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Analyzing Multiple Representations of Corrosion Content in General Chemistry Textbooks: A Content Analysis Study

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Abstract

Chemical representations and the connections among macroscopic, sub-microscopic, and symbolic levels are fundamental to meaningful chemistry learning. However, the quality and coherence of these representations in instructional materials often determine how effectively students construct conceptual understanding. This study aimed to investigate the types and interconnections of chemical representations related to corrosion presented in widely used general chemistry textbooks. A qualitative content analysis was conducted on five textbooks using an adapted framework from Gkitzia, which included the type of representation (C1), interpretation of surface features (C2), relatedness to the text (C3), caption quality (C4), and degree of correlation across multiple representations (C5). A total of 40 corrosion-related representations were identified. The analysis showed that symbolic representations were the most frequently used, although textbooks generally portrayed corrosion through macroscopic, real-world examples. Eight sets of multiple representations were found to demonstrate adequate coherence among macroscopic, sub-microscopic, and symbolic levels, effectively illustrating both the corrosion process and its prevention. Overall, the five textbooks presented the concept of corrosion with reasonable alignment across representational forms. These findings contribute to the improvement of chemistry education by informing educators and textbook authors about the strengths and limitations of current representational practices. The results also offer empirical support for implementing multiple-representation-based instruction to enhance students' conceptual understanding and ability to visualize and interpret corrosion phenomena.

Keywords*:* chemical representations, chemistry textbooks corrosion, multiple representations

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1. Introduction

A thorough understanding of chemical concepts empowers students to comprehend, predict, and facilitate informed judgements when addressing complex socio-environmental issues (Freire et al., 2019). Johnstone (1991) emphasized that understanding chemistry relies on three vital representational levels: macroscopic, sub-microscopic, and symbolic. Within this framework, on the macroscopic level, students are required to observe a phenomenon. In parallel, at the sub-microscopic level, they should explain particulate behavior such as atomic and molecular interactions. Then, on a symbolic level, students are asked to represent these interactions using chemical symbols and equations. The Johnstone's triangle has become a standard in chemistry education due to its emphasis on the interplay between macroscopic, sub-microscopic, and symbolic representations (Chen et al., 2019). The ability to seamlessly connect three levels of representation is essential for developing a comprehensive understanding and promoting longer-term retention of chemical concepts (Stieff, 2019). Research has demonstrated that students who effectively link these levels are able to visualize and interpret chemical phenomena (Schwedler & Kaldewey, 2020). In the context of chemistry education, this skill is referred to as intertextuality (Wiji et al., 2021). This framework has been widely utilized to analyze teaching and learning challenges in chemistry, including the evaluation of chemistry textbooks (Upahi & Ramnarain, 2019).

However, studies have consistently shown that students, including pre-service teachers, possess a limited understanding of chemical concepts. This limitation is attributed to difficulties in connecting macroscopic, sub-microscopic, and symbolic representations (Nakiboglu et al., 2023; Rahayu et al., 2022). Additionally, the tendency to present chemistry primarily as a collection of abstract symbols, formulas, and equations, without linking them to real-world applications further compounds these issues (Baptista et al., 2019). These challenges are also evident in the topic of corrosion. Corrosion is a sub-topic within electrochemistry, covered at both secondary and undergraduate levels. However, despite being a common environmental phenomenon, corrosion receives less emphasis than topics like voltaic and electrolytic cells (Sanders et al., 2018). According to the National Research Council Assessment of Corrosion Education, this is because corrosion typically receives only a single lecture and is not thoroughly integrated into the curriculum, leading to a limited students' understanding. Furthermore, Murniningsih et al. (2020) found that pre-service chemistry teachers held misconceptions about factors influencing corrosion rates and cathodic protection. For example, students often believe that only oxygen and water are involved in corrosion and that iron undergoes oxidation during cathodic protection with zinc metal. Other studies have similarly identified misconceptions among high school students and pre-service chemistry teachers regarding the factors affecting corrosion rate and corrosion's prevention strategies (Asih et al., 2020; Nisa & Fitriza, 2021; Yilmaz & Bayrakçeken, 2015). Barke et al., (2009) also revealed that students struggle comprehends electron transfer during the corrosion, as this process occurs at the sub-microscopic level.

Studies have shown that a lack of interconnected multiple representations in teaching electrochemical concepts hinders students from linking the chemical reactions occurring at the sub-microscopic level with macroscopic phenomena and from interpreting them conceptually (Nakiboglu et al., 2023; Rahayu et al., 2022). Therefore, a complete understanding of corrosion cannot be achieved without connecting the three levels of representation. To enhance students' conceptual understanding, it is crucial to create engaging learning experiences that facilitate their ability to link three levels: macroscopic, sub-microscopic, and symbolic (Nakiboglu et al., 2023; Rahayu et al., 2022). Additionally, textbooks play an important role in teaching and learning, serving as valuable resources for both teachers and students (Chen et al., 2019). Beyond introducing concepts, textbooks help students experience and internalize a subject. In chemistry education, general chemistry textbooks are the primary teaching materials. As a bridge between chemical concept and learners, these textbooks should incorporate both text and visual representations to convey information effectively (Akcay et al., 2020; Chen et al., 2019). Consequently, general chemistry books should present all three levels of representation and emphasize intertextuality.

Following studies by Gkitzia et al. (2011), which found that general chemistry textbooks employ diverse approaches to represent chemical concepts, they developed five categories to analyze the suitability of chemical representations in existing textbooks for enhancing students' conceptual understanding. Therefore, the current study aims to analyze the chemical representations in general chemistry textbooks, with a particular focus on the concept of corrosion. Through this research, we investigated how the three levels of corrosion concept are represented and interconnected in general chemistry textbooks.

2. Research Method

2.1. Research Design

To answer the research question, this study adopts a qualitative approach using a content analysis design to examine how the concept of corrosion is represented chemically in general chemistry textbooks commonly used in Indonesian undergraduate chemistry courses. Content analysis is considered an appropriate methodological choice, as highlighted by Fraenkel et al. (2011) and Krippendorff (2013), because it enables the systematic examination of various forms of communication such as textbooks, newspapers, pictures, videos, speeches, and other media. Using purposive sampling technique, five widely adopted general chemistry textbooks were selected for analysis (Brown et al., 2017; Chang, 2010; Petrucci et al., 2010; Silberberg, 2007; Zumdahl & DeCoste, 2019). The selection process involved reviewing the syllabi (RPS) of General Chemistry courses from several universities in Indonesia that have achieved "*Unggul*" accreditation. The names of the authors, publisher and the tittle of the selected textbooks are presented in Table 1.

Table 1. Identity of The Textbooks

Book Code	Identity of Textbooks
B1	Silberberg, M. S. (2007). *Principles of General Chemistry*. McGraw-Hill.
B2	Chang, R. (2010). *Chemistry 10th Edition*. McGraw-Hill.
B3	Brown et al. (2017). *Chemistry The Central Science 14th Edition*. Pearson.
B4	Zumdahl, S. S., & DeCoste, D. J. (2019). *Introductory Chemistry-A Foundation 9th Edition*. Cengage Learning.
B5	Petrucci et al. (2010). *General Chemistry: Principles and Modern Application 10th Edition*. Pearson Canada Inc.

2.2. Instrument and Data Analysis

This study examines the multiple representations of the corrosion concept by analyzing three key aspects: the corrosion process, the factors influencing corrosion, and the methods of corrosion prevention. Rather that developing new criteria for assessing chemical representational levels, this research employs the rubric developed by Gkitzia et al. (2011). The rubric consists of five criteria: type of representation (C1), interpretation of surface features (C2), relatedness to text (C3), existence and properties of a caption (C4), and degree of correlation between representations comprising a multiple one (C5). The three representational levels of the corrosion concept in each general chemistry textbook were systematically coded and analyzed based on the criteria summarized in Table 2.

As this study employed a qualitative content analysis approach, rigorous measures were taken to ensure the credibility, transferability, dependability, and confirmability of the data (Denzin & Lincoln, 2018; Lim, 2025; Stahl & King, 2020). To strengthen methodological rigor, a Focus Group Discussion (FGD) was conducted with experts in multiple representations in chemistry education, who also contributed as the second, third, and fourth authors. The FGD served to established agreement on the categorization criteria and to critically evaluate the data analysis procedures, thereby enhancing the trustworthiness of the research outcomes. The first author acted as the principal investigator, undertaking the primary responsibilities of data collection, coding, and preliminary analysis.

Table 2. Criteria for Evaluating Chemical Representations and Their Characteristic

Criterion	Typology for Each Criterion	Description
Type of Representation (C1)	Macro	Present only the observable and realistic aspect (M)
	Sub-micro	Illustrates unobservable particles and abstract aspect (S)
	Symbolic	Uses symbols and codes of chemistry (Sy)
	Multiple	Present chemical phenomenon with the sub-microscopic states and use symbols to represent the phenomenon (M+S+Sy)
	Hybrid	Present the chemical phenomenon and use symbols to represent it (M+Sy) Illustrated unobserved particles and use a symbol to represent them (S+Sy)
	Mixed	Analogy of one-level representation.
Interpretation of Surface Features (C2)	Explicit	Clearly and specifically explain the meaning of each surface feature
	Implicit	Only explain the meaning of some surface features
	Ambiguous	No indication of the meaning of any surface features
Relatedness to Text (C3	Completely related and linked	Representation depicts the exact text content and directly links the text and representations
	Completely related and unlinked	Representation depicts the exact text content, but indirectly links the text and representations
	Partially related and linked	Representation depicts the subject or a familiar subject to the text and directly links the text and representations
	Partially related and unlinked	Representation depicts the subject or a familiar subject to the text but indirectly links the text and representations
	Unrelated	Representation is irrelevant to the text content. The text describes the content without mentioning the correspondence with the representation
Existence and Properties of a Caption (C4)	Existence of appropriate caption	Caption of representation is explicit, brief, and comprehensive
	Existence of problematic caption	Caption of representation is implicit and incomplete
	No Caption	No caption of representation
Degree of Correlation Between Representations Comprising a Multiple One (C5)	Sufficiently linked	Equivalence of the surface features of the components is clearly indicated
	Insufficiently linked	Equivalence of only some surface features of the component is indicated clearly
	Unlinked	Including subordinate representations that are placed next to one another end there is no indication of the equivalence of their surface features

3. Result and Discussion

Across the five General Chemistry Textbooks analyzed, a total of 40 distinct representations of corrosion concepts were identified. These representations exhibited considerable variation in form, encompassing visual depictions, particle-level interactions, and chemical equations. The identified representations were subsequently categorized and analyzed according to three conceptual dimensions: the corrosion process, factors influencing corrosion, and strategies for corrosion prevention.

Table 3 indicates that textbook B2 includes the greatest variety of representation types, comprising 13 in total: 4 macroscopic representations, seven symbolic representations, one multiple representation and one hybrid representation combining macroscopic and symbolic elements. In contrast, textbook B1 contains the highest number of multiple representations of the corrosion concept compared to the other textbooks analyzed.

Table 3. Distribution of Each Level of Representations in The Textbooks

Typology	B1	B2	B3	B4	B5	Σ
Macro	2	4	1	2	3	12
Sub-micro	0	0	0	0	0	0
Symbolic	5	7	3	0	3	18
Multiple	3	1	2	0	2	8
Hybrid (M+Sy)	0	1	0	1	0	2
Hybrid (S+Sy)	0	0	0	0	0	0
Mixed	0	0	0	0	0	0
Total	10	13	6	3	8	40

Overall, the analysis reveals that all textbooks employ macroscopic representation to illustrate corrosion concepts. Four of the textbooks make extensive use of symbolic representations, primarily to depict corrosion reactions and explain cathodic protection as a preventive method. Multiple representations are utilized to describe both the corrosion process and prevention strategies. Additionally, hybrid representations, specifically those integrating macroscopic and symbolic elements, are identified in textbooks B2 and B4 in the context of corrosion prevention. However, no instances of sub-microscopic representations, hybrid representations combining sub-microscopic and symbolic levels, or mixed representations were found in any of the textbooks. The subsequent section elaborates on the multiple representations of corrosion concepts and their interrelationships as presented in the general chemistry textbooks.

3.1. Type of Representation

The type of chemical representations used to depict each corrosion concept are summarized in Table 4. Most textbooks illustrate real-world phenomena using macroscopic representations: however, there is notable variation in their frequency of use. Textbook B2 features the highest number of macroscopic representations, with three instances, compared to B1, B4, and B5, which each include only one. This distinction is further emphasized by B2's inclusion of a wider variety of examples, such as silver tarnish and the patina formation on the Statue of Liberty. In contrast, the other textbooks focus solely on iron corrosion, as illustrated in Figure 1a. These findings suggest that textbook B2 adopts a more comprehensive and diverse approach to presenting the corrosion concept, rather than confining the discussion to a single material.

As presented in Table 4, symbolic representations constitute the most prevalent type, with a total of 15 instances identified. These representations, encompassing symbols, chemical formulas, and equations, primarily illustrate redox reactions involved in corrosion and explain corrosion prevention mechanisms, particularly through cathodic protection.

$$Reduction: O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq)$$
$$Oxidation: 2Fe(s) \rightarrow 2Fe^{2+}(aq) + 4e^-$$
$$Reaction: 4Fe^{2+}(aq) + O_2(g) + (4+2x)H_2O(l) \longrightarrow 2Fe_2O_3.xH_2O(s) + 8H^+(aq)$$

However, symbolic representations should be complemented by both macroscopic and sub-microscopic levels, to ensure conceptual clarity. When presented in isolation, symbolic representations tend to be overly abstract, which can hinder readers' comprehension the underlying chemical concept (Chen et al., 2019).

Table 4. Distribution of Chemical Representation for Corrosion Concept in The Textbooks

Concept Label	Typology	B1	B2	B3	B4	B5	Σ
Corrosion Process	Macro	1	3	0	1	1	6
	Sub-micro	0	0	0	0	0	0
	Symbolic	5	5	2	0	3	15
	Multiple	1	1	1	0	0	3
	Hybrid (M+Sy)	0	0	0	0	0	0
	Hybrid (S+Sy)	0	0	0	0	0	0
	Mixed	0	0	0	0	0	0
Factors of Corrosion	Macro	0	0	0	0	0	0
	Sub-micro	0	0	0	0	0	0
	Symbolic	0	0	0	0	0	0
	Multiple	0	0	0	0	0	0
	Hybrid (M+Sy)	0	0	0	0	0	0
	Hybrid (S+Sy)	0	0	0	0	0	0
	Mixed	0	0	0	0	0	0
Prevention of Corrosion	Macro	1	1	1	1	2	6
	Sub-micro	0	0	0	0	0	0
	Symbolic	0	2	1	0	0	3
	Multiple	2	0	1	0	2	5
	Hybrid (M+Sy)	0	1	0	1	0	2
	Hybrid (S+Sy)	0	0	0	0	0	0
	Mixed	0	0	0	0	0	0
Total		10	13	6	3	8	**40**

Interestingly, none of the analyzed textbooks present sub-microscopic representations as independent forms. It suggests that the primary emphasis lies on macroscopic corrosion phenomena and their corresponding symbolic representation, which are often integrated within multiple representations. Similar multiple representations are found in textbooks B1, B2, and B3, used to illustrate the corrosion process on iron surfaces by depicting the transfer of electrons from the anode to the cathode regions on the same surface (Figure 1b). These representations combine a macroscopic depiction, such as a water droplet, an iron surface, and rust formation, with a sub-microscopic explanation of electron transfer and the associated chemical reaction equation. This integration enables students to connect observable corrosion phenomena on iron surfaces with the underlying sub-microscopic processes and their symbolic interpretations. Through multiple representations, students can develop a deeper, more coherent understanding of complex chemical concepts such as corrosion (Stieff, 2019).

Another type of representation identified in the textbooks is a hybrid representation, which integrates macroscopic and symbolic levels, as illustrated in Figure 1c. This form appears in textbooks B2 and B4, both of which depicts real-world applications of cathodic protection as a corrosion-prevention method. In B2, Chromium (Cr) is used, while in B4, Magnesium metal (Mg) is applied to protect an iron (Fe) tank from corrosion. The accompanying chemical equations clarify that magnesium, rather than iron, undergoes oxidation during the process. Based on our analysis of the type of representation criterion, the corrosion concepts presented in general chemistry textbooks demonstrate a variety of representational forms, including multiple representations that play a crucial role in supporting chemistry teaching and learning. Nonetheless, none of the textbooks adequately presents or explicitly explains the factors influencing corrosion, even though this concept is an essential component of the course's corrosion topic.

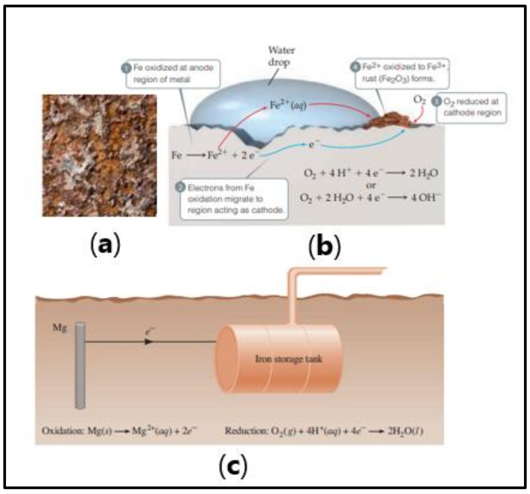

Figure 1. Example of (a) A Macroscopic Representation (Silberberg, 2007), (b) A Multiple Representation (Brown et al., 2017), (c) A Hybrid representation (macro and symbolic) (Chang, 2010)

3.2. Interpretation of Surface Features

To ensure high-quality chemical representation, each visual element should be clearly and explicitly explained in terms of its surface feature (Gkitzia et al., 2011). As described in Table 2, this criterion encompasses three typologies. Based on the analysis of 22 visual representations, all textbooks included explicit interpretations of surface features, with 12 representations meeting this criterion. Textbooks B1 and B3 contained the highest number of explicit representations, whereas textbook B2 exhibited the most ambiguous depictions of both the corrosion process and corrosion prevention. Additionally, implicit representations were identified in textbooks B1 and B5, both of which pertain to corrosion prevention, as summarized in Table 5.

Explicit interpretations were most frequently identified in the concept of corrosion prevention, rather than general corrosion concept. Notably, none of the textbooks included explicit interpretations related to the 'Factors of Corrosion'. All textbooks illustrated corrosion prevention on iron through the cathodic protection method (Figure 2a). The sub-microscopic process, including the corresponding chemical reactions, was symbolically represented and depicted across all textbooks, though textbook B2 provided less detail in its illustrations. Although less common, explicit interpretations were also found in representations of the corrosion process, particularly in textbooks B1, B2, and B3.

Table 5. Number of Surface Features Interpretation in The Textbooks

Concept Label	Typology	B1	B2	B3	B4	B5	Σ
Corrosion Process	Explicit	1	1	1	0	0	3
	Implicit	0	0	0	0	0	0
	Ambiguous	1	3	0	1	1	6
Factors of Corrosion	Explicit	0	0	0	0	0	0
	Implicit	0	0	0	0	0	0
	Ambiguous	0	0	0	0	0	0
Prevention of Corrosion	Explicit	2	1	2	2	2	9
	Implicit	1	0	0	0	1	2
	Ambiguous	0	1	0	0	1	2
Total		5	6	3	3	5	**22**

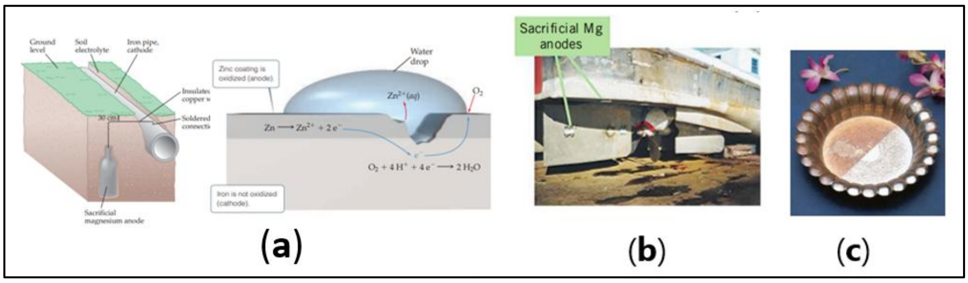

Figure 2. Example of (a) An Explicit Macroscopic and Multiple (Chang, 2010), (b) An Implicit Macroscopic (Petrucci et al., 2010), (c) An Ambiguous Macroscopic Representation (Chang, 2010)

Moreover, some visual representations provide only partial explanations of surface features, categorized as implicit typology (Gkitzia et al., 2011). This analysis indicated that implicit interpretations appeared in the corrosion prevention concept of textbook B1 and B5, both of which describe only selected aspects of the visual representation, as illustrated in Figure 2b. In this case, magnesium (Mg) is identified as the anode, yet the specific region of the iron surface protected from corrosion is not clearly indicated. Ambiguous interpretations were also most frequently observed in representations of the corrosion process, likely due to the inclusion of numerous real-life examples of corrosion. For instance, Figure 2c depicts tarnish on a silver plate without explicitly identifying the affected areas. This lack of clarity may make it difficult for students to understand the exact nature of the observed changes. Overall, the analysis suggests that the examined General Chemistry textbooks generally contain well-developed explicit visual representations, particularly in explaining the corrosion process and corrosion prevention concepts.

3.3. Relatedness to Text

In developing students' understanding of chemical concepts, clear, concise textual explanations are essential, alongside effective chemical representations. Therefore, this criterion evaluates the degree of correspondence between visual representations and their accompanying texts. The analysis revealed that 29 out of 40 representations were fully related and well-integrated with the explanatory text, as shown in Table 6. These closely linked representations were predominantly found in sections addressing the corrosion process and corrosion prevention. However, a few representations were identified as "completely related and unlinked," while others demonstrated only a "partially related and linked" relationship between the visual and textual components.

Based on the findings, all representations in textbook B3 were fully related and directly connected to their corresponding texts. Similarly, textbook B1 demonstrated a strong alignment between representations and textual explanations, with nine out of ten classified as 'completely related and linked'. In contrast, textbook B2 contained the highest number of 'completely related and unlinked' representations, totaling four instances. Both textbooks, B1 and B4, each included one representation categorized as 'partially related and linked' to the text. Notably, no 'unrelated' representations were identified in this analysis. A 'Completely related and linked' representation refers to a visual depiction that accurately reflects the textual content and establishes a direct connection between the image and accompanying explanation (Gkitzia et al., 2011). For instance, Figure 3a illustrates a multiple representation of the corrosion process, where the text explains that corrosion occurs when an iron surface comes into contact with water, designating one region as the anode (oxidation site) and another as the cathode. Hence, this representation is considered both related and explicitly linked to the text.

Table 6. Number of Relatedness Representations to Text in The Textbooks

Concept Label	Typology	B1	B2	B3	B4	B5
Corrosion Process	Completely related and linked	6	5	3	0	3
	Completely related and unlinked	1	3	0	1	1
	Partially related and linked	0	1	0	0	0
	Partially related and unlinked	0	0	0	0	0
	Unrelated	0	0	0	0	0
Factors of Corrosion	Completely related and linked	0	0	0	0	0
	Completely related and unlinked	0	0	0	0	0
	Partially related and linked	0	0	0	0	0
	Partially related and unlinked	0	0	0	0	0
	Unrelated	0	0	0	0	0
Prevention of Corrosion	Completely related and linked	3	3	3	1	2
	Completely related and unlinked	0	1	0	0	2
	Partially related and linked	0	0	0	1	0
	Partially related and unlinked	0	0	0	0	0
	Unrelated	0	0	0	0	0

Additionally, certain representations demonstrated only an indirect relationship with their accompanying text, as illustrated in Figure 3b. The image of the Statue of Liberty depicts patina formation as a form of copper corrosion; however, the accompanying text discusses corrosion processes in iron, creating a conceptual disconnect between the visual and textual explanations.

Partially related representations and accompanying texts were identified in textbooks B2 and B4. For instance, Figure 3c presents the cathodic protection method used to prevent iron corrosion by employing magnesium (Mg) as the anode. Although the visual and textual components are linked, the illustration provides limited detail, thereby categorizing it under the 'partially related and linked' typology.

3.4. Existence and Properties of a Caption

A visual representation should include an appropriate caption that is explicit, concise, and sufficiently comprehensive to ensure its interpretative autonomy (Gkitzia et al., 2011). Accordingly, this criterion evaluates the presence and quality of captions accompanying visual representations. A total of 22 visual representations were analyzed, all of which contained captions. Among these, 20 were categorized as appropriate, while two were identified as problematic. The problematic captions appeared in textbooks B4 and B5, both of which address the concept of corrosion prevention. The detailed results of this analysis are presented in Table 7.

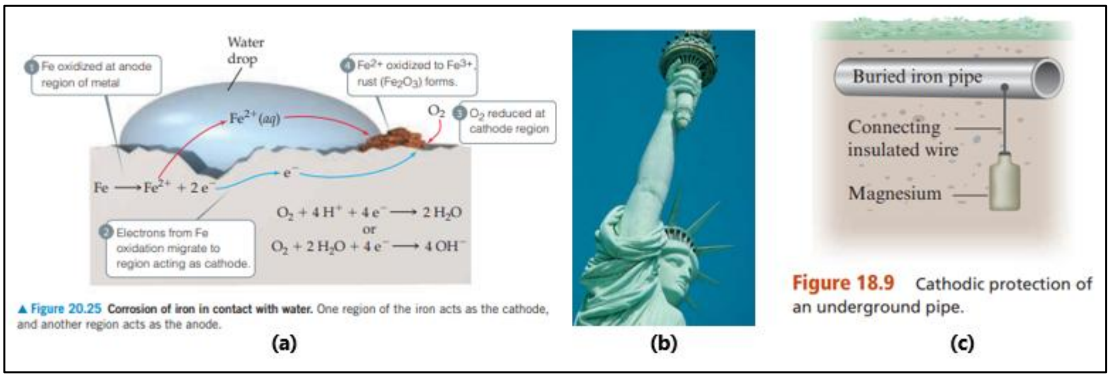

Figure 3. Example of (a) A Completely Related and Linked (Brown et al., 2017), (b) A Completely Related and Unlinked (Chang, 2010), (c) A Partially Related and Linked Representation (Zumdahl & DeCoste, 2019)

Table 7. Number of Existence and Properties of a Caption in The Textbooks

Concept Label	Typology	B1	B2	B3	B4	B5	Σ
Corrosion Process	Existence of appropriate caption	2	4	1	1	1	9
	Existence of problematic caption	0	0	0	0	0	0
	No Caption	0	0	0	0	0	0
Factors of Corrosion	Existence of appropriate caption	0	0	0	0	0	0
	Existence of problematic caption	0	0	0	0	0	0
	No Caption	0	0	0	0	0	0
Prevention of Corrosion	Existence of appropriate caption	3	2	2	1	3	11
	Existence of problematic caption	0	0	0	1	1	2
	No Caption	0	0	0	0	0	0
Total		5	6	3	3	5	**22**

All visual representations in textbooks B1, B2, and B3 were accompanied by appropriate captions. Consistent with the analysis of other criteria, well-formulated captions are essential for facilitating effective student learning (Gkitzia et al., 2011). Figure 4a illustrates an example of an appropriate caption, depicting a macroscopic representation of cathodic protection in which magnesium (Mg) metal serves as the anode to prevent iron corrosion. The caption clearly explains that magnesium, being a more active metal, is connected to underground iron pipes and undergoes oxidation in place of the iron. Conversely, problematic captions were also identified, as illustrated in Figure 4b. The caption, which merely states 'Galvanized nails', is considered inadequate because it fails to describe the galvanization process or explain how the zinc coating prevents corrosion. This lack of clarity may create ambiguity for students and impede their underlying chemical concept (Gkitzia et al., 2011).

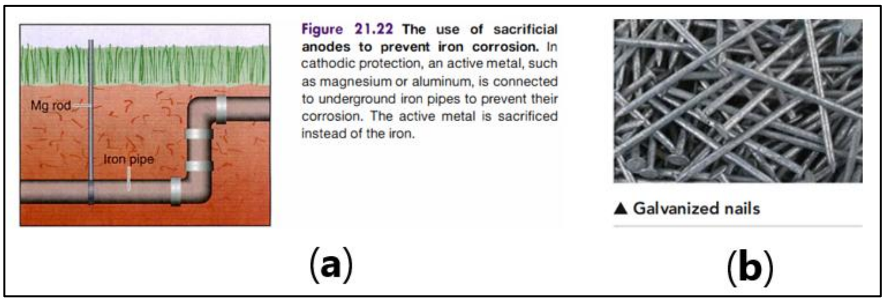

Figure 4. Example of (a) Existence of An Appropriate Caption (Silberberg, 2007), (b) Existence of A Problematic Caption (Petrucci et al., 2010)

3.5. Degree of Correlation Between Representation

This criterion examines the multiple representations identified in C1: *Type of Representation*, focusing on the interrelationship among the macroscopic, sub-microscopic, and symbolic levels within a single composite representation. As shown in Table 3, a total of eight multiple representations were identified across the analyzed textbooks, appearing within the concepts of the corrosion process and corrosion prevention. Specifically, textbook B1 contained three instances, B2 one, B3 two, B4 none, and B5 two. Further analysis of these multiple representations was conducted, and the results are summarized in Table 8.

All identified multiple representations were found to be sufficiently interconnected. For instance, Figure 5a illustrates a multiple representation of the iron corrosion process that integrates macroscopic, sub-microscopic, and symbolic elements. The macroscopic level is represented by the depiction of a water droplet and an iron surface, which is complemented by a sub-microscopic explanation of electron transfer and a symbolic chemical equation describing the corrosion reaction.

Similarly, Figure 5b also illustrates multiple representations. This figure compares the corrosion behavior of iron coated with copper and iron coated with zinc. The sub-microscopic representations show that when iron is coated with copper, it readily donates electrons, resulting in rapid oxidation. Conversely, when iron is coated with zinc, the zinc metal preferentially donates electrons, thereby undergoing oxidation in place of the iron. Both Figures 5a and 5b demonstrate well-connected multiple representations, in which the macroscopic, sub-microscopic, and symbolic levels are coherently integrated. As previously mentioned before, Johnstone's Triangle plays a pivotal role in facilitating the understanding of chemical concepts. The ability to effectively integrate the three levels of representation, macroscopic, sub-microscopic, and symbolic, is essential for developing a holistic understanding of chemical phenomena and for enhancing students' capacity to visualize and interpret these processes (Schwedler & Kaldewey, 2020; Stieff, 2019). The analyzed textbooks appropriately addressed the corrosion process and corrosion prevention through these representations. However, the factors influencing corrosion were predominantly explained through textual descriptions, with minimal visual support. This limitation is noteworthy, as understanding the factors contributing to corrosion is fundamental to achieving a complete and integrated understanding of the overall corrosion concept.

Table 8. Number of Correlation Between Macroscopic, Sub-microscopic, and Symbolics

Concept Label	Typology	B1	B2	B3	B4	B5	Σ
Corrosion Process	Sufficiently linked	1	1	1	0	0	3
	Insufficiently linked	0	0	0	0	0	0
	Unlinked	0	0	0	0	0	0
Factors of Corrosion	Sufficiently linked	0	0	0	0	0	0
	Insufficiently linked	0	0	0	0	0	0
	Unlinked	0	0	0	0	0	0
Prevention of Corrosion	Sufficiently linked	2	0	1	0	2	5
	Insufficiently linked	0	0	0	0	0	0
	Unlinked	0	0	0	0	0	0
Total		3	1	2	0	2	**8**

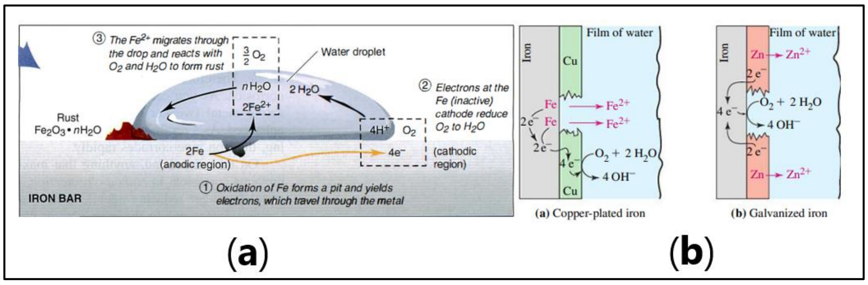

Figure 5. Example of (a) A Sufficiently Linked Representations of Corrosion Process (Silberberg, 2007), (b) A Sufficiently Linked Representations of Corrosion Prevention (Petrucci et al., 2010)

The findings of this study indicate that inadequacies in visual representations within chemistry teaching and learning significantly affect students' conceptual understanding. As emphasized in previous research, multiple representations play a crucial role in linking observable macroscopic phenomena with underlying sub-microscopic processes, which are further conveyed through symbolic representation (Hasanah et al., 2024; Rusek & Vojíř, 2019; Wiji et al., 2021). Consequently, any flaws or inaccuracies in these representations may lead directly to students' misconceptions and hinder their ability to develop a coherent understanding of chemical concepts.

Furthermore, the analysis reveals challenges in integrating the three levels of chemical representation cohesively. For instance, although the multiple representations demonstrate sufficient correlation (C5), the absence of an independent sub-microscopic representation (C1) presents a potential limitation. This lack of explicit molecular-level depiction may hinder students who require more detailed explanations at that level, thereby creating gaps in their understanding of the corrosion process.

4. Conclusion

This study examined the representation of corrosion concepts in five widely used general chemistry textbooks, focusing on the coherence among macroscopic, sub-microscopic, and symbolic levels. The results show that corrosion is mainly presented through macroscopic illustrations and symbolic representations, particularly chemical equations of redox reactions and cathodic protection, while independent sub-microscopic representations and visual explanations of influencing factors are largely lacking. Although most visuals are well aligned with the text and captions, the uneven distribution of representational forms indicates a strong reliance on symbolic explanations, potentially limiting students' molecular-level understanding of corrosion processes.

This study contributes empirical evidence to chemistry education research by clarifying current representational practices in corrosion-related textbook content and reinforcing the pedagogical value of well-integrated multiple representations. Future research should extend beyond textbook analysis to investigate how these representations are enacted in classrooms and interpreted by students, as well as to support the development of instructional materials that explicitly strengthen sub-microscopic representations and conceptual integration in electrochemistry learning.

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