

Article

Making Redox Tangible: Physical Models in Electrochemistry Education

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Abstract

This study addresses the persistent challenges that students face in understanding redox reactions, particularly the link between symbolic and particulate representations in electrochemistry. The purpose was to explore whether physical modeling with clay could enhance the conceptual understanding of electron transfer and oxidation–reduction processes. Two groups of Swedish upper secondary students participated in instructional sessions: Group A used clay models to visualize electron movement, while Group B relied solely on symbolic notation. Data were collected through a written test and follow-up interviews. Results indicate that Group A outperformed Group B in tasks involving metal displacement and identifying the number of electrons transferred in a more complex reaction combining redox and acid–base processes. However, differences were minimal in synthesis reactions and fundamental conceptual questions. Both groups exhibited widespread alternative understandings, although Group A demonstrated fewer alternative understandings and greater accuracy in applying the concept of charge. The findings suggest that clay modeling can support the visualization of electron transfer and reduce alternative understandings but does not independently foster deeper conceptual understanding. The effective integration of modeling with explicit instruction on particulate-level reasoning and scientific terminology is essential in bridging representational gaps in electrochemistry.

Keywords: chemistry education; electrochemistry; electron transfer; oxidation–reduction; particulate level; physical modeling; redox reactions; symbolic representation



Academic Editor: Andrea C. Borowczak

Received: 11 December 2025

Revised: 30 January 2026

Accepted: 6 February 2026

Published: 10 February 2026

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1. Introduction

Electrochemical energy refers to the conversion of chemical energy into electrical energy. This area of chemistry is rapidly evolving in response to the growing demand for efficient energy: storage, management, and release from various sources. The study of electrochemical processes, commonly known as electrochemistry (EC), is today an important component of the chemistry curriculum, as electrochemical reactions are the basis of vital processes such as photosynthesis, cellular respiration, and combustion. It is also a part of chemistry that will become increasingly important in managing future energy needs (Yamine et al., 2024).

Unfortunately, EC is often regarded by students as one of the more challenging areas due to its many abstract concepts and complex applications (De Jong & Treagust, 2002; Österlund et al., 2010). To describe the complexity of the area, the terms “concept”, “model”,

and “application” are used. Some of the fundamental concepts of EC used in secondary chemistry are ions, atoms, ionic compounds, chemical bonding, spectator ions, molecules, reduction, oxidation, oxidation agents, reducing agents, electrolytes, electron transfer, electrolytic conduction, oxidation–reduction reactions, half-reactions, and electrochemical cells. Four general models are used for predicting and explaining redox reactions (an abbreviation for reduction–oxidation reactions) at the upper secondary school level: (1) the oxygen model, (2) the hydrogen model, (3) the electron transfer model, and (4) oxidation numbers (ONs). However, the electrochemical series is also used to predict a redox reaction. Applications of the different models include the ability to identify reactants as oxidizing or reducing agents, recognizing the interdependence and the dynamics of the two half-reactions, understanding the process of electron transfer, and determining which substances are oxidized or reduced to predict the products of redox reactions. Understanding EC includes balancing reactions—an aspect that also necessitates an understanding of the stoichiometry of electron transfer. This complexity is also amplified by the fact that these different concepts, models, and their applications occur at different levels. The terms macro-level, symbolic, and submicroscopic-level are here used to describe the different levels of chemistry (Johnstone, 1982). Given the above-described challenges that students face, it is crucial to support them in developing an integrated understanding to facilitate meaningful learning in EC. This study was designed to explore students’ understanding of the macro–submicroscopic–symbolic shift in EC. For this study, the term “submicroscopic representations” is used to describe visualizations showing the particulate, submicroscopic level of chemistry.

2. Background

Describing chemistry and chemical knowledge can be achieved at different levels. One widely accepted framework identifies three levels of chemistry: the macroscopic level (descriptive, representing observable phenomena), the symbolic level (chemical symbols, formulas, charges, states of matter, and nomenclature), and the submicroscopic level (explanatory, representing the invisible world of atoms and molecules) (Johnstone, 1982). The symbolic level is a way to visualize the submicroscopic level of chemical processes, designed to facilitate written communication. The symbolic level is the international language of chemistry and the way that chemistry is communicated to the learner.

Like any other language, the active interpretation of its symbolic representations is essential in understanding the intended meanings of these symbols. Failure to engage in this process may lead to minimal or no understanding of the underlying chemical processes (Davidowitz et al., 2010; Krajcik, 1991; Laugier & Dumon, 2004; Nakhleh, 1992; Papaphotis & Tsaparlis, 2008; Salta & Tzougraki, 2011; Tasker & Dalton, 2008; Treagust et al., 2009). For example, students may perceive chemical equations merely as mathematical exercises and fail to see them as representations of atomic rearrangements and the breaking and forming of chemical bonds (Ben-Zvi et al., 1987; Chiu, 2007; D. L. Gabel & Bunce, 1994; Krajcik, 1991; Laugier & Dumon, 2004; Lee et al., 1993; Osborne & Cosgrove, 1983). The term “alternative understanding” is used here to denote students’ interpretations of chemical concepts that diverge from the established consensus at this educational level.

In a study aimed at exploring the gaps in students’ understanding of redox reactions, an alternative understanding was identified at all three of the different levels (macroscopic, symbolic, and submicroscopic/particulate level) (Brandriet & Bretz, 2014b). The study revealed six especially difficult areas for EC:

1. The translational process at the symbolic level of chemical representations;
2. Electron transfer processes—the mechanisms of electron transfer in redox reactions;
3. ONs—applying and interpreting charges and oxidation states;

4. The role of spectator ions—the function of spectator ions in simple single-displacement redox reactions;
5. The particulate and dynamic nature of reactions—the dynamic behavior of particles during reactions;
6. Charges and bonding—chemical bonding, electrostatic attractions, or charge replacement between ions in redox processes.

2.1. Educational Models Used in Teaching Electrochemistry

“Educational models” is the term used here to describe the content of the taught chemistry at the upper secondary school level. Educational models are simplified versions of scientific models, adapted for a specific educational level. Models are here seen as explanatory tools (Passmore et al., 2014). Many of the models and concepts that are important for EC are introduced early on in education and are used for different areas of chemistry, providing students with the means to expand their understanding of concepts, models, and their applications over time. The four models used today in determining electron transfer have developed over time and are used in different fields of chemistry. The oxygen and hydrogen models are mainly used in organic and biochemistry. The oxygen model defines oxidation as the gain of oxygen and reduction as the loss of oxygen. The hydrogen model defines reduction as the gain of hydrogen and oxidation as the loss of hydrogen. The electron model is the most general model and describes reduction as a gain of electrons and oxidation as a loss of electrons. This model and the ON model are the models that are most used in inorganic chemistry. The ON is a way to determine partial electron transfer in molecules and can be used in predicting all types of reductions and oxidations, as well as calculating stoichiometry for these types of reactions.

The students included in this study were introduced to EC during their first year of upper secondary school. The oxygen model was initially presented from a historical perspective and illustrated through the combustion of magnesium, a reaction characterized by complete electron transfer. The subsequent example involved the reaction between hydrogen and chlorine, which entails partial electron transfer and naturally leads to the introduction of ONs and their application in stoichiometric calculations. To exemplify this, the dissolution of copper in nitric acid was used.

The work then continued with metals as reducing agents and the introduction of Daniell’s cell, in which the reaction between Zn(s) and $\text{Cu}^{2+}(\text{aq})$ produces $\text{Zn}^{2+}(\text{aq})$ and Cu(s) . This was discussed in conjunction with the electrochemical series. The concepts of galvanic cells, half-cells, and overall cell reactions were introduced using this reaction, alongside electrode potentials, electromotive force, and the associated calculations. The instructional sequence concluded with the topic of corrosion, presented as an example of a galvanic cell, followed by methods for mitigating corrosion. The problem-solving tasks addressed the following areas: ONs (five problems), stoichiometry (four), electrochemical series (four), cell reactions (four), electromotive force (four), corrosion (one), and electrolysis (three).

2.2. Previous Research on Students’ Understanding of Electrochemistry

The research literature provides examples of concepts and models in EC that students find challenging. Many are derived from symbolic-level interpretations of EC reactions (i.e., the number and type of products formed, plus or minus signs, the swapping of chemical symbols, or the physical states of substances). Identifying redox reactions from chemical equations is one area where an alternative understanding regarding the symbolic level can be derived, and visible charges seem to be a key aspect. In general terms, the difficulties for students lie in interpreting the change in charge: if reactions only include partial charges, i.e., no charges are visible in the chemical equation, then the reaction is not perceived as

a redox reaction. The opposite generalization is also apparent: all reactions where there are visible changes in charge are seen as redox reactions—for example, a change in phase through dissolving or acid–base reactions (Brandriet, 2014).

Other issues with symbolic-level interpretations affecting EC include cations and anions: students may recognize that the symbol (aq) denotes an aqueous solution, where the dissolved species are present in water. The charged species also lead students to conceptualize dissolved cations and anions as being closely associated due to electrostatic attraction, or even as being chemically bonded.

When taking a closer look at difficult issues regarding the particulate level and specifically electron transfer, students often struggle to conceptualize the mechanisms of electron transfer in redox reactions, regarding where, how, and when the transfer occurs. These difficulties are tied to their understanding of how atoms, molecules, and ions interact at the submicroscopic level to facilitate electron movement. Students' most common alternative understandings are that electron transfer occurs when bonds are broken or formed, anions are responsible for transporting electrons, electrons move freely through aqueous solutions, and electrons travel through an electrolyte by being attracted to positively charged ions in the solution (Brandriet, 2014; Brandriet & Bretz, 2014a; Garnett & Treagust, 1992a, 1992b; Masykuri et al., 2019; Sanger & Greenbowe, 1997). Preservice chemistry teachers also exhibited similar alternative conceptions regarding the movement of electrons during this process (Hadinugrahaningsih et al., 2022).

Electrons and electron movement seem difficult for students to conceptualize, and, even when students correctly identify where and how electrons are transferred in a chemical reaction, they often fail to describe the underlying particulate processes represented by the symbolic reaction equation (Brandriet, 2014). Difficulties in conceptualizing electron transfer processes also contribute to students' challenges in understanding and correctly applying ONs (Basuki, 2020; Brandriet & Bretz, 2014a; Garnett & Treagust, 1992a).

Visual charge again becomes a problem in assigning ONs to polyatomic molecules or ions and using changes in the overall charges of such units to identify redox reactions. For instance, students may erroneously conclude that the conversion of carbonate ions (CO_3^{2-}) to carbon dioxide (CO_2) involves the oxidation of the carbonate ion.

2.3. Different Types of Models Used in Teaching the Particulate Level of Chemistry

Despite the wide range of challenges associated with teaching and learning redox reactions, research on pedagogical approaches in this area remains limited. A systematic review of the literature between 2000 and 2019 identified only 54 relevant studies (Goes et al., 2020). Most of these studies focused on instruction at the university level and primarily advocated for experimental approaches as effective methods for teaching redox reactions.

One of the main challenges in studying EC at the submicroscopic level is that different structural models can be used to represent the same chemical species or substances (Chittleborough & Treagust, 2008; D. Gabel, 1999; Johnstone, 1993; Justi & Gilbert, 2000). For example, simple particle models depict particles as generalized circles (Figure 1a) and represent chemical changes as the basic rearrangement of these particles. In contrast, the atomic model (Figure 1b) defines atoms, ions, and molecules more rigorously: an atom is electrically neutral, having equal numbers of protons and electrons; an ion has an imbalance in protons and electrons, resulting in a net charge; and a molecule is a collection of atoms with balanced charges, making it neutral overall.

Each model has its pedagogical strengths. The atomic model, for instance, is well suited to illustrating the transfer of electrons between particles, while the simple particle model can support complex reasoning about chemical changes at a more abstract level (Cheng, 2018).

Additionally, a third model—the free electron model—depicts delocalized valence electrons surrounding metal cations (Figure 1c). This model is typically used to explain the physical properties of metals, such as malleability and thermal and electrical conductivity.

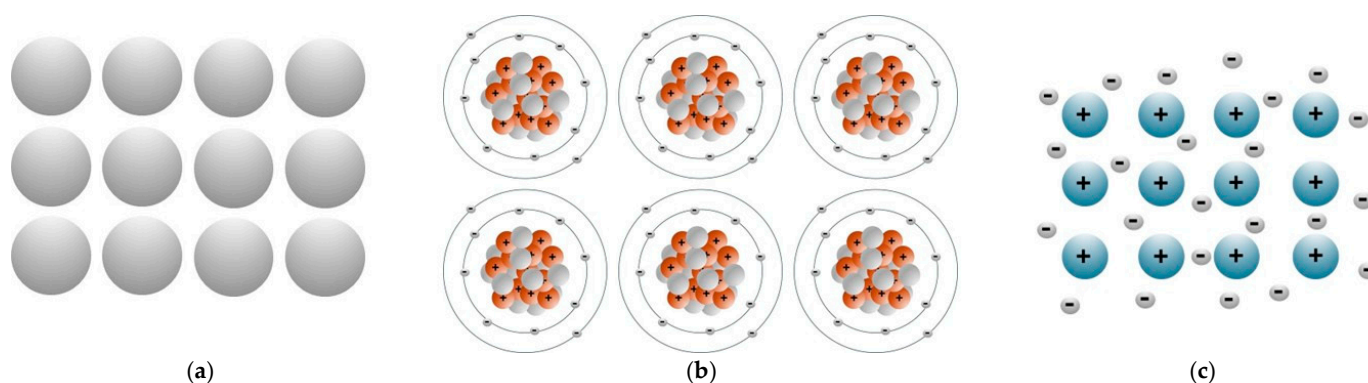


Figure 1. Representation models of the metal magnesium (Mg). (a) Simple particle model—each metal atom represented as one particle. (b) Atomic model—an atom is composed of protons, neutrons, and electrons. The electron configuration of Mg is 2,8,2. (c) Free electronic model—metal cations of Mg and delocalized valence electrons.

Simple particle models of chemical reactions often omit electron involvement; these models are commonly found in chemistry textbooks to visualize molecular reactions (Dori & Kaberman, 2012). In contrast, the atomic model is more appropriate for depicting changes in electron configurations during ion formation (Cheng & Gilbert, 2017), as it not only reflects structural transformations but also explicitly shows electron transfer. However, using the free electron model to illustrate electron movement in redox reactions presents unique challenges, particularly in representing half-reactions in which a metal undergoes oxidation at the submicroscopic level.

Research shows that computer animations representing the particulate level can be beneficial (Cole et al., 2019). Such learning interventions have also been found to enhance students' spatial reasoning skills (Al-Balushi et al., 2017; Hinze et al., 2013). However, inaccurate representations of atoms, molecules, and ions in animations can lead to further alternative understandings (Tasker & Dalton, 2008). Another concern is the complexity of animations. If animations are overly detailed or information-rich, they may contribute to cognitive overload or distract students from the core concepts. It is therefore important to simplify and streamline the information presented in order to highlight the most essential features (Mayer et al., 2001; Rosenthal & Sanger, 2012). Simplified animations have been shown to produce more effective visualizations and support the development of robust mental models of redox processes compared to more complex visualizations (Bussey et al., 2013). Furthermore, animations that contain excessive information appear to reduce students' tendencies to reference electron transfer processes in their explanations. For example, in one study, students who viewed a simplified animation of copper being placed in a silver nitrate solution were significantly more likely to include accurate electron transfer descriptions in their explanations compared to those who viewed a more complex version of the animation. The latter group tended to omit key aspects of redox reactions, such as electron movement, from their accounts (Cole et al., 2019).

The same study also emphasized that explicitly showing the number of electrons transferred, as well as the charges on atoms and ions before and after the reaction, can enhance students' understanding of electron transfer mechanisms. Simplified animations thus appear to be more useful both for visual representation and in helping students to construct a coherent mental model of oxidation–reduction processes (Bussey et al., 2013). Finally, students

often face challenges in identifying the number of electrons gained or lost during a reaction, in understanding and balancing redox equations, and in recognizing how electron transfer affects the sizes of metal atoms or ions (Cole et al., 2019; Rosenthal & Sanger, 2012). These difficulties can further hinder their comprehension of the physical transformations that occur during redox processes. An alternative approach to visualizing reactions at the particulate level is the use of physical modeling. Modeling with clay has been shown to support both teachers and students in translating the symbolic level of atomic nuclei and chemical reactions into more tangible representations (Adbo & Akesson-Nilsson, 2022; Akesson-Nilsson & Adbo, 2024). This approach can aid in understanding the atomic composition, molecular structure, and atomic distribution in different substances and the rearrangement of atoms during chemical reactions.

2.4. Challenges with Physical Models in Teaching

The use of physical models in chemistry education entails several challenges that teachers must address. A central issue concerns simplifications and hidden assumptions. Atomic and molecular models necessarily reduce details to make complex concepts manageable; however, students often interpret these models as literal representations of reality (Harrison & Treagust, 1996). As a result, simplified depictions, such as the idea that “atoms are small spheres”, may be perceived as truths (Taber, 2003). In particular, when only one model is presented, students may believe that there is a single “correct image” of a scientific phenomenon (Justi & Gilbert, 2016). Physical models also rarely reproduce proportions accurately, which can lead to alternative understandings of size, scale, and density. These issues highlight the importance of explicitly clarifying both the purpose and the limitations of models in instruction (Förtsch et al., 2018; Oh & Oh, 2011).

Other challenges involve misunderstandings related to model purpose, analogies, and intended dynamics. Students may transfer unintended properties from the model to the target concept, such as interpreting representations as static rather than dynamic. This can limit their understanding of processes, probability, and variation (Oh & Oh, 2011). There is also a risk that students’ attention will shift from a conceptual understanding to the physical object itself, underscoring the need for careful didactic framing and teacher guidance (Justi & Gilbert, 2016; Treagust, 2008).

2.5. Aim of the Study

Previous research on students’ understanding of redox reactions has primarily focused on their comprehension at the symbolic level (De Jong et al., 1995; Garnett & Treagust, 1992a; Rosenthal & Sanger, 2012; Schmidt & Volke, 2003), whereas studies addressing students’ understanding of the particulate nature of redox processes—such as the dynamic interactions of particles and electron transfer—are limited. Meanwhile, research on students’ understanding of electrochemical cells has mainly focused on the particulate level (Burke et al., 1998; Garnett & Treagust, 1992a, 1992b; Liu et al., 2008; Reid & Yang, 2002; Sanger & Greenbowe, 1997, 2000), even though students typically receive no specific instruction on this when first introduced to the fundamentals of redox reactions.

Traditional teaching of the fundamentals of redox reactions is largely confined to the symbolic level. However, since students often struggle to connect the symbolic level with the submicroscopic level, it is important to provide support for this understanding so that they can later grasp electrochemistry.

The aim of this study is to gain a deeper understanding of how chemistry instruction can be designed to enhance students’ learning of redox reactions and make these processes more comprehensible through visualizations at the particulate level.

The study specifically focuses on how the use of simple models, such as clay models, can support students' conceptual understanding of key aspects within EC. By supplementing chemical notation with particle-based representations, the study seeks to illustrate a didactic approach that facilitates students' grasp of the underlying mechanisms of redox reactions and addresses common learning obstacles in this abstract and complex domain.

Research Questions:

1. How does the use of models affect students' understanding of key concepts related to redox reactions, particularly in identifying such reactions and understanding electron transfer in these chemical processes?
2. In what ways can models help students to connect symbolic observations to the underlying chemical processes?

3. Methods

3.1. Participants and Implementation

The study was conducted at an upper secondary school in Sweden and involved two classes in the natural science program, which were comparable in their chemistry knowledge. The participants were in their second year and had completed the introductory chemistry course (Chemistry 1); at the time of the study, they were approximately halfway through the second chemistry course (Chemistry 2).

To ensure that the results of the two groups were as comparable as possible, the study was conducted at the same school with the same chemistry teacher teaching two different classes, with similar average grades. The same teacher conducted all sessions related to the study.

A total of 41 students participated in the initial instructional session on EC. These students were divided into two groups: 20 students in Group A and 21 students in Group B. One week after the instructional session, the teacher administered a written test, followed by interviews with selected students.

Of the original participants, 19 students from each class completed the test, but, in Group B, only 18 students were included in the study because one student chose to take the test but declined to participate in the study.

Responses from the tests were judged to be correct if they aligned with established scientific knowledge. The assessment focused strictly on chemical accuracy rather than on linguistic formulation.

Nine students from each group were then selected for interviews. The selection was based on two criteria: (1) the number of correct answers—students were chosen to represent a range from few to many correct responses, ensuring diversity in performance; (2) the quality of explanations—this was assessed by evaluating how well students articulated their reasoning, including clarity, logical structure, and the use of relevant chemical concepts. Explanations that demonstrated a deeper understanding and the accurate application of concepts were considered of higher quality. The aim was to create an interview group that was as heterogeneous as possible to explore the results of modeling at the particulate level.

3.2. Ethical Aspects

Participation in the study was voluntary. All students, as well as the parents of students who had not yet reached the age of the majority, were informed about the study's purpose and procedures and about how the data would be processed in accordance with the [Swedish Ethical Review Act \(2003, p. 460\)](#), the principles of good research practice, and the EU General Data Protection Regulation (GDPR). The participants were notified of their right to withdraw from the study at any time without negative consequences.

Since the content of the lessons was the same, with only one difference—the methodological approach of building atoms, ions and molecules with clay—the impact on the

student groups was considered minimal: neither group received instruction that was inferior to the standard, nationally accepted curriculum. The regular teacher participated during the study and could consciously compensate for any discrepancies between the two groups after its completion if needed.

3.3. Instructional Session on Redox Reactions

During the instructional session on EC, two distinct teaching methods were employed. Both groups received the same instructions, with the exception that Group A also used clay models to visualize particulate-level electron transfer in redox reactions. Group B only relied on the symbolic level, using chemical symbols and arrows within reaction equations. The sessions were conducted separately for each group and lasted approximately 60 min.

The students who used clay to visualize electron movement were introduced to a particle model of the atom, which, in some respects, resembled the free electron model illustrating cations surrounded by electrons. The difference was that the modified free electron model used in this study represented only individual cations (positively charged ions) surrounded by electrons participating in the chemical reaction. Once these electrons were released, only the cation remained (Figure 2).

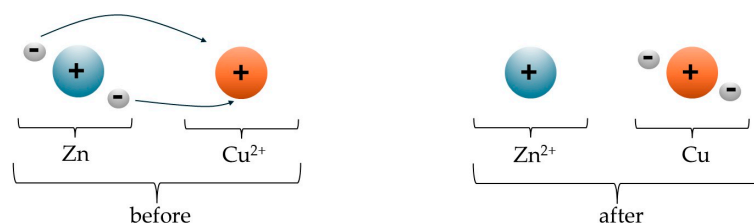


Figure 2. Model of the reaction between zinc metal (Zn) and a copper ion (Cu^{2+}). The image illustrates the particles present before and after the reaction. The zinc atom is represented as a cation (+) (blue) surrounded by electrons (−) (grey) that participate in the reaction, while the copper atom is represented as a cation (+) (orange) surrounded by electrons (−). Zn^{2+} is represented only as a cation (blue) and Cu^{2+} is represented only as a cation (red). Before: The arrows indicate the movement of electrons from the zinc atom (Zn) to the copper cation (Cu^{2+}). After: A zinc cation (Zn^{2+}) and a copper atom (Cu) are formed.

When two molecular substances, such as hydrogen and oxygen, react with each other, no ions are formed because the electron transfer is only partial. To illustrate this electron movement, the students built a corresponding model. To represent the redox reaction, they moved the models closer together and shifted the valence electrons in the hydrogen atoms closer to the oxygen atom (Figure 3). This increased the distance between the hydrogen electrons and their protons slightly, and the partial movement of electrons was explained as the redox reaction.

The instruction was organized around repeated exposure to the content, combined with teacher-guided modeling and group discussions. The study employed a repeated instructional design, with each instructional session divided into three phases. The first phase focused on a single displacement reaction between a metal atom and a metal ion, selected because changes in electrical charge are relatively easy to track. Using the reaction between zinc and copper(II) ions as an example, students were introduced to the concepts of oxidation and reduction. The teacher presented the balanced reaction equation, demonstrated its division into oxidation and reduction half-reactions, and briefly discussed the role of spectator ions. Students then worked individually or in pairs on questions related to electron transfer, charge changes, oxidation and reduction, and differences between atoms and ions. Group A used clay models to represent atoms and ions and physically demon-

strated electron transfer, whereas Group B relied on symbolic representations, indicating electron movement using arrows and electron symbols in the chemical equation.

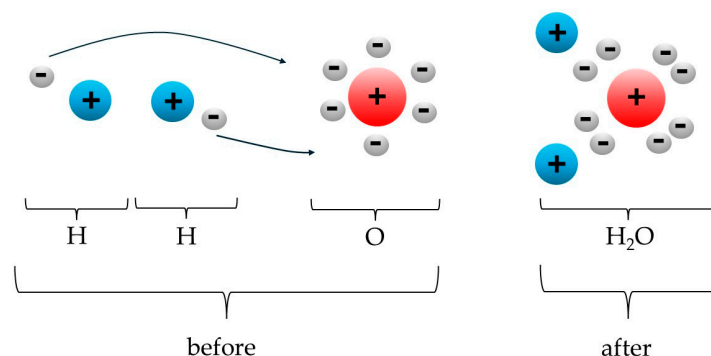


Figure 3. Model of the reaction between hydrogen (H) and oxygen (O), where water is formed (H_2O). The image illustrates the particles present before and after the reaction. The hydrogen atoms are represented as a cation (+) (blue) surrounded by electrons (−) (grey) that participate in the reaction, while the oxygen atom is represented as a cation (+) (red) surrounded by electrons (−). Before: The arrows indicate the movement of electrons from the hydrogen atom (H) to the oxygen atom (O). After: A water molecule is formed.

Figure 4 illustrates an example of the clay models that the students worked with during the exercise, in this case representing the reaction between one zinc atom and one copper ion. Figure 4a shows the first stage of the process—that is, the situation prior to the reaction. Figure 4b depicts the reaction in progress, and Figure 4c shows the products formed after the reaction had taken place.

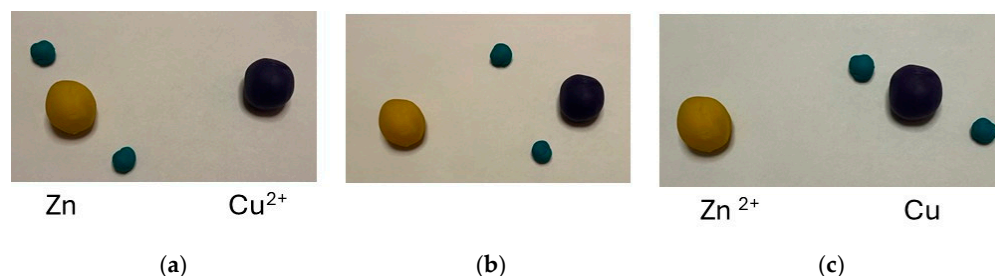


Figure 4. Examples of clay models constructed by students to represent the redox reaction between zinc (Zn) and a copper ion (Cu^{2+}). (a) The initial stage of the process (reactants); (b) the reaction in progress, with the electrons approaching the copper ion; (c) the products formed after the reaction has taken place. Yellow spheres represent zinc cations, dark blue spheres represent copper cations, and small green spheres represent electrons.

The second phase addressed a synthesis reaction in which two neutral elements reacted to form a neutral compound, using the formation of water from hydrogen and oxygen as the example. Instruction emphasized changes in oxidation numbers and how these related to electron distribution and redox processes in reactions without ions. Group A constructed clay models of hydrogen and oxygen atoms, visualizing partial electron transfer and polar covalent bonding by repositioning valence electrons, while Group B worked with symbolic notation to represent electron movement. Students answered questions concerning the electron transfer direction and extent, the number of electrons involved, and the identification of oxidation and reduction based on oxidation numbers.

Figure 5 presents the corresponding clay models for the redox reaction between hydrogen and oxygen, resulting in the formation of water (H_2O).

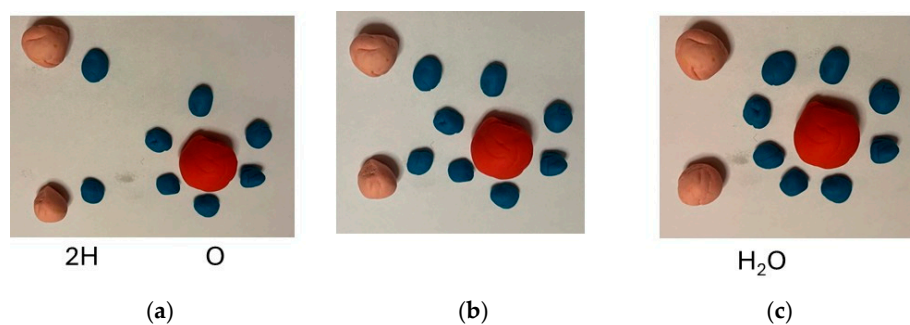


Figure 5. Examples of clay models constructed by students to represent the redox reaction between two hydrogen atoms (H) and one oxygen atom (O). (a) The first stage of the process (the reactants); (b) the reaction in progress, with the hydrogen atoms approaching the oxygen atom; (c) the products formed after the reaction has taken place. The electrons originally associated with the hydrogen atoms are located closer to the oxygen atom than to the hydrogen atoms. Pink spheres represent hydrogen cations, the red sphere represents an oxygen cation, and the small blue spheres represent electrons.

The third phase focused on the electrochemical series as a tool for predicting which metal is oxidized in a redox reaction. After reviewing the electrochemical series and its implications for electron donation tendencies, students analyzed electron transfer between zinc and copper(II) ions and between zinc(II) ions and copper. Group A used clay models in combination with the electrochemical series to illustrate ion formation and electron transfer, while Group B employed symbolic representations with arrows and electron notation.

Overall, students in Group A had no significant difficulty in creating their models. While they enjoyed the activity, some expressed initial skepticism, perceiving clay modeling as an elementary technique. Nevertheless, they successfully built their models and accurately depicted electron movement. Group B, working solely with symbolic notation, also showed no notable difficulties in representing electron transfer in their reaction equations.

3.4. Follow-Up Test and Data Analysis

Students completed a written assessment focused on redox reactions (Appendix A). The test lasted approximately 60 min and consisted of multiple-choice questions, each followed by an open-ended follow-up question in which students were asked to justify their answers. As reference materials, students had access to the periodic table and the electrochemical series.

The test questions were designed based on six thematic areas where prior research has identified common alternative understandings in redox chemistry (Brandriet, 2014). The multiple-choice test was composed of six questions designed to probe students' understandings of various aspects of EC. The questions and alternative answers were chosen to explore some of the most common alternative understandings.

Questions 1 to 3: Determining whether students could correctly classify a given reaction as a redox reaction. Students were first asked to decide whether the presented reaction was a redox reaction and then justify their answer by selecting one or more explanatory alternatives. These alternatives targeted various dimensions of the reaction, including changes in electrical charge, variations in oxidation states, electron transfer, macroscopic properties (e.g., visible changes), and surface-level indicators (e.g., symbolic features in the reaction formula, such as exchange reactions, oxygen transfer, or charge representations).

The reactions used in these questions represented three different types of chemical processes: a simple single-replacement reaction (metal displacement); an acid–base reaction, in which copper(II)oxide dissolves in sulfuric acid to form copper(II)sulfate and water; and a synthesis reaction involving two neutral substances reacting to form a new neutral compound—a reaction that included only neutral molecules and no ionic species.

Question 4: Probing students' conceptual understanding by presenting a series of statements about redox reactions. These statements addressed, among other aspects, whether the presence of oxygen or metals is a necessary condition for a reaction to be classified as redox and whether oxidation can occur in the absence of a corresponding reduction. The statement about whether oxidation can occur without reduction aimed to assess whether students understood the reciprocal nature of redox processes—namely, that oxidation and reduction always occur concurrently and are interdependent.

Questions 5 and 6: Focused on students' understandings of electron transfer within redox reactions. Question 5 presented a straightforward single-replacement reaction, where a metal ion served as the oxidizing agent. Question 6 dealt with a more complex scenario involving both a redox process and an acid–base reaction. In this case, nitric acid acted as the oxidizing agent. A particular challenge in this question was that not all nitrate ions participate in the redox reaction—some remain unchanged (none of the answer options were entirely correct).

During the interviews, the same questions as in the written tasks were asked. The students were given the opportunity to clarify their explanations, and, in cases where a written explanation was missing, they were given the opportunity to try to explain their answers orally. An additional purpose of the interviews was to deepen the understanding of how and why the students reasoned as they did. The interview responses were therefore used to complement the written responses.

The analysis of student responses considered both the multiple-choice questions and the written explanations, as well as the interview data.

The written responses and interview data were categorized according to analytical depth—that is, the extent to which students could reason around and justify their answers in a way that demonstrated an understanding of the underlying chemical processes (Table 1). Analytical responses were characterized by clear reasoning and the correct use of terminology.

Another category was “incomplete” responses. These included factual statements without contextual understanding, the use of terms without explanation, a lack of reasoning, or overly brief responses. A response could be formally correct but lack analysis or reflection. If a student only provided an analytical explanation for part of the question, the answer was still categorized as incomplete.

An alternative understanding was noted when student explanations contained incorrect interpretations or the inappropriate use of chemical concepts. A fourth category, “no answer”, included blank answers or those stating that they did not know. Examples of the analysis are shown in Table 1; however, the fourth category is excluded from the table as answers were absent or stated “do not know”.

Table 1. Examples of responses within the different categories: analytical responses, incomplete responses, and alternative understandings.

Is this a redox reaction? $2\text{Mg (s)} + \text{O}_2 \text{ (g)} \rightarrow 2\text{MgO (s)}$ I chose my answer because...		
Analytical responses	Incomplete responses	Alternative understanding
Choice of explanation: A redox reaction occurs because <i>“The oxidation numbers change from before the reaction to after. Mg increases in oxidation number, meaning it is oxidized. Oxygen is reduced, as its oxidation number decreases.”</i> During the interview, the student also correctly explained the connection between the ON and charge.	Choice of explanation: A redox reaction occurs because <i>“Two elements react, the charge changes.”</i> Does not explain how the charge changes.	Choice of explanation: A redox reaction does not occur because <i>“There are only two terms that become one product, meaning two reactants form one product.”</i> During the interview, the student confirmed that he/she believed a redox reaction must result in two products.

Table 1. Cont.

Study the following reaction: $Zn(s) + Cu(NO_3)_2(aq) \rightarrow Zn(NO_3)_2(aq) + Cu(s)$ In this reaction, an electron transfer occurs from...		
Analytical responses	Incomplete responses	Alternative understanding
Choice of explanation: In this reaction, there is a transfer of electrons from zinc to copper by... <i>"Copper takes up electrons from zinc, which is reduced to pure copper. We see this by studying the oxidation numbers. Zn increases, meaning it is oxidized and loses electrons, and Cu decreases, meaning it is reduced and gains electrons."</i> During the interview, the student responded that pure copper is copper in its elemental form and that it is formed when copper ion takes up electrons.	Choice of explanation: In this reaction, there is a transfer of electrons from zinc to copper by... <i>"Zinc gives away an electron so that copper becomes free, then zinc takes its place."</i> The description of the electron transfer was not complete.	Choice of explanation: In this reaction, there is a transfer of electrons from copper to nitrate by... <i>"Zn binds to NO₃ and solid Cu is formed, meaning it is not charged."</i> Zn does not bind directly to NO ₃ ; it is Zn ²⁺ that can do so, and it is only if the salt precipitates.

In most cases, the interview responses confirmed the categorization of the written responses. In a smaller number of cases, the categorization was adjusted based on the explanations provided by the students during the interviews. Most of the students who had not provided a written explanation responded "I don't know" to the same question during the interview.

4. Results

Several different types of analysis were performed on the students' answers. The initial analysis was an overall analysis of the number of correct answers to the multiple-choice questions. Where correct answers to each question were given, 1 p was assigned, and the average for the two groups was calculated. Group A (who modeled electron movement) consistently outperformed Group B (who only used symbolic representations) in overall accuracy, with an average score of 2.9 p compared to 2.1 p for a total of 6 p.

The most significant differences between the groups were found in Questions 1, 2, and 6 (Table 2), i.e., recognising redox reactions including metal displacement, understanding that the dissolution of a metal oxide in an acid is not a redox reaction, and an understanding of electron transfer in a more complex reaction, including both a redox- and an acid–base reaction. Using models of clay appeared to have the greatest impact on the students' ability to solve complex tasks involving interpreting reactions including metal displacement, dissolving metal oxides in an acid, and electron transfer involving both a redox process and an acid–base reaction. However, it had little or no effect on students' ability to solve tasks involving recognizing a synthesis reaction as a redox reaction (Question 3) and the conceptual understanding of electron transfer in a straightforward single-replacement redox reaction (Question 5).

Table 2. Proportion of correct answers in the response options for Questions 1–6 for Group A and Group B. The proportion of correct answers is presented as a percentage (%).

Group	1	2	3	4	5	6
A (%)	58	47	16	47	68	47
B (%)	33	16	11	44	67	17

4.1. Students' Ability to Identify Redox Reactions

The modeling activities seemed to affect the interpretation of the visual symbolic level of a chemical reaction. The results suggested that more Group A students had moved away from viewing redox reactions as merely a change in charge.

Group A consistently outperformed Group B on Questions 1–3 (Figure 4), even if the students in Group B used more chemical terminology in their explanations. The most pronounced difference between the groups was observed in the prevalence of alternative understandings in Question 1: 44% of the explanations from Group B in Question 1 contained incorrect reasoning, compared to only 16% in Group A.

In Group A, these alternative understandings typically involved claims that bonds form between iron and the sulfate ion in an aqueous solution—an assertion that is incorrect—as well as misinterpretations of copper’s role relative to the sulfate ion and improper use of the electrochemical series (1–3).

1. *“I thought that electrons move from copper sulfate to the iron, forming bonds between iron and the sulfate ion, and that copper gains a new charge.”* (Group A)
2. *“It is a redox reaction because the iron dissolves with SO_4 . Copper gives away SO_4 to the iron because it has an oxidation number of 0 and can dissolve.”* (Group A)
3. *“Copper is positioned to the right in the electrochemical series and gives away electrons to Fe, which is to the left in the series. Otherwise, everything else remains the same.”* (Group A)

Conversely, alternative understandings in Group B included the belief that iron is in its elemental form and therefore cannot participate in a redox reaction, an overreliance on superficial characteristics of the reaction formula (such as the swapping of symbols), misuse of the electrochemical series, and the incorrect assertion that iron acts as an oxidizing agent (4–8).

4. *“Iron is in its elemental form, so no redox reaction occurs.”* (Group B)
5. *“Iron is initially in its elemental form, and then it bonds with the sulfur oxide, while copper becomes elemental.”* (Group B)
6. *“In redox reactions, one substance is oxidized and another is reduced. In this case, only SO_4 is transferred.”* (Group B)
7. *“Fe comes before Cu in the electrochemical series. Therefore, copper cannot donate electrons to iron.”* (Group B)
8. *“The iron was used as an oxidizing agent here.”* (Group B)

Even if a student wrote that a metal was in its elemental form, it appeared that they did not always understand the charge of the substance in this state—an aspect that became evident during the interviews regarding the response in Question 5 (9).

9. Interviewer: *“What charge do you have here then?”* (points to Fe)
 Student: *“It’s still positive.”*
 Interviewer: *“So the iron here is positively charged from the beginning?”*
 Student: *“Yes”*
 Interviewer: *“And the copper here?”* (points to Cu)
 Student: *“It’s also positive.”*
 Interviewer: *“You mean the copper here that is alone?”*
 Student: *“No, it’s negative.”*

A closer analysis of the students’ justifications of their answers revealed more differences between the groups, both in terms of correctness and conceptual depth.

In students’ answers to Questions 1–3 about redox reactions, clear differences emerged between the groups. Group B more often claimed that a redox reaction occurs (in Question 1), since iron and copper switch places. In Question 2, the group expressed greater uncertainty, with a wider variety of answers, such as copper losing oxygen, water being formed, or copper oxide dissolving. In Question 3, again, more students in Group B showed misunderstandings about the direction of electron transfer, stating that oxygen gives electrons to magnesium.

There were also differences in the students’ explanations between the two groups. Group A mainly based their reasoning on visible changes, such as phases, while Group B

attempted to use chemical concepts like ONs and electron transfer, albeit often with alternative understandings. In Group B, it was more common that students focused on the changes in the chemical symbols, without understanding the underlying mechanisms. Both groups struggled to interpret charges and ONs correctly, but Group B showed greater conceptual ambition. Concept use was more visual in Group A and more chemically oriented (but uncertain) in Group B (Table 3).

Table 3. Common alternative understandings in Questions 1–3 in Group A vs. Group B.

Aspect	Alternative Understanding in Group A	Alternative Understanding in Group B
Use of Concepts	Some students incorrectly used visual descriptions, such as referring to a substance as “solid” or “liquid”, to explain the chemical process.	Alternative understanding is more concept-oriented, with attempts to use chemical terms, but often incorrectly linked to the reaction process.
Chemical Reaction Formula	Misunderstanding of the reaction by focusing only on changes in chemical symbols, without understanding the underlying chemical mechanism.	The same misunderstanding as in Group A, but this type of alternative understanding occurred more frequently in Group B.
Charge	Several students believed that a charge was only visible when a “+” or “-” is shown in the formula.	Several students believed the same as in Group A, but this type of alternative understanding occurred more frequently in Group B.
ONs	Determined or interpreted ONs incorrectly or confused them with charges.	Showed the same mistakes as in Group A, but this type of alternative understanding occurred more frequently in Group B.
Electron Transfer	Misunderstood the direction of electron movement or believed that no electron transfer occurred because a bond was formed.	The same misunderstanding as in Group A, but this type of alternative understanding occurred more frequently in Group B.

The results suggest that Group A possessed a stronger conceptual foundation, particularly in identifying redox reactions—specifically those classified as simple substitution reactions—and in the correct usage of the concept of charge. The larger proportion of students correctly employing the term “charge” indicates a deeper conceptual understanding. The use of modeling clay in instruction may have contributed to this enhanced understanding, especially in tasks resembling those practiced during lessons. Nevertheless, both groups demonstrated limitations in their use of key concepts such as oxidation states and the mechanisms underlying redox reactions.

However, Group B used particle concepts such as electrons and ions somewhat more frequently, as well as the concept of noble gas configuration. Despite this, these terms were often misapplied in their reasoning.

The incorporation of modeling clay appeared to positively influence students’ abilities to respond to questions related to redox reactions. Group A exhibited a stronger conceptual understanding in this task, as evidenced by their greater ability to correctly identify the reaction as a redox process and provide accurate justifications. Despite differences in the number of correct answers and conceptual usage, the proportion of students reaching an analytical level of reasoning was approximately equal in both groups. This suggests that, while both groups had similar reasoning abilities, Group A benefitted from better prior knowledge or a more solid conceptual base.

Regarding the evaluation of statements about redox reactions in Question 4, differences between groups were minor. Fewer than half of the students in either group correctly identified that all statements were false—47% in Group A and 44% in Group B—indicating general uncertainty about the fundamental logic of redox concepts.

In summary, despite Group B’s more frequent use of chemical terminology in their explanations, these concepts were often incorrectly applied. Group A displayed fewer alternative understandings, indicative of a more stable conceptual foundation. These differences fur-

ther suggest that the use of modeling clay in instruction may help to mitigate fundamental alternative understandings in determining whether a chemical reaction is a redox reaction.

Both groups showed a limited understanding of redox reactions. Alternative understandings were evenly spread, with Group A struggling more with oxidation–reduction links and Group B with oxygen’s role. Group B gave more elaborate but not always accurate answers; Group A used simpler but sometimes more precise terms. Physical models had little impact on theoretical knowledge but may aid in applying concepts.

4.2. Student Perspectives on Electron Transfer in Redox Reactions

The investigation of students’ conceptual understanding of electron transfer in redox reactions involved two distinct tasks. In one task, students answered questions related to electron transfer in a single-displacement reaction, where a metal ion functioned as the oxidizing agent. In the other task, students analyzed a more complex chemical reaction in which redox and acid–base reactions occurred simultaneously.

Both groups demonstrated comparable abilities to correctly identify electron transfer in a simple redox reaction, namely a single-displacement reaction.

Despite these similarities, differences emerged in students’ reasoning and conceptual language. Group B had a slightly larger proportion of students reaching an analytical level compared to Group A, although Group B also exhibited a greater prevalence of alternative understandings, indicating that more advanced terminology does not necessarily correspond to a deeper understanding. Incomplete explanations were notably more frequent in Group A than in Group B, which may suggest that students in Group A possessed some understanding but lacked the means to fully articulate it.

Regarding the response quality in Question 6, concerning a more complex chemical reaction in which redox and acid–base reactions occurred simultaneously, there was a large difference between the two groups. Almost half of the students in Group A (47%) provided correct answers, compared to 17% in Group B (Table 1).

Alternative understandings in Group A varied but often reflected a limited understanding of the role of electrons in the reaction, with students struggling to explain how electron transfer was involved in the process. In Question 5, some assumed that the electrons moved from zinc to nitrate via nitrate ion participates by forming bonds or transporting electrons (10, 11).

10. *“Bonds between zinc and nitrate are formed.”* (Group A)

11. *“Nitrate holds the electrons that may be picked up by zinc. Then copper takes the extra electrons.”* (Group A)

In Group B, several students also believed that the nitrate ion participated in the electron transfer; some believed that substances in solid form were positively charged, or they misunderstood how the electrochemical series should be used (12, 13).

12. *“Zn, as a solid substance, has a +2 charge. Zinc is lower in the electrochemical series and therefore takes Cu’s place. This leads to Cu being released as Cu^{2+} .”* (Group B)

13. *“Zinc gives away two electrons to the nitrate, which causes zinc to get a +2 charge. Zinc cannot give any electrons to copper because copper is further to the right in the electrochemical series.”* (Group B)

Overall, in Question 5, both groups displayed similar competence in identifying correct electron transfer in this reaction type. Group B had more students achieving an analytical level but also exhibited a higher frequency of alternative understandings, whereas Group A had more incomplete explanations. This suggests that the use of modeling materials in Group A may have facilitated students’ visualization and concretization of electron transfer, reducing alternative understandings. However, they less frequently reached an analytical level compared to Group B, whose students attempted to apply more advanced chemical terminology—albeit

often inaccurately. Group B demonstrated more fundamental misunderstandings about electron transfer and charge, despite their more frequent use of chemical vocabulary.

In Question 6, although not all nitrogen atoms accepted electrons, the nitrogen atoms involved in the redox reaction each accepted three electrons. Students who did not mark their answer but provided a correct explanation in their written response were assessed as correct. These students demonstrated awareness that not all nitrogen atoms participated in the redox reaction.

The analysis of students' responses in Question 6 reveals several clear differences between Group A and Group B, both in terms of accuracy and the types of alternative understandings. The most accurate answer—that each copper atom donates two electrons and each nitrogen atom accepts three electrons—was selected by a larger proportion of students in Group A (47%) compared to Group B (39%). Although students in Group B could identify parts of the correct mechanism, many lacked a coherent understanding of the entire reaction process.

A pronounced difference between the groups was found in the proportion of students who indicated that no electron transfer occurred in the reaction (Question 6). This alternative understanding was considerably more common in Group B (28%) than in Group A (5%), indicating deeper conceptual confusion regarding the fundamental mechanism of redox reactions in Group B.

The belief that nitrate ions are involved in electron transport also appeared in the explanations in Question 6 (14).

14. *"The six electrons come from $(NO_3)_2$ because they reacted with Cu, then NO_3^- takes up the three electrons in order to react."* (Group A)

Some students in Group B explained that no redox reaction occurred because copper was in its elemental form or because only metals can participate in redox reactions. Difficulties in using oxidation states and charge to determine the reaction process were also observed in Group A but were less frequent.

Both groups exhibited significant challenges in correctly explaining the redox reaction. Only 11% of students in each group provided responses classified as both correct and analytical. Despite this shared difficulty, clear differences emerged in how students approached the task.

Both groups showed substantial difficulty in applying chemical concepts correctly in their explanations of a complex redox reaction. Nonetheless, they differed in their approaches and terminology use (Table 4).

Regarding students' understanding of the number of electrons released by each copper atom during dissolution in nitric acid, a clear difference between the groups emerges. In Group A, 68% of the students stated that the number was two, whereas the corresponding proportion in Group B was 39%. The difference between the groups was also substantial when determining the number of electrons accepted by the nitrogen atom. Half of the students in Group A indicated that the nitrogen atom accepted three electrons, compared to only 17% in Group B. These findings suggest that students in Group A were more capable of identifying, based on the chemical symbols in the reaction formula, the number of electrons released and accepted in the process.

In summary, the results indicate that Group A was more successful in answering questions related to the more complex redox reaction, while Group B employed more chemistry-relevant terminology, suggesting some conceptual awareness. However, this was often not accompanied by a deeper understanding, resulting in a large proportion of alternative understandings. Group A used fewer concepts, possibly reflecting uncertainty or a weaker conceptual foundation, but exhibited fewer incorrect reasonings. The use of

modeling materials, such as clay, appears to have some impact on performance in this type of task, which requires abstract conceptual application rather than concrete visualization.

Table 4. Common alternative understandings in Questions 5 and 6—Group A vs. Group B.

Aspect	Group A	Group B
Use of Concepts	Alternative understandings include superficial interpretations, such as substances switching places or bonds forming, without understanding electron transfer.	Alternative understandings are more concept-oriented, with attempts to use chemical terms, but often incorrectly linked to the reaction process.
Chemical Reaction Formula	Misunderstanding the reaction by focusing only on changes in chemical symbols, such as nitrate appearing to switch places, without grasping the underlying mechanisms.	This type of alternative understanding is more common, with students focusing on symbolic changes rather than the actual chemical processes.
Assessment of Charge	Alternative understandings include difficulties in understanding how the charge changes, how it should be applied, and confusion between elemental and ionic forms.	Fewer alternative understandings about charge are observed, although some still occur.
Understanding of ONs	Determining or interpreting ONs incorrectly or confusing them with charge as they mistakenly believe that the ON equals the total charge—for example, assigning (-1) to the entire nitrate ion.	Similar alternative understandings occur and to the same extent as in Group A.
Electron Transfer	Unclear ideas about how electrons move—such as nitrate picking up electrons, even when it acts as a spectator ion or an oxidizing agent, or failing to recognize that electrons are involved at all.	The concept of electron transfer is used more frequently, but students often misunderstand which species receives the electrons or fail to recognize that electron transfer occurs.

5. Discussion

5.1. Identifying Redox Reactions

Group A, which received instruction supported by clay modeling, generally performed better than Group B in identifying redox reactions, particularly in tasks similar to those where modeling had been used as a concrete instructional tool.

By working with the physical particle model in clay, which can be regarded as a simplified visualization of a redox reaction, students may have been provided with opportunities to notice the dynamic nature of particles in the process. This may, in turn, have contributed to an improved understanding of electron transfer and its connection to changes in charge—similar to what simplified data animations achieve in supporting students' understanding of redox reactions (Bussey et al., 2013).

However, the differences between the groups became less pronounced in Question 3, which involved a synthesis reaction. The proportion of correct responses was low in both groups—16% in Group A and 11% in Group B—while alternative understandings were widespread. This suggests that modeling primarily had an impact regarding replacement reactions, which are often used in the introduction of redox reactions, but was not sufficient to foster a deeper understanding of the underlying mechanisms of redox reactions.

This may partly be explained by the fact that, in redox reactions involving synthesis rather than electron exchange, as in replacement reactions, the transfer of electrons is less apparent. This can be seen in Figure 3, where it is shown that water is formed by oxygen and hydrogen atoms combining. This can partly be explained by the students' lack of ability to describe the underlying particulate processes represented by the symbols in the reactions (Brandriet, 2014). In their responses, the students also stated that, in a synthesis reaction, the atoms are simply combined, and this does not require any movement of electrons (Table 3). Another explanation is that students are not accustomed to working at the submicroscopic level when analyzing chemical reactions. Instead, they tend to rely on symbolic cues—such as phase changes, visible charges, or the exchange of substances—as these are more familiar and easier to interpret (Brandriet, 2014). Approaching chemical reactions from a particulate perspective is not an established part of students' analytical practice, and developing this skill requires time and targeted instruction. This might be explained by the fact that the three different forms of atomic models (Figure 1) are commonly used in teaching to illustrate how atoms rearrange during a chemical reaction, how ions are formed, or how chemical bonding occurs (Cheng, 2018; Cheng & Gilbert, 2017; Dori & Kaberman, 2012). However, none of these models are

suitable for illustrating redox reactions, which may explain why students are not trained to use particle models to represent this type of chemical reaction, and there is a risk that inaccurate models will lead to further alternative understandings. However, the modified free electron model of the atomic structure might serve as a sufficiently simple representation that can be used without posing a significant risk in terms of students developing alternative conceptions of redox reactions (Tasker & Dalton, 2008).

In this context, it is perhaps not surprising that modeling with clay did not lead to the increased use of concepts such as “electron” or “ion” in students’ explanations. While these models may help to concretize certain aspects of a reaction, their effectiveness as a conceptual tool depends on their deliberate and explicit connection to the particulate level.

5.2. Electron Transfer

Modeling appears to have helped students in Group A, compared to Group B, to a greater extent in visualizing and concretizing electron transfer. This was particularly evident in Question 6, where they were significantly more successful in specifying the correct numbers of electrons released and accepted in this redox reaction.

The modified free electron model might be comparable to simplified animations, which have been shown to improve the visualization of electron transfer and charges. This could explain why students in Group A performed better in identifying the number of electrons involved in the reaction and how charges change, being similar to the benefits observed with simplified animations (Bussey et al., 2013). In turn, this might reduce the occurrence of alternative conceptions. Group A demonstrated fewer incorrect reasoning patterns and used certain terms, such as “charge”, more accurately.

This modified atomic model also visually demonstrates that the atomic and ion radii change during the process, which is a challenge that students may overlook when only symbolic representations are used (Cole et al., 2019; Rosenthal & Sanger, 2012).

Although the students in Group A used chemical concepts only to a limited extent, when they did use them, they applied them correctly. This was not the case in Group B, where students were much more inclined to use chemical concepts in their answers, but often incorrectly. The modified free electron model, which seems to have facilitated students’ understanding of the number of electrons transferred, may have also, to a greater extent, improved their understanding of the symbolic representation in relation to chemical reactions.

This may be explained by the fact that the students in Group A had an improved understanding of symbolic representations in relation to chemical reactions. They seemed to understand to a greater extent that a chemical equation is not a mathematical operation, although they did not fully grasp how bonds break and new bonds form—an area that represents one of the major challenges in students’ understanding of chemical equations (Ben-Zvi et al., 1987; Chiu, 2007; D. L. Gabel & Bunce, 1994; Krajcik, 1991; Laugier & Dumon, 2004; Lee et al., 1993; Osborne & Cosgrove, 1983).

This highlights the importance of integrating modeling with instruction that emphasizes reasoning at the particulate level and the accurate use of scientific language.

There are several possible explanations regarding why the relationship between the groups’ test performance was not simple or straightforward. One contributing factor may have been pre-existing differences, such as motivation, teacher–student relationships, the classroom culture, or prior experience with modeling. Since both groups had the same chemistry teacher and the same teacher conducted both lessons, differences in instructional discourse were considered limited. However, students in Group A reported that the session was more enjoyable, despite initial skepticism, compared to Group B. This may suggest a novelty effect, which may have increased students’ attention, emotional engagement, and collaborative interaction, thereby improving their reasoning.

The use of clay modeling may also negatively affect alternative conception by, for example, reinforcing the idea that electrons are small spheres rather than quantum-mechanical entities (Taber, 2003).

6. Conclusions

Clay modeling appears to have had a modest positive effect on students' ability to identify redox reactions. The results suggest that physical modeling can support the understanding of electron transfer and changes in charge in familiar contexts. However, the differences between the groups diminished in tasks involving synthesis reactions and in understanding the fundamental concepts of redox reactions, indicating that modeling alone is insufficient for developing a deeper understanding of the underlying mechanisms.

Notably, the term "electron" was used only sparingly in both groups and almost not at all in Group A, despite the modeling activities being explicitly designed to visualize electron transfer. This suggests that the model alone did not foster a deeper conceptual understanding. For modeling to be effective, it must be integrated with explicit instruction on the meanings of key concepts and their connections to the particulate level. Students need guidance in interpreting models as representations of invisible chemical processes rather than merely as visual aids.

Although the introductory use of clay modeling did not lead to a significant increase in students' correct use of chemical concepts within electrochemistry (EC), it appears to have contributed to a slight improvement in their conceptual understanding of the underlying mechanisms. The fact that students who worked with clay relied considerably less on alternative conceptions in their responses suggests that these students progressed further in bridging the gap between the symbolic and particulate levels. The limited impact of clay modeling on students' willingness to use chemical terminology related to EC underscores the substantial challenges posed by the abstract and complex nature of these applications (De Jong & Treagust, 2002; Österlund et al., 2010).

Clay modeling has potential as a didactic tool, but its impact depends on how well—and how consistently—it is embedded in conceptually focused teaching that trains students to use the language of chemistry and to reason across multiple representational levels. The atomic models traditionally used in teaching are not designed to illustrate redox reactions. If students rely on these models in their conceptual thinking, there is a risk that inaccurate representations will lead to alternative conceptions. While clay modeling can help to concretize certain aspects of reactions, its effectiveness as a conceptual tool depends on its deliberate connection to the particulate level and the accurate use of chemical terminology.

The minimal use of particle models in teaching the fundamental theory of redox reactions, compared to their later introduction in electrochemistry, may be explained by the inadequacy of conventional atomic models in illustrating redox processes at the particulate level. A modified atomic model, depicting the atom without its valence electrons or representing electrons involved in the reaction as a cation surrounded by the participating electrons, could potentially support students' understanding of electron transfer between different atomic species, particularly in reactions involving metals. However, in synthesis reactions, electron transfer is less apparent, even with this model. This suggests that students may first need to become familiar with the modified atomic model and apply it to redox reactions involving atoms and metal atoms before extending its use to synthesis reactions.

Author Contributions: Conceptualization, G.A.-N. and K.A.; methodology, G.A.-N. and K.A.; software, G.A.-N. and K.A.; validation, G.A.-N. and K.A.; formal analysis, G.A.-N. and K.A.; investigation, G.A.-N. and K.A.; resources, G.A.-N. and K.A.; data curation, G.A.-N. and K.A.; writing—original draft preparation, G.A.-N. and K.A.; writing—review and editing, G.A.-N. and K.A.; visualization, G.A.-N.

and K.A.; supervision, G.A.-N. and K.A.; project administration, G.A.-N. and K.A.; funding acquisition, G.A.-N. and K.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Ethical review and approval was not required for this study involving human participants, in accordance with the local legislation and institutional requirements. All participants, and the parents of students who had not reached the age of the majority, provided written informed consent to participate in the study.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: We would like to express our sincere gratitude to the students for their participation in this study, which made this research possible. We also extend our thanks to the teacher who supported the implementation of the study in the classrooms and facilitated access to the learning environment. Their collaboration and commitment were invaluable to the success of this work.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

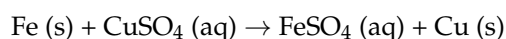
The following abbreviations are used in this manuscript:

EC Electrochemistry
ON Oxidation number

Appendix A

Follow-Up Test

1 Är detta en redoxreaktion?



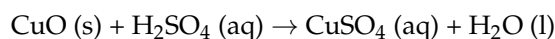
Ja ___ Nej ____

Jag valde mitt svar för att:

- järnet och kopparn byter plast i reaktionen
- laddningen hos järnet och kopparn ändras
- laddningen hos järn, kopparsvavel och syre är oförändrade
- allt sker i en vattenlösning och det bildas ett fast ämne
- det sker bara en oxidationsreaktion
- oxidationstalen ändras inte
- järnet löses upp

Förtydliga ditt svar med egna ord!

2 Är detta en redoxreaktion?



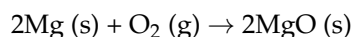
Ja ___ Nej ____

Jag valde mitt svar för att:

- oxidationstalen ändras inte
- kopparsvavel har förlorat syre och det har bildats vatten
- det bildas inget fast ämne
- ingen av produkterna är laddad vilket innebär att det inte har skett någon elektronförflyttning
- det sker bara en reduktionsreaktion
- kopparoxiden löses upp

Förtydliga ditt svar med egna ord!

- 3 Är detta en redoxreaktion?



Ja ___ Nej ____

Jag valde mitt svar för att:

- laddningen hos magnesium och syre ändras
- ämnena är inte laddade vilket betyder att det inte har skett någon elektronförflyttning
- det bildas bara en produkt
- det sker bara en oxidationsreaktion
- reaktionen sker inte i en vattenlösning.
- syre avger elektroner till magnesium så att det kan bildas en bindning.

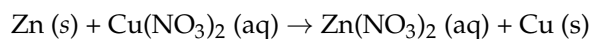
Förtydliga ditt svar med egna ord!

- 4 Vad är sant eller falsk angående redoxreaktioner?

- Det måste finnas syre närvarande.
 - Oxidation kan ske utan att det sker en reduktion.
 - Det är bara metaller som kan delta i redoxreaktioner.
- endast I är korrekt
 - endast II är korrekt
 - endast III är korrekt
 - både I och III är korrekta
 - ingen av dem är korrekt

Förtydliga ditt svar med egna ord!

- 5 Studera följande reaktion:

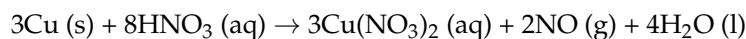


I denna reaktion sker det en elektronförflyttning

- från zink till nitrat
- från koppar till nitrat
- från nitrat till zink
- från zink till koppar
- från nitrat till zink, och sedan från zink till koppar

Förtydliga ditt svar med egna ord!

- 6 Studera följande reaktion:



Vad stämmer? Varje kopparatom avger.

- sex elektroner till sin omgivning.
- två elektroner och varje väte tar upp en elektron.
- två elektroner och varje kväve tar upp tre elektroner.
- sex elektroner och NO_3^- tar upp en elektron.
- två elektroner och NO_3^- tar upp tre elektroner.
- inga elektroner och det sker ingen elektronförflyttning i denna reaktion

Förtydliga ditt svar med egna ord!

References

- Adbo, K., & Aakesson-Nilsson, G. (2022). Moving beyond the language—visualizing chemical concepts through one's own creative expression. *Frontiers in Education*, 7, 1034140. [CrossRef]
- Akesson-Nilsson, G., & Adbo, K. (2024). Student translations of the symbolic level of chemistry. *Education Sciences*, 14(7), 775. [CrossRef]
- Al-Balushi, S. M., Al-Musawi, A. S., Ambusaidi, A. K., & Al-Hajri, F. H. (2017). The effectiveness of interacting with scientific animations in chemistry using mobile devices on grade 12 students' spatial ability and scientific reasoning skills. *Journal of Science Education and Technology*, 26(1), 70–81. [CrossRef]
- Basuki, R. (2020). Conceptual difficulties experienced by first-year undergraduate chemistry students in assigning oxidation number: A case study of high school chemistry textbooks. *Indonesian Journal of Chemistry*, 20(1), 223–236. [CrossRef]
- Ben-Zvi, R., Silberstein, J., & Eylon, B. S. (1987). Students' visualization of a chemical reaction. *Education in Chemistry*, 24, 117–120.
- Brandriet, A. R. (2014). *Investigating students' understandings of the symbolic, macroscopic, and particulate domains of oxidation-reduction and the development of the redox concept inventory*. Miami University/OhioLINK.
- Brandriet, A. R., & Bretz, S. L. (2014a). Measuring meta-ignorance through the lens of confidence: Examining students' redox misconceptions about oxidation numbers, charge, and electron transfer. *Chemistry Education Research and Practice*, 15(4), 729–746. [CrossRef]
- Brandriet, A. R., & Bretz, S. L. (2014b). The development of the redox concept inventory as a measure of students' symbolic and particulate redox understandings and confidence. *Journal of Chemical Education*, 91(8), 1132–1144. [CrossRef]
- Burke, K. A., Greenbowe, T. J., & Windschitl, M. A. (1998). Developing and using conceptual computer animations for chemistry instruction. *Journal of Chemical Education*, 75(12), 1658–1661. [CrossRef]
- Bussey, T. J., Orgill, M. K., & Crippen, K. J. (2013). Variation theory: A theory of learning and a useful theoretical framework for chemical education research. *Chemistry Education Research and Practice*, 14(1), 9–22. [CrossRef]
- Cheng, M. M. W. (2018). Students' visualisation of chemical reactions—Insights into the particle model and the atomic model. *Chemistry Education Research and Practice*, 19(1), 227–239. [CrossRef]
- Cheng, M. M. W., & Gilbert, J. K. (2017). Modelling students' visualisation of chemical reaction. *International Journal of Science Education*, 39(9), 1173–1193. [CrossRef]
- Chittleborough, G., & Treagust, D. (2008). Correct interpretation of chemical diagrams requires transforming from one level of representation to another. *Research in Science Education*, 38(4), 463–482. [CrossRef]
- Chiu, M. H. (2007). A national survey of students' conceptions of chemistry in Taiwan. *International Journal of Science Education*, 29(4), 421–452. [CrossRef]
- Cole, M. H., Rosenthal, D. P., & Sanger, M. S. (2019). Two studies comparing students' explanations of an oxidation-reduction reaction after viewing a single computer animation: The effect of varying the complexity of visual images and depicting water molecules. *Chemistry Education Research and Practice*, 2(4), 738–759. [CrossRef]
- Davidowitz, B., Chittleborough, G., & Murray, E. (2010). Student-generated submicro diagrams: A useful tool for teaching and learning chemical equations and stoichiometry. *Chemistry Education Research and Practice*, 11(3), 154–164. [CrossRef]
- De Jong, O., Acampo, J., & Verdonk, A. (1995). Problems in teaching the topic of redox reactions: Actions and conceptions of chemistry teachers. *Journal of Research in Science Teaching*, 32(10), 1097–1110. [CrossRef]
- De Jong, O., & Treagust, D. (2002). The teaching and learning of electrochemistry. In *Chemical education: Towards research-based practice* (pp. 317–337). Kluwer Academic Publishers.
- Dori, Y. J., & Kaberman, Z. (2012). Assessing high school chemistry students' modeling sub-skills in a computerized molecular modeling learning environment. *Instructional Science*, 40(1), 69–91. [CrossRef]
- Förtsch, S., Förtsch, C., Von Kotzebue, C. K., & Neuhaus, B. J. (2018). Effects of teachers' professional knowledge and their use of three-dimensional physical models in biology lessons on students' achievement. *Education Sciences*, 8(3), 118. [CrossRef]
- Gabel, D. (1999). Improving teaching and learning through chemistry education research: A look to the future. *Journal of Chemical Education*, 76(4), 548–554. [CrossRef]
- Gabel, D. L., & Bunce, D. M. (1994). Research on problem solving: Chemistry. In D. L. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 301–321). Macmillan; Maxwell Macmillan Canada; Maxwell Macmillan International.
- Garnett, P. J., & Treagust, D. F. (1992a). Conceptual difficulties experienced by senior high school students of electrochemistry: Electric circuits and oxidation-reduction equations. *Journal of Research in Science Teaching*, 29(2), 121–142. [CrossRef]
- Garnett, P. J., & Treagust, D. F. (1992b). Conceptual difficulties experienced by senior high school students of electrochemistry: Electrochemical (galvanic) and electrolytic cells. *Journal of Research in Science Teaching*, 29(10), 1079–1099. [CrossRef]
- Goes, L. F., Nogueira, K. S. C., & Fernandez, C. (2020). Limitations of teaching and learning redox: A systematic review. *Problems of Education in the 21st Century*, 78(5), 698–718. [CrossRef]
- Hadinugrahaningsih, T., Rahmawati, Y., & Suryani, E. (2022). An analysis of preservice chemistry teachers' misconceptions of reduction-oxidation reaction concepts. *Journal of Technology and Science Education*, 12(2), 448–465. [CrossRef]
- Harrison, A. G., & Treagust, D. F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education*, 80(5), 509–534. [CrossRef]

- Hinze, S. R., Williamson, V. M., Shultz, M. J., Williamson, K. C., Deslongchamps, G., & Rapp, D. N. (2013). When do spatial abilities support student comprehension of STEM visualizations? *Cognitive Processing*, 14(2), 129–142. [CrossRef]
- Johnstone, A. H. (1982). Macro- and micro-chemistry. *School Science Review*, 64, 377–379.
- Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to changing demand. *Journal of Chemical Education*, 70(9), 701–705. [CrossRef]
- Justi, R., & Gilbert, J. (2000). History and philosophy of science through models: Some challenges in the case of “the atom”. *International Journal of Science Education*, 22(9), 993–1009. [CrossRef]
- Justi, R., & Gilbert, J. (2016). Models of modelling. In *Modelling-based teaching in science education* (Vol. 9, pp. 17–40). Springer International Publishing AG.
- Krajcik, J. S. (1991). Developing understanding of chemical concepts. In S. M. Glynn, R. H. Yeany, & B. K. Brittons (Eds.), *The psychology of learning science* (pp. 117–147). Erlbaum.
- Laugier, A., & Dumon, A. (2004). The equation of reaction: A cluster of obstacles which are difficult to overcome. *Chemistry Education Research and Practice*, 5(3), 327–342. [CrossRef]
- Lee, O., Eichinger, D. C., Anderson, C. W., Berkheimer, G. D., & Blakeslee, T. D. (1993). Changing middle school students’ conceptions of matter and molecules. *Journal of Research in Science Teaching*, 30(3), 249–270. [CrossRef]
- Liu, H.-C., Andre, T., & Greenbowe, T. (2008). The impact of learner’s prior knowledge on their use of chemistry computer simulations: A case study. *Journal of Science Education and Technology*, 17(5), 466–482. [CrossRef]
- Masykuri, M., Afifa, F. N., & Ashadi, A. (2019). Students’ misconceptions on basic concept of redox reaction. *AIP Conference Proceedings*, 2194(1), 020062. [CrossRef]
- Mayer, R. E., Heiser, J., & Lonn, S. (2001). Cognitive constraints on multimedia learning: When presenting more material results in less understanding. *Journal of Educational Psychology*, 93(1), 187–198. [CrossRef]
- Nakhleh, M. B. (1992). Why some students don’t learn chemistry: Chemical misconceptions. *Journal of Chemical Education*, 69(3), 191–196. [CrossRef]
- Oh, P. S., & Oh, S. J. (2011). What teachers of science need to know about models: An overview. *International Journal of Science Education*, 33(8), 1109–1130. [CrossRef]
- Osborne, R. J., & Cosgrove, M. M. (1983). Children’s conceptions of the changes of state of water. *Journal of Research in Science Teaching*, 20(9), 825. [CrossRef]
- Österlund, L.-L., Berg, A., & Ekborg, M. (2010). Redox models in chemistry textbooks for the upper secondary school: Friend or foe? *Chemistry Education Research and Practice*, 11, 182. [CrossRef]
- Papaphotis, G., & Tsaparlis, G. (2008). Conceptual versus algorithmic learning in high school chemistry: The case of basic quantum chemical concepts. Part 1. Statistical analysis of a quantitative study. *Chemistry Education Research and Practice*, 9(4), 323–331. [CrossRef]
- Passmore, C., Gouvea, J. S., & Giere, R. (2014). Models in science and in learning science: Focusing scientific practice on sense-making. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 1171–1202). Springer.
- Reid, N., & Yang, M.-J. (2002). Open-ended problem solving in school chemistry: A preliminary investigation. *International Journal of Science Education*, 24(12), 1313–1332. [CrossRef]
- Rosenthal, D. P., & Sanger, M. J. (2012). Student misinterpretations and misconceptions based on their explanations of two computer animations of varying complexity depicting the same oxidation-reduction reaction. *Chemistry Education Research and Practice*, 13(4), 471–483. [CrossRef]
- Salta, K., & Tzougraki, C. (2011). Conceptual versus algorithmic problem-solving: Focusing on problems dealing with conservation of matter in chemistry. *Research in Science Education*, 41(4), 587–609. [CrossRef]
- Sanger, M. J., & Greenbowe, T. J. (1997). Common student misconceptions in electrochemistry: Galvanic, Electrolytic, and concentration cells. *Journal of Research in Science Teaching*, 34(4), 377–398. [CrossRef]
- Sanger, M. J., & Greenbowe, T. J. (2000). Addressing student misconceptions concerning electron flow in aqueous solutions with instruction including computer animations and conceptual change strategies. *International Journal of Science Education*, 22(5), 521–537. [CrossRef]
- Schmidt, H.-J., & Volke, D. (2003). Shift of meaning and students’ alternative concepts. *International Journal of Science Education*, 25(11), 1409–1424. [CrossRef]
- Swedish Ethical Review Act. (2003). *The ethical review act (SFS 2003:460)*. Available online: https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/lag-2003460-om-etikprovning-av-forskning-som_sfs-2003-460/ (accessed on 5 February 2026).
- Taber, K. S. (2003). The atom in the chemistry curriculum: Fundamental concept, teaching model or epistemological obstacle? *Foundations of Chemistry*, 5(3), 43. [CrossRef]
- Tasker, R., & Dalton, R. (2008). Visualizing the molecular world—Design, evaluation, and use of animations. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 103–131). Springer.
- Treagust, D. (2008). *The role of multiple representations in learning science* (Y.-J. Lee, & A.-L. Tan, Eds.). Sense Publishers.

- Treagust, D., Driel, J. H., Gilbert, J. K., Gobert, J., Justi, R., & Treagust, D. (2009). *Multiple representations in chemical education* (1. Aufl., Vol. 4). Springer Netherlands.
- Yamine, P., El-Nakat, H., Kassab, R., Mansour, A., El Khoury, B., Koumeir, D., Matar, Z., & Chmayssem, A. (2024). Recent advances in applied electrochemistry: A review. *Chemistry*, 6(3), 407–434. [[CrossRef](#)]

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