (D1) or iron (D2), they identified molecular oxygen as the oxidizing agent.

The results regarding the students' conceptions of all the studied issues are summarised in Table 6.

Table 6. A summary of the majority of the students' conceptions of redox model, reducing and oxidizing agent, product and ASOM as a tool in the different reactions. The electron model is abbreviated e-model.

Discussion

Situations	Reaction	Redox model	Reducing agent	ASOM	Oxidizing agent	ASOM	Product
Situation 1	A	e-model	Iron	Tool	Water	No tool	Iron oxide/ hydrogen- or oxygen gas
	B	e-model	Iron	Tool	Water	No tool	Iron oxide/ hydrogen- or oxygen gas
Situation 2	C	e-model	Zinc	Tool	Copper ion/ Copper	Tool	Copper Zinc ions
Situation 3	D1	e-model	Copper	No tool	Molecular oxygen	No tool	Iron oxide/ Copper oxide
	D2	e-model	Iron	No tool	Molecular oxygen	No tool	Iron oxide/ Copper oxide
	D3	e-model	Iron	Tool	Water	No tool	Iron oxide

The aim of this study was to investigate how students in secondary school, natural science programme, reasoned about redox reactions in three inorganic situations, and if the students transferred knowledge between domains.

Redox models

Although the main teaching regarding inorganic oxidation and reduction was performed more than one year earlier, the electron model seemed to be fundamental to the students, and reinforced. They explained each redox reaction with electron transfer. Even if the sample is small it still indicates that the teacher has succeeded in getting the students to adopt the model. Findings in De Jong et al. (1995) show that teachers experience difficulties in enabling students to adopt this model. In the study reported here, some students argued that oxygen is a participator in all redox reactions As these students achieved above average it is reasonable to believe that this idea is common among students. However, many examples of redox made both by the teacher and the textbook were redox reactions influenced by oxygen. Schimidt (1997) explains this conception with the statement "students apparently conclude from the syllable "ox" in redOX that oxygen is involved in all redox reactions". More and deeper interview questions regarding this issue could have been asked in this study to validate this result.

The majority of the students had the conception that a redox reaction is mutual oxidation and reduction. This is not supported by sources in the research review by De Jong and Treagust (2002) where findings indicate that students perceive oxidation and reduction reactions occurring independently. Also in the study reported here, one student stated oxidation and reduction as independently occurring reactions. It is difficult to draw any conclusions from a single statement but it gives an indication that the conception of oxidation and reduction as non-mutual reactions still appears.

Reducing agent

In this study none of the students seemed to have problems with identifying the reducing agent in any situation, whereas De Jong and Treagust (2002) show that students have a problem with the identification of reactants as reducing agents. In the reactions where the metals appeared as single, they identified these metals directly as reducing agents. They seemed aware of the ability of the transition metals to create positive ions, in this case Fe^{2+} ions and Cu^{+}- alternatively Cu^{2+} ions, which they also have been taught in the topic "chemical bonding".

In the reaction B and D3 - where the metals had contact with each other and in reaction C - the zinc plate and copper sulphate solution - all students used ASOM for the identification of the reducing agent. ASOM as a tool for identification of the reducing agent seemed to be reinforced in this way, by comparing two metals as noble and ignoble. This was in line with the teaching where the metals' reducing ability has been taught from the view of ASOM.

Oxidizing agent

In many of the reduction reactions, ASOM was not used as a tool by the students. Some of the students were a little puzzled because ASOM did not 'fit' in the way they were used to applying the series. One major problem for the students in this study was to identify the oxidizing agent in the reactions A, B and D3. However, most of the students stated water and the oxygen atom in the molecule as the electron acceptor. Some students motivated this with the oxygen atom's high electro negativity. Another explanation could be what has been described by sources in De Jong and Taber (2007) that students tend to interpret chemical formulas in an additive way. For example, H_2O is seen as H_2 and O. Since just a few of the students had the concept of the molecular oxygen as the electron acceptor, it may be relevant to think that it was the oxygen atom in the water molecule that gained the electrons.

Only a few students in reactions A and B identified dissolved oxygen as the electron acceptor according to the scientific model. Apparently, knowledge about gases' solubility in liquids has not been understood by the students.

On the contrary, in reactions D1 and D2, at the sculpture, the majority of the students identified oxygen as the oxidizing agent. One explanation could be that the most visible metal of the sculpture was the copper metal (D1). Copper as a metal, its properties and oxide formation has reappeared in these students' chemistry education mostly in combination with oxygen. Air instead of water surrounding the sculpture may have been very obvious to the students. The students' conception of molecular oxygen as the oxidizing agent also seemed to be applied to iron (D2). However, the interviewer did not evaluate this further. More in-depth interview questions may have changed this result.

The identification of the oxidizing agent in reaction C, zinc and copper sulphate solution, was unproblematic, and the use of ASOM seemed reinforced.

To conclude, the students had difficulties in identify the oxidizing agent in reactions A and B, where they could not use ASOM. However, in the case of copper or iron in isolation, exposed outdoors to air and water, the majority students could identify the right oxidizing agent. ASOM was easily used in identifying of the oxidizing agent in reaction C, zinc in copper sulphate solution.

Product

The corrosion of iron is a very complex redox reaction. Even if the majority of students missed the presence of the dissolved oxygen in reactions A and B, they were able to write down a chemical reaction between iron and water with a product of iron oxide in some form. Some students asserted an additional product to the iron oxide, hydrogen- or oxygen gas. In this case too, an explanation of the students' idea of hydrogen formation may be that they saw the water molecule in an additive way (H_2 and O), in line with sources in De Jong and Taber (2007). Another explanation for the students' identification of gas as a product may be that ASOM became a hindrance in their reasoning. It seemed as though they tried to use the series in their explanations and therefore explained the displacement of hydrogen when iron was in the water accordingly. If so, the students do not have an established knowledge of which metals displace hydrogen from water.

The students identified the oxides at the sculpture as copper oxide and iron oxide respectively. However, the formation of copper oxide is a less complex redox reaction than oxide of rust, and can be explained with fundamental oxidation- and reduction half reactions. On the other hand, just one student noted the formation of hydrogen gas in addition to copper oxide when considering product formation. It seemed that the students' attention was drawn away from ASOM in this situation and they were reasoning more freely.

The identification of the product in reaction C - zinc and copper sulphate solution - seemed unproblematic for the majority of the students. The overall chemical reasoning for the product formation in this redox reaction seemed reinforced.

To conclude, it seemed as ASOM became a hindrance for some students when identifying the product in reactions A and B, The prediction of hydrogen formation could be due to the students' interpretation of the water molecule in an additive way ($H_2 + O$) . In reaction C, ASOM seemed to be a tool in their reasoning. In reaction D1-D3 their attention seemed to be drawn from ASOM

Transfer of knowledge

The difference between a school situation and a daily life situation is very subtle. However, according to the study reported here, the students concluded that a redox reaction had taken place in the outdoor situation. Soudani et al. (2000) claims that students have difficulties in applying theoretical knowledge of redox reactions to everyday phenomena. However, these students were able to identify the right oxides of the sculpture after some specific starting questions. They applied the electron model and had the conception of oxidation and reduction as mutual reactions both in the classroom's reactions as well as outdoors. They also used ASOM to identify the reducing agent in a similar way where ASOM was suitable. The students seemed to be able to transfer this fundamental knowledge. Some students used their knowledge of ASOM when prompted with questions about the construction of the sculpture. They seemed aware of the consequences that iron and copper in contact has from the view of a redox process.

The students became more aware of molecular oxygen as the oxidizing agent outdoors. Maybe this is due to the fact that they were outdoors which made them think of air and oxygen, in opposite to the laboratory practical where the metals were covered by water. Or perhaps the copper as a metal is very familiar to the students.

Surprisingly, where the metals were in contact, the students still preferred water as the oxidizing agent like the indoor experiment.

The students who participated in the study reported here were high achieving students and still they had some conceptual problems with redox reactions. It is therefore reasonable to believe that these problems also exist among other students.

Method discussion

One can ask how new the situation of the sculpture was, as the arrangement of the metals resembled the laboratory practical on corrosion. The sculpture was a black oxidized copper sculpture with areas of green verdigris. The time that passed between the interviews about the laboratory work of corrosion and the interviews about the sculpture was several weeks. The starting questions about the sculpture were not posed in chemistry terms, but rather in terms of what the students observed in an everyday way. The follow-up questions were couched in more scientific terms. These arguments support that the sculpture was a new situation.

The interviews at the sculpture were conducted as two individual and four pair interviews. It would have been better if all of them had been done individually as in the indoor reactions, to make individual comparisons possible. In the group interview, the students influenced each other by discussing the interview questions, so it was difficult to interpret their individual conceptions.

The students showed use of their chemical knowledge, but not spontaneously: they had to be prompted by a specific question first. However, during the interview with continuous follow-up questions, they described their understanding of the redox reactions in combination with drawings.

Some interview questions could have been developed further by more follow-up questions during the interviews. The oxygen's participation in all redox reactions was not followed up in reaction C and D1-D3. However, the students' drawings have facilitated the interpretations of their conceptions.

Implications for teaching and research

The ASOM seemed to be regarded by these students as a well-known analytical tool for familiar redox reactions such as zinc and copper sulphate solution. This established knowledge of the series could be used by gradually introducing non metallic elements in the series. Similarities in redox reactions of ASOM could be applied on non-metallic elements and the electron model could be highlighted. This could be the basic content if the teacher decides to work further with the standard electrode potential. In other cases this approach could clarify for the students that redox reactions occur in accordance with reactions explained from the ASOM but with a non-metallic electron acceptor. Hopefully, the students would realise that oxygen is one among several substances participating in redox reactions and has nothing to do with the syllable ox in redox (Schmidt, 1997).

A design of ASOM as described above could also become a basis when working in biochemistry for example with the electron transport chain. Instead of seeing electrons simply "jumping" between the complexes in the chain, the driving force of the electron transport could be compared with redox reactions predicted by ASOM.

The presentation of ASOM with hydrogen placed among the metals, which is consistent with the metal's ability to generate hydrogen gas from acid, may in this study give an indication of a problem for the students. It is difficult, from ASOM, to predict what metal has the ability to displace hydrogen gas and from what source. A suggestion is that an image, which shows how ASOM can be used to predict hydrogen gas displacement from water, steam and acid is included in the textbooks.

The corrosion of rust is a rather complex redox reaction, which is represented in many different ways in textbooks. Maybe we should question whether students should be taught this complicated reaction? On the other hand, it is a common daily life phenomenon with connection to school chemistry and redox reactions. The presentation of the rust formation process can be simplified, in comparison to copper oxide formation at this level of chemistry education.

This study indicates that some knowledge transfer from the classroom to a common outdoor occurrence of rust and copper oxides occurs. If connecting school chemistry and redox phenomena outdoors these oxides can be examined. Some examples for examination is; protecting and non-protecting oxides, what metal is behind the colour of the oxide, the cracking of concrete due to volume extension when rust forms and offer metals. Of course the oxides can be referred to redox reactions as a process.

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