JOURNAL OF BALTIC SCIENCE EDUCATION

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

This is an open access article under the Creative Commons Attribution 4.0 International License

# USING BAYESIAN NETWORKS FOR COGNITIVE DIAGNOSIS ASSESSMENT OF UPPER-SECONDARY SCHOOL STUDENTS UNDERSTANDING IN REDOX REACTION

**Min Qi,**
**Xinyang Hu,**
**Hualin Bi**

**Abstract.** *The redox reaction is a core concept of upper-secondary school chemistry curriculum. Accurate diagnosis of students' conceptual understanding of the redox reaction from a cognitive structure perspective is critical for enhancing their understanding of chemical concepts. This study utilized Bayesian networks to investigate the cognitive structures of Chinese students regarding the redox reaction. A total of 409 upper-secondary school students participated, with 227 in 11th grade and 182 in 12th grade. Seven cognitive attributes related to the redox reaction were identified, and their hierarchical relationships were mapped. The research process of cognitive diagnosis assessment of redox reaction based on Bayesian network was developed. The results indicated that Bayesian networks can effectively assess students' cognitive structures of the redox reaction. Key attributes identified in students' cognitive structures were "electron transfer", "oxidation reaction / reduction reaction" and "oxidability / reducibility". Furthermore, a comparison of the cognitive structures between 11th and 12th graders showed that 12th graders had a more advanced understanding with fewer conceptual gaps, while 11th graders demonstrated less developed cognitive pathways, which may be attributed to a lack of deep conceptual understanding.*

**Keywords:** *Bayesian network, cognitive diagnostic assessment, redox reaction, cognitive structure*

**Min Qi, Xinyang Hu, Hualin Bi**
*Shandong Normal University, P. R. China*

## Introduction

In today's rapidly evolving global knowledge economy, the goals of education have moved beyond the mere transmission of facts and information. Instead, the focus has shifted to developing students' conceptual understanding. Students' understanding of core concepts has always been an important issue in scientific education (Ainsworth, 2008; Chang et al., 2010; Kampourakis, 2018; Trnova & Trna, 2015; Wong et al., 2020). The foundational elements of scientific knowledge are concepts and principles, and the efficacy of students' problem-solving abilities hinges on their genuine comprehension of these scientific concepts (Mi et al., 2020). Thus, it is essential for students to achieve conceptual understanding. Conceptual understanding is described as the achievement of an expert level of cognitive structure within a domain (Hatano & Inagaki ,1986). Cognitive structure (Atabek-Yigit, 2015; Gercek, 2018; Tasci & Yurdugul, 2017), is also known as knowledge structure and conceptual structure (Kurt, 2013a, 2013b). Chemical knowledge usually exists in students' minds in the form of conceptual networks (Nakiboglu, 2008). Some researchers contend that students' complete grasp of a subject depends on their comprehension of both the fundamental concepts and the interconnections among those components (Lin et al., 2022).

The redox reaction is a core chemical concept throughout the upper-secondary chemistry courses (Basheer et al., 2016; Laliyo et al., 2019; Lu et al., 2018; Tang et al., 2024). Through the study of the redox reaction, students can deepen their understanding of the transformation of elements and substances. Additionally, the redox reaction is the foundation for students' future study of electrochemistry (Brandriet & Bretz, 2014; Şekerci, & Erdem, 2022; Tang et al., 2024). However, the redox reaction is a challenging concept for students to understand (Delisma et al., 2019; Jaber & BouJaoude, 2012; Øyehaug & Holt, 2013; Rosenthal & Sanger, 2012; Tang et al., 2022). Furthermore, studies also reveal that teachers regard the redox reaction as a difficult topic to teach (De Jong et al., 1995).



https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

Accurately assessing students' understanding of scientific concepts is of great significance in promoting students' development (Bayrak, 2013) and guiding teachers' teaching (Osborne & Gilbert, 1980). In recent years, many researchers have focused on assessing students' conceptual understanding of the redox reaction, particularly on identifying common misconceptions (Brandriet & Bretz, 2014; De Jong et al., 1995; Garnett & Treagust,1992; Rosenthal & Sanger, 2012; Stains & Talanquer, 2008). Researchers have employed various methods to evaluate students' understanding, including multiple-choice questions (Primastuti & Priyambodo, 2018), concept maps (Chiang et al., 2014), two-tier diagnostic tests (Laliyo et al., 2019; Şekerci, & Erdem, 2022), and three-tier diagnostic tests (Masykuri et al., 2019; Silaban et al., 2024).

While multiple-choice questions are effective for assessing large groups of students, they fall short in evaluating and analyzing students' cognitive structures (Osborne & Cosgrove, 1983). Concept maps can uncover students' misconceptions and the cognitive structures underlying their understanding (Schroeder et al., 2018). Nevertheless, the complexity of analyzing and scoring makes concept maps more suitable for small-scale assessments rather than large-scale assessments (Snow & Lohman, 1989). Two-tier and three-tier diagnostic tests can identify students' misconceptions and the reasons behind them (Mintzes et al., 2005), but they do not fully reveal the cognitive structures in students' minds. To assess students' conceptual understanding of the redox reaction more accurately and objectively, it is essential to find a more suitable assessment method (Treagust, 2006).

Cognitive diagnostic assessment can estimate students' unobservable (or latent) knowledge states and cognitive structures by obtaining observable response patterns during testing (Leighton & Gierl, 2007). This approach offers a new method for assessing conceptual understanding, as it not only provides insights into students' overall mastery levels and cognitive structures through test analysis but also offers personalized feedback based on individual responses (Martin & VanLehn, 2012). Researchers employed cognitive diagnostic models (CDMs) such as the rule-space model (RSM) (Birenbaum et al., 1993), the attribute hierarchy model (AHM) (Wang & Gier, 2011), the deterministic-input noisy-AND-gate model (DINA) (Wafa et al., 2020), the higher-order DINA model (HO-DINA) (De La Torre, 2009), and the G-DINA model (Chen & Chen, 2016) for application in the field of educational measurement. Bayesian networks are advantageous in their ability to address complex and uncertain problems and provide high accuracy (Almond, 2015; Zou & Yue, 2017), which distinguishes them from other traditional CDMs. While many researchers have applied Bayesian networks to empirical studies in science education (Culbertson, 2016; Emden et al., 2018; Jiang et al., 2023; Todd et al., 2022; Wang et al., 2023), few have used Bayesian networks for diagnostic evaluation in chemistry education.

### *Bayesian Networks*

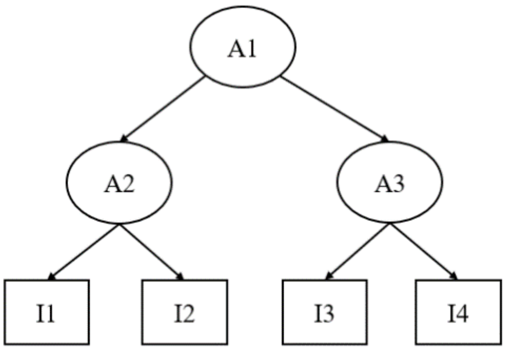
Bayesian networks offer a convenient and intuitive method for specifying complex joint probability distributions that include both latent and observed variables (Pearl, 1988). Rather than being a specific type of model, Bayesian networks serve as a framework or methodology for constructing models by leveraging the relationships between a graphical structure and a complex joint probability distribution (Culbertson, 2016).

A Bayesian network comprises a directed acyclic graph and a set of conditional probability distributions. An example of a simple Bayesian network for cognitive diagnosis is shown in Figure 1. In this graph, the directed acyclic structure illustrates the qualitative relationships between nodes, where each node represents a random variable, and the edges connecting the nodes depict relationships between variables. Pairs of connected nodes are referred to as "parents" and "children", with directed edges flowing from "parents" to "children". The conditional probability distribution describes the quantitative relationship between nodes, the joint probability distribution of all random variables can be factorized into a product of a chain of conditional probabilities. Once the Bayesian network structure has been identified, we need to specify the Bayesian network parameters (i.e., the conditional probabilities and the marginal probabilities) in order to use this network for inference (Wang et al., 2023).


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

**Figure 1**
*A Simple Bayesian Network for Cognitive Diagnosis*




$$P(A_1, A_2, A_3, I_1, I_2, I_3, I_4)=P(A_1)P(A_2 \mid A_1)P(A_3 \mid A_1,A_2)P(I_1 \mid A_1,A_2,A_3)$$
$$\times P(I_2 \mid A_1,A_2,A_3,I_1)P(I_3 \mid A_1,A_2,A_3,I_1,I_2)P(I_4 \mid A_1,A_2,A_3,I_1,I_2,I_3)$$

* Circles represent latent variables, while boxes indicate observed variables. Arrows signify conditional dependencies, with variables at the tail of an arrow termed "parents," and those at the head called "children." For example, A2 is the parent of I1 and the child of A1.

In educational measurement, latent variables often represent cognitive characteristics of relevant content domains, known as cognitive attributes, which refer to the knowledge, cognitive processing skills, and strategies that students use in conceptual understanding (Leighton et al., 2004). Observable variables represent test items (e.g., traditional multiple-choice questions, etc.). Test items can be connected to one or more nodes, depending on the question design of the study. Experts' estimates, grounded in their existing knowledge and experience, can be employed as initial probabilities, while data-derived probabilities serve as empirical marginal and conditional probabilities (Lee & Corter, 2011). Once the Bayesian network structure and parameters are defined, the network can be used for probabilistic inference, predicting students' knowledge states.

*Research Problem*

The purpose of this study was to utilize Bayesian networks to assess students' conceptual understanding of redox reaction and to explore their real cognitive structures. The study aimed to address the following research questions:

1. How can Bayesian networks be employed to evaluate students' cognitive structures regarding the redox reaction?
2. What are the key attributes in the cognitive structures of upper-secondary school students in the redox reaction?
3. What are the cognitive structures of $11^{th}$ and $12^{th}$ graders in the redox reaction?

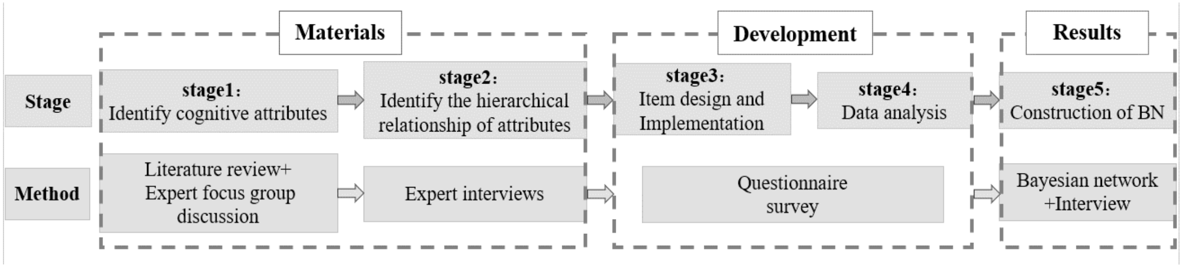
*Cognitive Diagnostic Assessment of Redox Reaction—Research Process*

Cognitive attributes and the hierarchical relationships among attributes are critical to the effectiveness of cognitive diagnostic assessment. A research process for cognitive diagnostic assessment was proposed by Wang et al. (2023), in which the term 'material' was employed to denote the identification of cognitive attributes and the hierarchical relationships among them. Building on this foundation, a Bayesian network-based cognitive diagnostic assessment process for redox reaction is proposed in this study, as illustrated in Figure 2.


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

**Figure 2**
*Research Process*




## Materials

*Identify Cognitive Attributes*

Cognitive diagnostic assessment starts with an analysis of the cognitive domain. Similarly, diagnosing students' understanding of the redox reaction requires an in-depth analysis of the topic and its associated concepts. To accurately identify the cognitive attributes related to redox reaction, a systematic review of recent studies was conducted, with particular emphasis on works that clarify the cognitive dimensions of this topic. The results of this review are summarized in Table 1.

**Table 1**
*Redox Reaction Test Content*

| | Acar (2007) | Brandriet (2014) | Chiang (2014) | Delisma (2020) | Goes (2020) | Laliyo (2019) | Österlund (2010) | ŞEKERCİ (2022) | Tang (2022–2024) | Frequency statistics |
|---|---|---|---|---|---|---|---|---|---|---|
| Losing and gaining oxygen | | √ | √ | √ | √ | | √ | | √ | 6 |
| Oxidation number | | √ | √ | √ | √ | | √ | √ | √ | 7 |
| Electron transfer | | √ | √ | √ | √ | √ | √ | √ | √ | 8 |
| Molecular structure | | √ | | | | | | | | 1 |
| Single/double track bridge model | | | | | | | | | √ | 1 |
| Oxidizing agent / Reducing agent | | | √ | √ | √ | √ | | √ | √ | 6 |
| Oxidation product / Reduction product | √ | | √ | | √ | √ | | √ | √ | 6 |
| Oxidation reaction / Reduction reaction | √ | | √ | | √ | √ | | √ | √ | 6 |
| Gain and loss electronics | | | √ | | | | √ | | √ | 3 |
| Equation balancing and calculation | | | | | | √ | | | | 1 |
| Electrode potential | √ | | | | √ | | | √ | | 3 |
| galvanic cell Electrolytic cell | √ | | | | √ | | | √ | | 3 |
| Application of redox reaction | √ | | | | √ | | | | | 2 |

*Note*: Due to space constraints, only the first author is identified in the references cited in the table


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

As can be seen from Table 1, most researchers have identified thirteen cognitive attributes such as "losing and gaining oxygen (6)", "oxidation number (7)", "electron transfer (8)", "oxidizing agent / reducing agent (6)", "oxidation product / reduction product (6)" and "oxidation reaction / reduction reaction (6)" as cognitive attributes under the topic of redox reaction.

On the basis of the cognition of the above cognitive attributes, Expert focus group discussion was used to identify the cognitive attributes of this study. Expert focus group discussion is a method where researchers convene a panel of seasoned experts and practitioners within a specific discipline to engage in focused discussions on pertinent research issues (Cornwall & Jewkes ,1995; Morgan et al., 1998). This approach is designed to harness the rich professional insights, perspectives, and knowledge of the participants through a structured and moderated dialogue, with the goal of arriving at more nuanced and comprehensive conclusions (Nyumba et al., 2018).

Experts were defined as people who have an "institutionalized authority to construct reality" (Meuser & Nagel, 2009). Experts were selected based on the following criteria: having participated in the preparation and revision of textbooks, having rich teaching experience in upper-secondary schools, having a deep understanding of redox reaction, and having published relevant research papers. Von Soest (2023) proposed that the selection of experts should be centered on problems and expertise, rather than status-oriented. Attention should be paid not only to high-level experts but also to low-level internal experts. Ultimately, seven experts with substantial knowledge of redox reaction were identified to form the focus group for this study.

The members of this focus group also participated in the expert group responsible for identifying the attribute hierarchy and developing test measurements. The demographic information of the experts is provided in Table 2.

**Table 2**
*Demographic Characteristics of Experts*

| Code | Gender | Age | Profession | Disciplines | Education | Related working experience | Number of relevant papers published |
|---|---|---|---|---|---|---|---|
| Expert 1 | Male | 59 | professor | Education | PhD | More than 30 years of teaching experience in colleges, involved in the revision of textbooks | 32 |
| Expert 2 | Female | 47 | professor | Education | PhD | More than 20 years of teaching experience in colleges, involved in the revision of textbooks | 7 |
| Expert 3 | Female | 44 | professor | Chemistry | PhD | More than 20 years of teaching experience in colleges, involved in the revision of textbooks | 11 |
| Expert 4 | Female | 46 | teacher | Chemistry | Master | More than 20 years of upper-secondary school teaching experience | 3 |
| Expert 5 | Female | 37 | associate professor | Education | PhD | 7 years of college teaching experience | 7 |
| Expert 6 | Male | 31 | lecturer | Education | PhD | 2 years of teaching experience in colleges and 2 years of teaching experience in upper-secondary school | 5 |
| Expert 7 | Male | 44 | teacher | Education | Master | More than 20 years of upper-secondary school teaching experience | 4 |

The discussion questions for the expert focus group were: (1) Were the thirteen selected cognitive attributes reasonable, and why? (2) Could you give specific suggestions on the selection of cognitive attributes? The experts discussed and answered the questions in the light of their own educational experiences and research experiences. The following examples illustrate some of the experts' opinions and demonstrate the process of reaching consensus.

*Expert 1: The essence of the current generated by a galvanic cell is the potential difference between the two poles, and the core application of redox reaction is also the galvanic cell. Therefore, it is necessary to combine " galvanic cell / electrolytic cell" and " electrode potential " to refer to them as "electrode potential". Both "oxidizing agent / reducing agent" and "oxida-*


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

*tion product / reduction product" are related to the properties of the substances involved in the redox reaction, so they can be combined into "oxidability / reducibility ".*

*Expert 3: I believe that in order to gain a deeper understanding of chemical reactions, it is necessary to consider the structure and dynamic properties of particles, including electrostatic interactions and bonding mechanisms in redox reaction environments, such as the binding of charged species. Therefore, "molecular structure" should be considered as one of the cognitive attributes within the domain of the redox reaction.*

The discussion data of the expert group was collected and analyzed after the expert discussion. In the end, the experts identified seven cognitive attributes. Only part of the process of the opinions discussed by the experts is shown here:

Expert 1's view was widely accepted by the focus group, which agreed that consolidating certain attributes would make the cognitive framework more streamlined and effective. Consequently, "electrode potential" and "oxidability / reducibility " were integrated as attributes within the domain of redox reaction. In chemical reactions, the interactions between particles were related to their own structure; In organic chemistry, the structural characteristics of molecules could be used to analyze their chemical properties and determine reactions. Therefore, after the discussion of the expert group, "molecular structure" was introduced into the conceptual system of redox reaction as a new cognitive attribute.

In this study, the cognitive attributes of redox reaction identified by literature and expert focus group interview included: C1 (losing and gaining oxygen), C2 (molecular structure), C3 (oxidation number), C4 (electron transfer), C5 (oxidation reaction / reduction reaction), C6 (oxidability / reducibility), and C7 (electrode potential). A detailed description of each attribute is provided in Table 3.

**Table 3**
*Cognitive Attributes of Redox Reaction*

| Code | Cognitive attributes | Specific description |
|---|---|---|
| C1 | Losing and gaining oxygen | Identify information such as oxygen elements and oxygen in chemical equations; Understand that a reaction involving oxygen is classified as an oxidation reaction; Judge redox reaction from the perspective of oxygen gain and loss. |
| C2 | Molecular structure | Understand that atoms tend to form stable structures; it is clear that the ease with which atoms gain or lose electrons during chemical changes is closely related to the number of electrons in their outermost shell; Additionally, it is important to recognize that molecules possess a certain spatial configuration.; By understanding the various bonding modes of carbon atoms, we can discern the bonding characteristics and recognize the presence of special functional groups in carbon atoms within simple organic compounds, such as methane and ethylene; Analyze the chemical properties of organic molecules based on their structural characteristics and to determine the reactions they undergo. |
| C3 | Oxidation number | Understand the concept of oxidation number and identify the oxidation number of each element in polyatomic compounds. It is also important to recognize that most elements can exhibit varying oxidation states in different substances; Understand the oxidation number from the perspective of the microstructure of substances; Accurately identify the change in oxidation number of a specific element before and after a chemical reaction. |
| C4 | Electron transfer | Understanding the essence of redox reaction is the transfer of electrons; Understanding that the variation in oxidation number of elements is the external manifestation of electron transfer; Determine the electron transfer situation of elements in substances and express the process of electron transfer using symbols. |
| C5 | Oxidation reaction / reduction reaction | Understand the characteristics of redox reaction and recognize the unique significance of oxidation and reduction processes within organic chemistry; Understand the simultaneity and interdependence of oxidation and reduction reactions, recognizing that in electrochemistry, while oxidation and reduction occur at two distinct electrodes, they are not independent processes; Judge whether a chemical reaction is redox reaction based on the changes in oxidation number of the elements involved; Design battery reactions based on oxidation and reduction reactions. |
| C6 | Oxidability/ reducibility | Know common oxidizing agent and reducing agent; Understand that the strength of a substance's oxidability or reducibility is determined by its ability to gain or lose electrons; Utilize redox reaction to assess and compare the relative strength of a material's oxidability or reducibility; Study the chemical properties of substances through the lens of oxidation and reduction and formulate reaction schemes to facilitate the transformation of substances. |


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

| Code | Cognitive attributes | Specific description |
|---|---|---|
| C7 | Electrode potential | Understand the concepts of electrode potential and the differences in potential energy between electrodes; Understanding that the flow of electrons in a system is caused by the potential difference, which arises from different electrode potentials, and recognizing that electrolytic cells facilitate redox reaction by applying an external voltage; Determine the identities of the positive and negative electrodes in a battery based on their distinct electrode potentials; Judge the direction of a redox reaction based on the electrode potentials. |

*Identify the Hierarchical Relationship of Attributes*

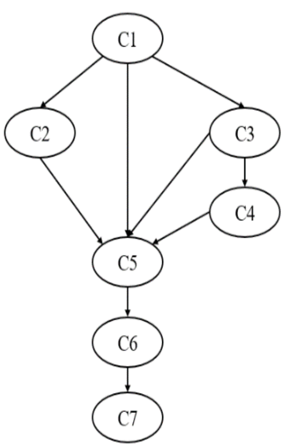
After identifying the cognitive attributes and their connotations, it was also necessary to establish the hierarchical relationships among these attributes. The order of textbook compilation adhered to the cognitive development of students, and therefore could serve as a reference for identifying the hierarchical relationship among attributes. Additionally, a panel of experts was convened to establish these hierarchical relationships. Examples of opinions from some experts are as follows:

> *Expert 2: Students' initial exposure to redox reaction is through the concept of "losing and gaining oxygen" (commonly referred to as the oxygen model). Consequently, "losing and gaining oxygen "should be considered the most fundamental cognitive attribute in this domain. Electrode potential, a concept of considerable complexity and comprehensiveness, occupies the highest level within the conceptual system of redox reaction. Consequently, a profound understanding of this concept necessitates the prior mastery of the other six cognitive attributes.*

> *Expert 5: Building on the understanding of "losing and gaining oxygen", students can discern the propensity of atoms to form stable structures. They can also identify redox reaction by observing changes in the oxidation number of elements or the structural features of specific molecules. This process enables them to progressively acquire a comprehensive grasp of the "molecular structure" and "oxidation number". As students delve deeper into their studies, they are able to recognize from a microscopic perspective that the change in oxidation number is attributable to the transfer of electrons, and they can grasp the process of electron transfer. Thus, "electron transfer" is a higher cognitive attribute than "oxidation number".*

As a result of the focus group discussions, a consistent agreement was reached: The hierarchical relationships among the attributes were depicted in Figure 3. This structure reflected the cognitive structure of redox reaction that experts anticipate students should master. The attribute hierarchy described the sequential relationships among the seven cognitive attributes slated for assessment. For instance, a thorough understanding of C5 (oxidation reaction / reduction reaction) was essential as a foundation for grasping C6 (oxidability / reducibility).

**Figure 3**
*The Hierarchical Attribute Relationships of Redox Reaction*





https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

## Research Methodology

*Item Design*

1) Q matrix

After identifying the hierarchical relationships among attributes, the Q matrix can be utilized to describe the relationships between attributes and items, thereby facilitating representation and manipulation. In the process of cognitive diagnosis, the Q matrix is derived through matrix operations. Based on the direct logical relationships of the attributes, the adjacent matrix, also known as the A matrix, can be constructed.

By performing Boolean operations on A matrix one can derive the reachable matrix, namely the R matrix (Chen et al., 2017; Evangelatos, 1989). Specifically, this involves Boolean addition (OR) and Boolean multiplication (AND) of matrices. For directed graphs, the R matrix can be obtained by iteratively performing matrix multiplication on A matrix using Boolean arithmetic until all reachable paths are identified. In this context, matrix multiplication involves the Boolean 'AND' operation for each element, and the result of these multiplications is then combined using the Boolean 'OR' operation to determine the R matrix.

A network analysis platform called FlexCDMs is employed to calculate the R matrix (Mi, 2021). The corresponding R matrix can be output by importing a Microsoft Excel file containing the A matrix directly into the analysis platform. The R matrix is shown in Table 4. In the table, "1" represents a direct or indirect logical relationship between two attributes, while "0" indicates the absence of any relationship.

**Table 4**
*R Matrix of the Attributes*

| | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
|---|---|---|---|---|---|---|---|
| C1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| C2 | 0 | 1 | 0 | 0 | 1 | 1 | 1 |
| C3 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| C4 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| C5 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| C6 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| C7 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

The redox reaction encompasses seven cognitive attributes. Without considering the hierarchical relationships among these attributes, the relationship between attributes and potential items can be represented by a $k \times i$ matrix, yielding $2^7=128$ possible types of items. However, in the educational measurement, there is no scenario in which attribute C7 (electrode potential) is considered in isolation. Therefore, by consulting the R matrix and eliminating item types that do not conform to the required cognitive attributes, a refined assessment matrix can be constructed. Transposing this matrix reveals the attribute mastery patterns (AMPs) of the subject, which is presented in Table 5 as the AMPs matrix for this study. In the table, "1" represents mastery of the attribute while "0 " represents non-mastery of the attribute.

**Table 5**
*The AMPs Matrix Obtained from R Matrix*

| AMP | Attribute | | | | | | |
|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
| I1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| I2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| I3 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| I4 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

| AMP | Attribute | | | | | | |
|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
| I5 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| I6 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| I7 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| I8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| I9 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| I10 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |

Patterns that reflect a complete lack of understanding (where all seven cognitive attributes are "0") are excluded from the AMPs matrix. Based on the aforementioned matrix, it is determined that there are a total of nine distinct item explore patterns. This implies that, in the development of an assessment instrument, nine distinct types of questions must be formulated. A two-way checklist of the item and item explore patterns is shown in Appendix I. Subsequently, we construct a Q matrix to delineate the relationships between the targeted cognitive attributes and the assessment items. The Q matrix developed in this study is displayed in Table 6. In the Q matrix, "1" signifies that the item is designed to measure the corresponding attribute, while "0" indicates the absence of a relationship between the item and the attribute.

**Table 6**
*Q Matrix*

| Item | Attribute | | | | | | |
|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 4 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 5 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 6 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 7 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 8 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| 9 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| 10 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| 11 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| 12 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 13 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 14 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 15 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 16 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 17 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 18 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 19 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 20 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 21 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 22 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 23 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |



https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

| Item | Attribute | | | | | | |
|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
| 24 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| 25 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |

2) Design of test items

A preliminary set of 30 test items was developed using the Q-matrix and drawing on relevant literature on the assessment of the redox reaction (Acar & Tarhan, 2007; Brandriet & Bretz, 2014; Chiang et al., 2014; Delisma & Widhiyanti, 2020; Tang et al., 2022; Tang et al., 2024).

Following a thorough discussion by a panel of experts focusing on language description and item coverage, a set of 25 items was identified for inclusion in the measurement instrument. The test items were designed to meet the following criteria: (1) adherence to the identified hierarchical relationships of attributes and the Q-matrix, and (2) ensuring that each attribute was assessed at least three times. The testing instrument comprised 25 items, including multiple-choice and short-answer questions. All items were scored dichotomously: "1" for correct responses and "0" for incorrect responses.

*For example: Below is a redox reaction. Which of the following descriptions is correct?*

$$Fe(s) + CdSO_4(aq) \rightarrow FeSO_4(aq) + Cd(s)$$

*A. This reaction does not involve oxygen, so it is not a redox reaction.*

*B. In the above reaction, electrons transfer from iron to cadmium.*

*C. In $CdSO_4$, the oxidation number of the cadmium element is +4.*

*D. Electron transfer is the external manifestation of changes in the oxidation number of an element.*

This item belongs to the fourth type ($I_5$) of item explore patterns. Option A is designed to assess the C1 (losing and gaining oxygen), primarily to evaluate students' proficiency in the methods for identifying redox reaction. Option B examines the C4 (electron transfer) and focuses on testing whether students understand the electron transfer in redox reaction. Option C assesses the C3 (oxidation number) and focuses on evaluating whether students can accurately ascertain the oxidation number of elements within polyatomic molecules. Option D provides a comprehensive assessment of the attributes C1 (losing and gaining oxygen), C3 (oxidation number), and C4 (electron transfer) within the item, focusing on the understanding of the essential characteristics of redox reaction. The 25 test items utilized in this study adhere to the Q matrix, thoroughly evaluating students' comprehension of the redox reaction.

*General Background*

In China, students begin studying redox reaction in Grade 9, followed by a systematic study of redox reaction in Grades 10 to 12. The study extensively covered the conceptual system of redox reaction, including the majority of its components. Since the test questionnaire was distributed in September 2023—when $10^{th}$ graders had only just begun upper-secondary school and had not yet studied redox reaction—it was deemed appropriate to limit the measurement to $11^{th}$ and $12^{th}$ graders. This decision ensures alignment with the students' cognitive development and maintains the rigor of the study.

*Participants and Procedures*

Cognitive diagnostic models might exhibit significant bias with small sample sizes (Sorrel et al., 2023) and generally, an increase in sample size was positively associated with enhanced reliability of the outcomes (Sen & Cohen, 2021). A cluster sampling method was adopted to select participants. The participants were $11^{th}$ and $12^{th}$ graders from an ordinary upper-secondary school in Shandong Province, with an average age range of 16 to 18 years old. Students were stratified according to grade level, and four classes were randomly selected at each grade. All students in these classes were included in the study to provide a comprehensive and scientific sample evidence.

A total of 409 students participated in this study. The students had all completed the study of redox reaction as presented in the chemistry curriculum. Their learning progress was similar, and the testing was administered on a per-class basis, overseen by the respective chemistry teachers. Participants' demographic information is displayed in Table 7.


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

**Table 7**
*Demographic Characteristics of Participants*

| Grade | Number | Recovery rate / % | Gender | |
|---|---|---|---|---|
| | | | Male | Female |
| 11th | 227 | 89.87 | 95 | 132 |
| 12th | 182 | 92.86 | 107 | 75 |

Prior to the implementation, researchers explained to the participants its purpose, emphasizing that participation was voluntary and that students could withdraw at any time. They also clarified that the data collected would be used solely for the study and would not contribute to the school's curriculum evaluation. Upon completion of the survey questionnaire collection, 36 invalid questionnaires were identified and excluded, resulting in a final tally of 373 valid questionnaires.

*Data Analysis*

To construct a Bayesian network in Netica (Retrieved from http://www.norsys.com), the specific steps are as follows: 1) Clearly define the research content and decompose it into the desired constituents, i.e. the previously identified seven cognitive attributes. 2) Specify or learn the structural relationships among various attributes, and employ arrows to represent these connections (i.e. the hierarchical relationship of attributes established in the preceding text). 3) Organizing the established hierarchical relationships of attributes and the interrelationships between attributes and items into a complete Bayesian network constitutes the basic cognitive model. 4) Finally, the processed data will be incorporated into a Bayesian network to facilitate parameter estimation, thereby revealing students' knowledge states.

To enhance the efficiency of data analysis and processing, the collected questionnaires were sequentially numbered and organized according to grade level. The responses from the 373 participants were then encoded as Id 1 through Id 373. Subsequently, Microsoft Excel was utilized to statistically analyze the data and to archive the corresponding student answers associated with each identifier.

Following the questionnaire testing, 15 students from each grade were randomly selected for interviews. These interviews were conducted within a week after the test and lasted approximately 20 minutes each. The audio recordings of the interviews were transcribed into text and saved in Microsoft Word.

This study employed two distinct methodologies for data processing. First, the collected data were analyzed using SPSS 26.0 to evaluate the reliability of the testing instrument. Subsequently, the test data were processed with Netica software to assess the quality of the Bayesian network model. The response data from 11th and 12th graders were processed separately, with the datasets imported into Netica for Bayesian network structure learning, thereby deriving the cognitive structures specific to each grade level.

## Research Results

*Quality Analysis*

Cronbach's alpha coefficient was .708, indicating good reliability of the test instrument (Tavakol & Dennick, 2011). Based on the participants' performance in this test and the attributes assessed by each item, the AMPs of all participants could be obtained. This test comprised 25 questions, each crafted to evaluate one or more of the seven cognitive attributes. For example, consider the response pattern for participant Id 113: "1100011100000000000000000". In this context, "1" indicates a correct answer, while "0" indicates an incorrect answer. Items 1 and 2 were designed to assess the understanding of C1 (losing and gaining oxygen). Items 3, 4, and 5 evaluated the understanding of both C1 (losing and gaining oxygen) and C2 (molecular structure). Furthermore, items 6, 7, and 8 assessed the understanding of C1 (losing and gaining oxygen) and C3 (oxidation number).

By applying an 'OR' operation to the attributes corresponding to the questions correctly answered by each participant, an attribute mastery pattern, such as (1010000), could be derived. By sequentially analyzing the responses of the 373 participants, an individual attribute mastery pattern could be established for each. These


https://doi.org/10.33225/jbse/24.23.1243

Journal of Baltic Science Education, Vol. 23, No. 6, 2024

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

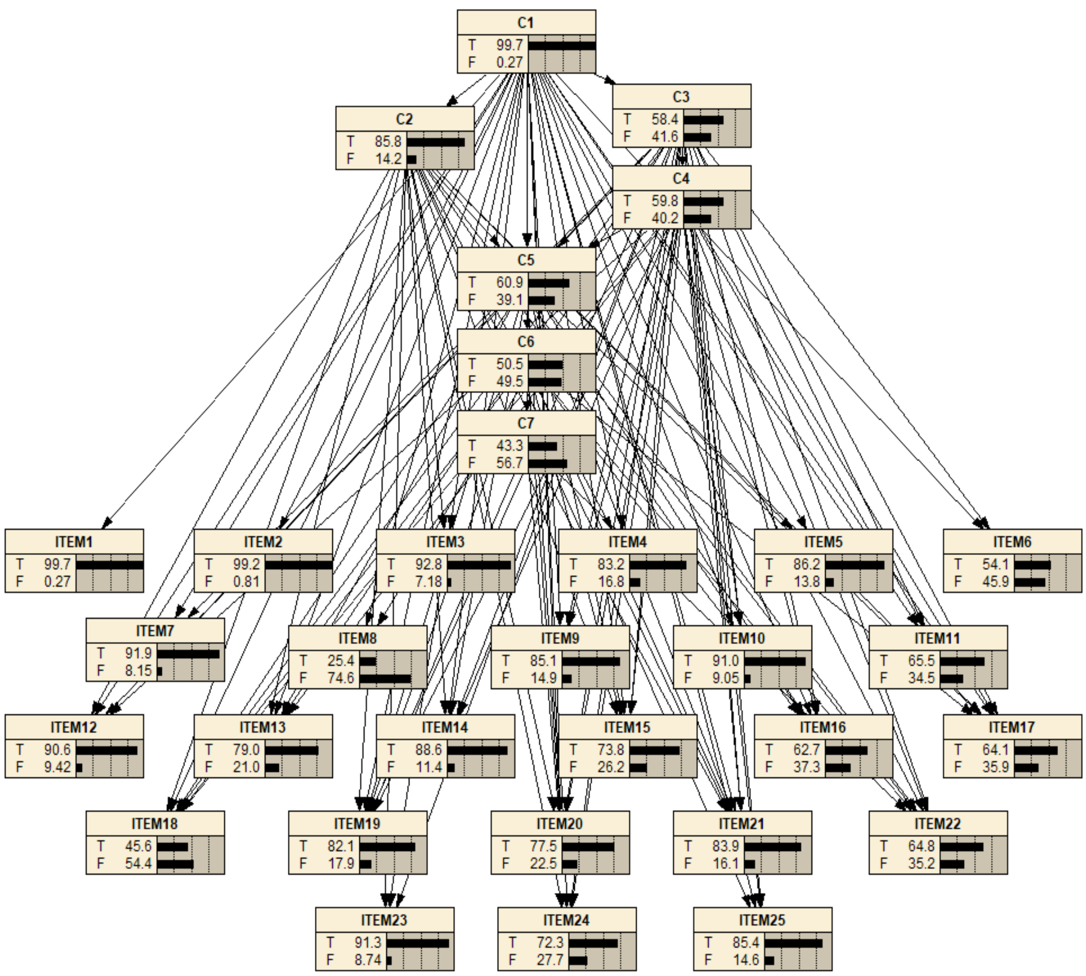
patterns served as the dataset for parameter estimation within Bayesian networks.

In this study, the Receiver Operating Characteristic (ROC) curve was used to analyze the diagnostic performance of Bayesian networks. The ROC curve represented the probability of correctly identifying positive and negative outcomes for each sample and served as an indicator of the diagnostic performance across the entire model (Fawcett, 2006a; Singh & Babbar, 2018). For comparative analysis, the model's performance was often assessed by calculating the Area Under the Curve (AUC) value (Ioannidis et al., 2016). The AUC value ranged from .5 to 1, with values closer to 1 indicating superior diagnostic performance of the model. An AUC value of .5 suggested that the diagnostic method was no better than chance and lacks diagnostic utility. When the AUC value was between .5 and .7, it indicated that the diagnostic or predictive performance of the model was average. Values between .7 and .9 indicated good diagnostic performance, while values above .9 suggested a high level of accuracy (Fawcett, 2006b). The data were analyzed for the diagnostic performance of the model using Netica software based on the basic cognitive model, and the value of AUC was obtained as .7206, which indicated that the diagnostic performance of the model was good.

Key Attributes in the Cognitive Structure of Redox Reaction in Upper-secondary School Students

According to the steps mentioned above, a Bayesian network was initially constructed, and the collected data were imported to obtain the cognitive model of students understanding in redox reaction, as shown in Figure 4.

**Figure 4**
*A Cognitive Model of Redox Reaction for 11th and 12th Graders*




*Note*: In the figure T and F denote true and false, and the numbers indicate conditional probabilities.


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

As can be seen from Figure 4, students' mastery of C1 (losing and gaining oxygen) to C7 (electrode potential) roughly presented a process from proficient to a general understanding. The probability of mastering C1 (losing and gaining oxygen) and C2 (molecular structure) was 99.7% and 85.5%, indicating that the majority of students had mastered these two attributes. As the complexity of attributes increases, the probabilities of mastering C3 (oxidation number), C4 (electron transfer), C5 (oxidation reaction / reduction reaction), and C6 (oxidability / reducibility) were around 50-60%. This indicated that students had a relatively stable understanding of these attributes. Understanding C7 (electrode potential) was essential for understanding the working principles of galvanic cell; however, with a mastery probability of only 43.3%, it was clear that this attribute should be emphasized in subsequent teaching to enhance student understanding.

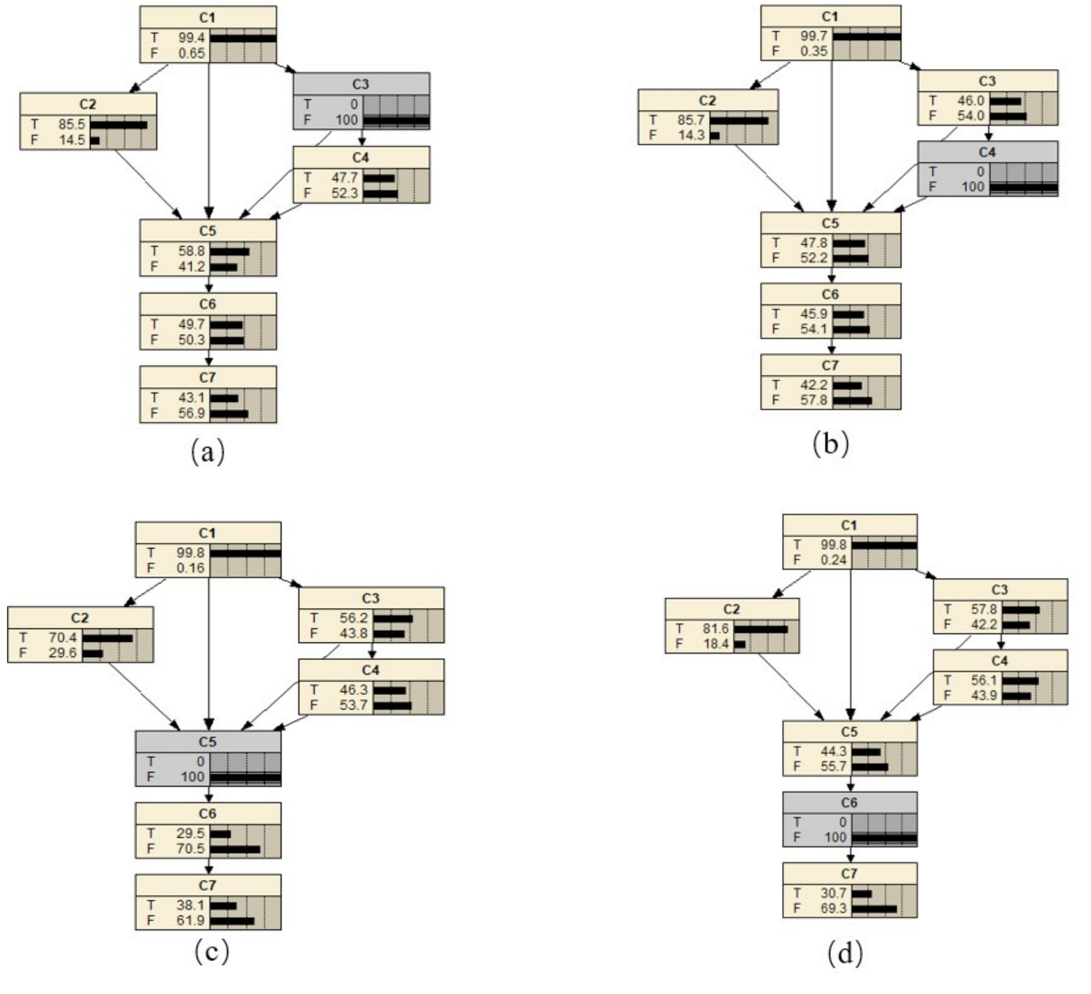
To further identify the key attributes in the cognitive structures of upper-secondary school students' redox reaction, an in-depth analysis was conducted on the attributes C3 (oxidation number), C4 (electron transfer), C5 (oxidation reaction / reduction reaction), and C6 (oxidability / reducibility).

For ease of analysis, the item component within the cognitive model was hidden, while only the attribute component was presented. The relationships between cognitive attributes were analyzed using the "trial and error method" (Shi, 2024). Specifically, if a specific cognitive attribute was not mastered, i.e. *F*=100% (the error probability represented by F in Figure 5), and the probability of mastering other related attributes did not change significantly, it indicated that the attribute was not a key attribute within the student's cognitive structure.

Employing the "trial and error method" for data analysis enabled the identification of the influence relationships among cognitive attributes and allowed for the quantitative identification of key attributes within the cognitive structure. In Figure 5, panels (a), (b), (c), and (d) show the changes in other cognitive attributes when C3 (oxidation number), C4 (electron transfer), C5 (oxidation reaction / reduction reaction), and C6 (oxidability / reducibility) were not mastered.

**Figure 5**

*The Results of Using the "Trial and Error Method" for Analysis*





https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

As depicted in Figure 5(a), it could be observed that if students had not mastered C3 (oxidation number), i.e., when *F*=100%, the probability of mastering other attributes changed.

Specifically, the mastery probabilities shifted as follows: C4 (electron transfer) from 59.8% to 47.7%, C5 (oxidation reaction / reduction reaction) from 60.9% to 58.8%, C6 (oxidability / reducibility) from 50.5% to 49.7%, and C7 (electrode potential) from 43.3% to 43.1%. These findings suggested that, with the exception of C4 (electron transfer), the mastery of other attributes remained relatively stable.

As shown in Figure 5(b), when students had not mastered C4 (electron transfer), the changes in the probability of mastery for other attributes were: C3 (oxidation number) from 58.4% to 46.0%; C5 (oxidation reaction / reduction reaction) from 60.9% to 47.8%; C6 (oxidability / reducibility) from 50.5% to 45.9%; C7 (electrode potential) from 43.3% to 43.1%.

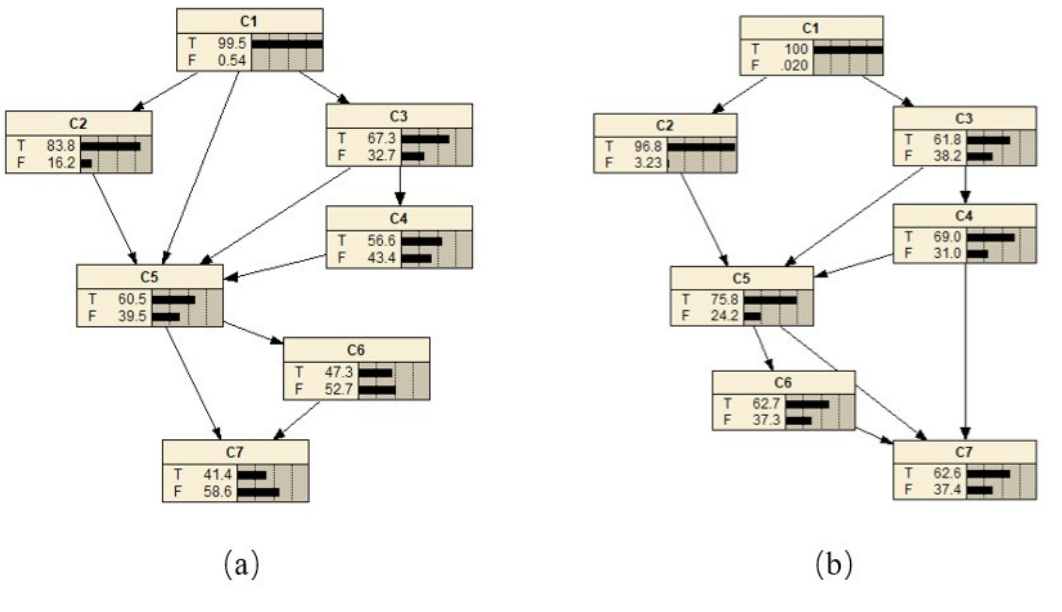
As shown in Figure 5(c), when students had not mastered C5 (oxidation reaction / reduction reaction), the changes in the probability of mastery for other attributes were: C3 (oxidation number) from 58.4% to 56.2%; C4 (electron transfer) from 59.8% to 46.3%; C6 (oxidability / reducibility) from 50.5% to 29.5%; C7 (electrode potential) from 43.3% to 38.1%. In addition, the probability of mastering C2 (molecular structure) had also changed, decreasing from 85.8% to 70.4%.

As shown in Figure 5(d), when students had not mastered C6 (oxidability / reducibility), the changes in the probability of mastery for other attributes were: C3 (oxidation number) from 58.4% to 57.8%; C4 (electron transfer) from 59.8% to 56.1%; C5 (oxidation reaction / reduction reaction) from 60.9% to 44.3%; C7 (electrode potential) from 43.3% to 30.7%.

*Cognitive Structure of 11th and 12th Graders*

Bayesian networks offered a distinct advantage in educational assessment, as they were capable of discerning novel network structures by analyzing actual response data from students. The hierarchical relationship of attributes established by the expert group reflected the redox reaction cognitive structure that experts expected students to master. However, these relationships might not accurately describe the actual cognitive structure that students possess. Therefore, Netica software was employed to perform structural learning on the response data from 11th and 12th graders. The resulting cognitive structures pertaining to redox reaction for 11th and 12th graders are shown in Figure 6.

**Figure 6**
*Cognitive Structure of 11th and 12th Graders in Redox Reaction*




*Note*:(a) for Grade 11, (b) for Grade 12


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

The results indicated that the probability of mastering nearly every attribute was higher among 12th graders compared to 11th graders. This difference was particularly pronounced for attributes of greater complexity, such as C5 (oxidation reaction / reduction reaction), C6 (oxidability / reducibility), and C7 (electrode potential), as shown in the data. For example, for C7 (electrode potential), the mastery probabilities for 11th and 12th graders were 41.4% and 62.6%, respectively. Moreover, the probability of mastering C3 (oxidation number) in 11th graders was higher than that in 12th graders, with 67.3% in 11th graders and 61.8% in 12th graders.

It was found that the cognitive structure of 11th and 12th graders in redox reaction basically matched the cognitive structure of redox reaction that experts expect students should have. However, a new edge between C5 (oxidation reaction / reduction reaction) and C7 (electrode potential) appeared in the cognitive structure of both grades. In the cognitive structure of 12th graders, the connection from C1 (losing and gaining oxygen) to C5 (oxidation reaction / reduction reaction) was absent, while a new linkage between C4 (electron transfer) and C7 (electrode potential) had been established.

This study could not only present the cognitive structure of students in redox reaction, but also analyzed the individual differences of students. The analysis of the responses of the two participants with the same scores is shown in Table 8.

**Table 8**
*The Responses of Different Participants with the Same Scores*

| Code | Id 69 | Id 187 |
|---|---|---|
| Score | 11 | 11 |
| Response Data | 11111000110110100100000000 | 11111110100010001000000 |
| AMP | 1101000 | 1110000 |

From the analysis of Table 8, it could be seen that although the scores of the two participants were the same, their attribute mastery patterns were different.

The attribute mastery mode for Id 69 is"1101000". This pattern suggested that this student had mastered the method of identifying redox reaction based on valid information in the equation; knew that a molecule has a certain spatial structure, and was able to identify the reaction based on the analysis of the molecular structure of the organic molecules to characterize their chemical properties; knew that the essence of redox reaction was the transfer of electrons, and was able to express the process of the transfer of electrons using symbols. However, this student was not clear about the meaning of oxidation number and could not accurately identify the oxidation number of elements in polyatomic particles. This deficiency also adversely affected this student's understanding of subsequent concepts related to redox reaction and other related knowledge.

The attribute mastery mode for Id 187 is"1110000". This pattern suggested that this student had mastered the method of identifying redox reaction based on valid information in the equation; knew that a molecule has a certain spatial structure, and was able to identify the reaction based on the analysis of the molecular structure of the organic molecules to characterize their chemical properties; understood the concept of oxidation number and was able to identify the oxidation states of elements in a substance. However, this student often failed to grasp the reasons for changes in oxidation number from a microscopic perspective, which could impede this student's understanding of subsequent concepts such as electron transfer and redox reaction.

Based on the analysis, Targeted teaching remediation could be implemented for these two participants. The analysis results for Participant Id 69 revealed a deficiency in the understanding of oxidation number. Consequently, it was essential to reinforce the learning of oxidation number concepts to establish a solid foundation for the understanding of "oxidation/reduction reaction" and other attributes. The analysis of Id 187 had shown that it must be guided to understand changes in oxidation number from a microscopic point of view. It was necessary to focus on the targeted learning of electron transfer, which lead to an essential understanding of redox reaction.


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

## Discussion

In this study, seven cognitive attributes and the hierarchical relationship of attributes in redox reaction were identified. Bayesian networks were employed to perform the cognitive structure of students' understanding of redox reaction.

### *Effectiveness of Bayesian Network Measurement*

This study introduced a novel method of using Bayesian networks to measure the cognitive structure of students' understanding in redox reaction, and specified the research process of using Bayesian networks for the diagnostic assessment of redox reaction cognition: 1) identification of cognitive attributes within the tested subject domain. 2) identification of the hierarchical relationship of attributes. 3) development of the test items in conjunction with the Q-matrix and administration of the test. 4) data coding and analysis. 5) Bayesian network construction.

The researchers meticulously followed this diagnostic assessment procedure and assembled an expert group to ensure methodological rigor. Based on a comprehensive literature analysis, the researchers identified the cognitive attributes and the hierarchical relationship of attributes. Subsequently, a Q matrix was established, corresponding testing items were developed, and testing was implemented. Then encode and analyze the collected data, and Bayesian networks were applied to analyze students' cognitive structures. The diagnostic performance of the Bayesian network model was analyzed, and the value of AUC was obtained as .7206 (Fawcett, 2006b). This result indicated that the Bayesian network model demonstrated good diagnostic performance, and the constructed Bayesian network was able to reflect the cognitive structure of students' understanding in redox reaction.

### *Identify Key Attributes in the Cognitive Structure of Redox Reaction for Upper-secondary School Students*

As depicted in Figure 4, the probability of students mastering cognitive attributes decreased with increasing complexity. This pattern revealed that students tended to exhibit high proficiency in simpler attributes while struggling with more complex ones.

The key attributes were defined as those attributes of knowledge and skills that were fundamental to the student's cognitive structure and the "trial and error method" was employed to identify the key attributes (Shi, 2024). The results of the "trial and error method" analysis for the cognitive attributes C3 (oxidation number), C4 (electron transfer), C5 (oxidation reaction / reduction reaction), and C6 (oxidability / reducibility) are shown in Figure 5.

As can be seen in Figure 5(a), there was a significant decrease in the probability of mastery of C4 (electron transfer) when learning of C3 (oxidation number) was impeded. Changes in oxidation number of elements was an external manifestation of electron transfer in redox reaction. Researchers believed that a deficiency in understanding of C3 (oxidation number) was likely to adversely affect the comprehension of C4 (electron transfer). However, the mastery probability of other attributes did not change much. Therefore, researchers believed that C3 (oxidation number) was not a key attribute in students' cognitive structure.

As shown in Figure 5 (b), a lack of understanding of C4 (electron transfer) affected not only the comprehension of C3 (oxidation number) but also the subsequent understanding of substance properties and electrochemical concepts. Some researchers have argued that understanding electron transfer could help students enhance their comprehension of redox reaction (Nieves et al., 2012). Therefore, C4 (electron transfer) was considered a key attribute in students' cognitive structures.

Figures 5(c) and (d) showed a significant decrease in the probability of students mastering C2 (molecular structure), C4 (electron transfer), and C7 (electrode potential) when their comprehension of C5 (oxidation reaction / reduction reaction) and C6 (oxidability / reducibility) was impeded. The correct understanding of "oxidation reaction / reduction reaction" and "oxidability / reducibility" was helpful for students to learn electrode reaction in a galvanic cell. Therefore, C5 (oxidation reaction / reduction reaction) and C6 (oxidability / reducibility) were considered as key attributes in students' cognitive structure.

Thus, the key attributes in the cognitive structure of students' redox reaction were identified as C4 (electron transfer), C5 (oxidation reaction / reduction reaction), and C6 (oxidability / reducibility). Analyzing the influence among these attributes also indirectly supported the rationality of the established hierarchical relationships.


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

*Cognitive Structure of 11th and 12th Graders in Redox Reaction*

The cognitive structure of students in the two grades is shown in Figure 6. Researchers found that 12th graders exhibited a higher probability of mastering almost every attribute than 11th graders. Interviews with 12th graders revealed the following causes:

*Student: After attending a teacher-organized review on the topic of redox reaction, I have changed some of my earlier misconceptions. Erm...for example...by drawing concept maps, I realized that I had been relying on oxidation number to recognize redox reaction, but this is actually wrong....you still need to learn from a microscopic point of view.... Electron transfer is very important to understand redox reaction. It is with the help of electron transfer that one can have a better understanding of this part of the galvanic cell and electrolytic cell.*

In China, 12th graders face the pressure of the entrance examination. Therefore, teachers will conduct a systematic and comprehensive thematic review of the learned knowledge. For example, in the study of redox reaction, the teacher summarized all the knowledge under this topic, and led students to systematically review this part of content by drawing concept maps and project-based learning, so as to help students better understand the redox reaction. The findings indicated that systematic learning of redox reaction improved students' ability to grasp complex cognitive attributes, thereby providing a foundation for the development of targeted instructional interventions in the future.

In addition, students were usually introduced to the concept of oxidation number during their Grades 9. At the time of the survey, it had been a long time since 12th graders were exposed to this part of knowledge due to the influence of the entrance examination. The study of chemical bonds, galvanic cells, and electrolytic cells also interfered with students' understanding of oxidation number. Moreover, oxidation number was more commonly used as a tool to identify redox reaction in the learning process of 12th graders (Silverstein, 2011). These were the reasons why the probability of mastery of C3 (oxidation number) was lower for 12th graders than for 11th graders. Therefore, it is suggested that teachers should arrange the teaching content reasonably to help students of different grades better understand the concept of oxidation number (Adu-Gyamfi & Ampiah, 2019).

Interviews with 11th and 12th graders revealed the reasons for the appearance of the relationship between C5 (oxidation reaction / reduction reaction) and C7 (electrode potential) relationship in the students' cognitive structure.

*Student: I think there is a relationship between the formation of galvanic cells and an electrolytic cell and the occurrence of an oxidation or reduction reaction. Erm...because the textbook always emphasizes the oxidation reaction when describing the galvanic cells and the electrolytic cell, so I think there is a relationship between them...is it the occurrence of the redox reaction that leads to the potential difference? Because I think there is some meaning to these two reactions as they appear many times in the textbook.*

Due to the inherent complexity and abstraction of C7 (electrode potential), students need to build on their understanding of C5 (oxidation reaction / reduction reaction) to delve deeper into C6 (oxidation/reduction). This further exploration was essential for a comprehensive grasp of the interplay between electron transfer and potential difference, which was fundamental to mastering the concept of electrode potential. However, 11th and 12th graders had insufficient understanding of the textbook. They might be led to a misconception by the repetitive descriptions of oxidation reactions and reduction reactions at electrodes in textbooks, which could lead them to believe that the redox reaction itself was the direct cause of potential difference generation and electron transfer between the poles. This perception may overshadow an understanding of the essential causes underlying the potential difference.

The absence of the relationship between C1 (losing and gaining oxygen) and C5 (oxidation reaction / reduction reaction) in students' cognitive structures was the result of students' gradual deepening of conceptual learning. Researchers had observed that in Grade 11, students still relied on a straightforward inference related to oxygen gain and loss to identify redox reaction (Masykuri et al., 2019). Figure 6(b) illustrated that


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

12th graders had achieved a 100% mastery rate in understanding the "losing and gaining oxygen", suggesting that after systematic learning, these students had recognized the limitations of using oxygen gain and loss as the sole criterion for identifying redox reaction. Consequently, the lack of the relationship between C1 (losing and gaining oxygen) and C5 (oxidation reaction / reduction reaction) in students' cognitive structures was in line with expected patterns of cognitive development.

The appearance of the relationship between C4 (electron transfer) and C7 (electrode potential) in students' cognitive structures was an indirect reflection of the improvement in 12th graders' conceptual understanding. On the one hand, researchers believed that the generation of current in galvanic cells was closely related to the potential difference and electron transfer between systems (Şekerci, & Erdem, 2022). On the other hand, interviews revealed that certain 12th graders, motivated by chemistry competitions or personal interest, had acquired knowledge of electrode potential and potential difference. They have also grasped the fundamental principle of transforming chemical energy into electrical energy within galvanic cells. As a result, the relationship between C4 (electron transfer) and C7 (electrode potential) appeared in their cognitive structure.

**Conclusions and Implications**

In this study, Bayesian networks were utilized to analyze the cognitive structures underlying students' understanding of redox reaction. The results indicated that the developed test instruments had good quality, and Bayesian networks were suitable for testing the students' cognitive structure of redox reaction. Bayesian networks provided a more intuitive model to characterize students' cognitive structures, which could be used to diagnose students' mastery.

In general, upper-secondary school students had a good grasp of redox reaction and had identified key attributes in their cognitive structures of redox reaction. There were differences in the cognitive structure of redox reaction between 11th and 12th graders, with 12th graders having a better grasp of redox reaction than 11th graders. Bayesian networks not only revealed the conceptual understanding of student groups, but also diagnosed individual differences in performance when achieving the same score.

The cognitive structure of students reflects the reality of their organization of knowledge content. In the cognitive structure, there are often some cognitive attributes that play a key role in students' understanding of subject knowledge, and these attributes are defined as the key attributes in this study. Based on the previous analysis, "electron transfer", "oxidation reaction / reduction reaction" and "oxidability /reducibility" are the key attributes in the cognitive structure of students in redox reaction, which should be focused on in education and teaching. In summary, this study provides a new perspective on the measurement of the cognitive structure of redox reaction.

In the context of evidence-based measurement in chemistry education, cognitive diagnostic tests utilizing Bayesian networks offer a more granular assessment of students' conceptual understanding than traditional tests. This enhanced granularity allows educators to precisely identify and understand students' mastery of specific attributes within particular concepts, as well as the influence of these attributes on students' cognitive structures. Such diagnostic insights provide valuable evidence to guide targeted instructional interventions and informed teaching decisions.

The hierarchical relationships among attributes within Bayesian networks correspond to the cognitive structures. The present study reveals that the cognitive structures of 11th and 12th graders exhibit differences. Furthermore, it is suggested that the relationships between cognitive attributes in actual learning environments may involve a degree of uncertainty. Bayesian networks, recognized for their ability to visually represent and infer uncertain knowledge, provide a robust framework for cognitive diagnostic assessments. Utilizing Bayesian networks can enhance the prediction of students' conceptual learning paths. Teachers can then organize their teaching based on the actual learning paths of students' cognitive development, thereby more effectively promoting meaningful learning. For example, when adding a lower-level attribute, the probability of successfully solving the problem corresponding to the upper-level attribute decreases, indicating that the lower-level attribute may be detrimental to learning the upper-level concept, and thus its learning sequence can be postponed.

Curriculum content is often divided into different levels of knowledge, where big ideas dominate the subordinate concepts. How to assess students' learning progression of large concepts containing complex


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

structures has always been a key concern in science education research. Bayesian networks can leverage these hierarchical relationships to construct learning progression maps, offering a novel approach to mapping students' progression in mastering overarching concepts. This is because the central theoretical basis assumes that the possibility of solving problems with more difficult superordinate concepts depends on solving previously easier (subordinate) problems. That is, for more superordinate concepts, the probability of student success in mastering them is lower, thus delineating a pathway for students to progressively learn the big ideas. It can be seen that exploring how to incorporate Bayesian networks for the learning progression of chemistry's big ideas may be an important concern for future research in chemistry education.

### Limitations of the Study

This study acknowledges certain limitations. Firstly, the experts selected for the focus group in this study were all from China, and course content was derived from the Chinese chemistry curriculum system, so the generalizability is poor; Secondly, the study's sample was constrained to two grades within a single upper-secondary school in a Chinese province, resulting in a small sample size. Therefore, this study also expects to expand the scope of research and further validate the research conclusions.

### Acknowledgements

This work was supported by the Youth Fund for Humanities and Social Sciences Research, Ministry of Education (Grant number: 24YJC880050).

### Declaration of Interest

The authors declare no competing interest.

### References

Acar, B., & Tarhan, L. (2007). Effect of cooperative learning strategies on students' understanding of concepts in electrochemistry. *International Journal of Science and Mathematics Education*, *5*, 349–373. https://doi.org/10.1007/s10763-006-9046-7

Adu-Gyamfi, K., Ampiah, J. G., & Agyei, D. D. (2020). Participatory teaching and learning approach: a framework for teaching redox reactions at high school level. *International Journal of Education and Practice*, *8*(1), 106–120. http://hdl.handle.net/123456789/8042

Ainsworth, S. (2008). The educational value of multiple-representations when learning complex scientific concepts. In Visualization: *Theory and practice in science education* (pp. 191–208). Springer Netherlands. https://doi.org/10.1007/978-1-4020-5267-5_9

Almond, R. G., Mislevy, R. J., Steinberg, L. S., Yan, D., & Williamson, D. M. (2015). *Bayesian networks in educational assessment*. Springer.

Atabek-Yigit, E. (2015). Exploring the relationship between cognitive structure outcomes and test achievements of pre-service science teachers on chemical bonding via flow mapping. *Journal of Baltic Science Education*, *14*(4), 524–534. https://dx.doi.org/10.33225/jbse/15.14.524

Basheer, A., Hugerat, M., Kortam, N., & Hofstein, A. (2016). The effectiveness of teachers' use of demonstrations for enhancing students' understanding of and attitudes to learning the oxidation-reduction concept. *Eurasia Journal of Mathematics, Science and Technology Education*, *13*(3), 555–570. https://doi.org/10.12973/eurasia.2017.00632a

Bayrak, B. K. (2013). Using two-tier test to identify primary students' conceptual understanding and alternative conceptions in acid Base. *Mevlana International Journal of Education*, *3*(2). 10.13054/mije.13.21.3.2

Birenbaum, M., Kelly, A. E., & Tatsuoka, K. K. (1993). Diagnosing knowledge states in algebra using the rule-space model. *Journal for Research in Mathematics Education*, *24*(5), 442–459. https://doi.org/10.5951/jresematheduc.24.5.0442

Brandriet, A. R., & Bretz, S. L. (2014). 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. https://doi.org/10.1021/ed500051n

Chang, C. Y., Yeh, T. K., & Barufaldi, J. P. (2010). The positive and negative effects of science concept tests on student conceptual understanding. *International Journal of Science Education, 32*(2), 265–282. https://doi.org/10.1080/09500690802650055

Chen, F., Zhang, S., Guo, Y., & Xin, T. (2017). Applying the rule space model to develop a learning progression for thermochemistry. *Research in Science Education*, *47*, 1357–1378. https://doi.org/10.1007/s11165-016-9553-7


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Chen, H., & Chen, J. (2016). Exploring reading comprehension skill relationships through the G-DINA model. *Educational Psychology*, *36*(6), 1049–1064. https://doi.org/10.1080/01443410.2015.1076764

Chiang, W. W., Chiu, M. H., Chung, S. L., & Liu, C. K. (2014). Survey of high school students' understanding of oxidation-reduction reaction. *Journal of Baltic Science Education*, *13*(5), 596. https://dx.doi.org/10.33225/jbse/14.13.596

Cornwall, A., & Jewkes, R. (1995). What is participatory research?. *Social Science & Medicine*, *12*(41), 1667–1676. https://doi.org/10.1016/0277-9536(95)00127-s

Culbertson, M. J. (2016). Bayesian networks in educational assessment: The state of the field. *Applied Psychological Measurement*, *40*(1), 3–21. https://doi.org/10.1177/0146621615590401

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. https://doi.org/10.1002/tea.3660321008

De La Torre, J. (2009). DINA model and parameter estimation: a didactic. *Journal of Educational and Behavioral Statistics*, *34*(1), 115–130. https://doi.org/10.3102/1076998607309474

Delisma, D., & Widhiyanti, T. (2020, March). Conception, threshold concept, and troublesome knowledge in redox reaction. In *Journal of Physics: Conference Series* (Vol. 1521, No. 4, p. 042070). IOP Publishing. 10.1088/1742-6596/1521/4/042070

Emden, M., Weber, K., & Sumfleth, E. (2018). Evaluating a learning progression on 'Transformation of Matter' on the lower secondary level. *Chemistry Education Research and Practice*, *19*(4), 1096–1116. https://doi.org/10.1039/C8RP00137E

Evangelatos, D. S. (1989). Reachability matrix by partitioning and related boolean results. *Journal of the Franklin Institute*, *326*(3), 409–419. https://doi.org/10.1016/0016-0032(89)90020-3

Fawcett, T. (2006a). An introduction to ROC analysis. *Pattern Recognition Letters*, *27*(8), 861–874. https://doi.org/10.1016/j.patrec.2005.10.010

Fawcett, T. (2006b). ROC graphs with instance-varying costs. *Pattern Recognition Letters*, *27*(8), 882–891. https://doi.org/10.1016/j.patrec.2005.10.012

Garnett, P. J., & Treagust, D. F. (1992). 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. https://doi.org/10.1002/tea.3660290204

Gerçek, C. (2018). Prospective teachers' cognitive structures concerning protein synthesis and their degree of understanding. *Journal of Baltic Science Education*, 17(1), 19–30. https://dx.doi.org/10.33225/jbse/18.17.19

Goes, L. F., & Fernandez, C. (2020). Limitations of teaching and learning redox: a systematic review. *Problems of Education in the 21st Century*, *78*(5), 698–718. https://dx.doi.org/10.33225/pec/20.78.698

Hatano, G., Inagaki, K., Stevenson, H. W., Azuma, H., & Hakuta, K. (1986). Child development and education in Japan. *Two Courses of Expertise*, 262–272. http://hdl.handle.net/2115/25206

Ioannidis, K., Chamberlain, S. R., Treder, M. S., Kiraly, F., Leppink, E. W., Redden, S. A., ... & Grant, J. E. (2016). Problematic internet use (PIU): associations with the impulsive-compulsive spectrum. An application of machine learning in psychiatry. *Journal of Psychiatric Research*, *83*, 94–102. https://doi.org/10.1016/j.jpsychires.2016.08.010

Jaber, L. Z., & BouJaoude, S. (2012). A macro–micro–symbolic teaching to promote relational understanding of chemical reactions. *International Journal of Science Education*, *34*(7), 973–998. https://doi.org/10.1080/09500693.2011.569959

Jiang, S., Huang, X., Sung, S. H., & Xie, C. (2023). Learning analytics for assessing hands-on laboratory skills in science classrooms using Bayesian network analysis. *Research in Science Education*, *53*(2), 425–444. 10.1007/s11165-022-10061-x

Kampourakis, K. (2018). On the meaning of concepts in science education. *Science & Education*, *27*, 591–592. https://doi.org/10.1007/s11191-018-0004-x

Kurt, H. (2013a). Determining biology teacher candidates' conceptual structures about energy and attitudes towards energy. *Journal of Baltic Science Education,* 12(4), 399–423. https://dx.doi.org/10.33225/jbse/13.12.399

Kurt, H. (2013b). Turkish student biology teachers' conceptual structures and semantic attitudes towards microbes. *Journal of Baltic Science Education,* 12(5), 608–639. https://dx.doi.org/10.33225/jbse/13.12.608

Laliyo, L. A. R., Botutihe, D. N., & Panigoro, C. (2019). The development of two-tier instrument based on distractor to assess conceptual understanding level and student misconceptions in explaining redox reactions. *International Journal of Learning, Teaching and Educational Research*, *18*(9), 216–237. https://doi.org/10.26803/ijlter.18.9.12

Lee, J., & Corter, J. E. (2011). Diagnosis of subtraction bugs using Bayesian networks. *Applied Psychological Measurement*, *35*(1), 27–47. https://doi.org/10.1177/0146621610377079

Leighton, J. P., Gierl, M. J., & Hunka, S. M. (2004). The attribute hierarchy method for cognitive assessment: A variation on Tatsuoka's rule-space approach. *Journal of Educational Measurement*, *41*(3), 205–237. https://doi.org/10.1111/j.1745-3984.2004.tb01163.x

Leighton, J. P., & Gierl, M. J. (2007). Defining and evaluating models of cognition used in educational measurement to make inferences about examinees' thinking processes. *Educational Measurement: Issues and Practice*, *26*(2), 3–16. https://doi.org/10.1111/j.1745-3992.2007.00090.x

Lin, H., Qian, Y., Wen, J., & Mai, Y. (2022). Utilizing multidimensional scaling to represent the conceptual structures of atomic structure in upper-secondary school teachers and students. *Journal of Baltic Science Education*, 21(3), 481–494. https://dx.doi.org/10.33225/jbse/22.21.481

Lu, S., Bi, H., & Liu, X. (2018). The effects of explanation-driven inquiry on students' conceptual understanding of redox. *International Journal of Science Education*, *40*(15), 1857–1873. https://doi.org/10.1080/09500693.2018.1513670

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Masykuri, M., & Afifa, F. N. (2019, December). Students' misconceptions on basic concept of redox reaction. In *The 2nd International Conference on Science, Mathematics, Environment, and Education* (Vol. 2194, No. 1, p. 020062). https://doi.org/10.1063/1.5139794

Martin, J., & VanLehn, K. (2012). A Bayesian approach to cognitive assessment. In Paul D. Nichols, Susan F. Chipman, Robert L. Brennan, *Cognitively diagnostic assessment* (pp. 141–165). Routledge. https://doi.org/10.4324/9780203052969

Meuser, M., Nagel, U. (2009). The expert interview and changes in knowledge production. In: Bogner, A., Littig, B., Menz, W. (eds) *Interviewing Experts. Research Methods Series.* (pp. 17–42). Springer. https://doi.org/10.1057/9780230244276_2

Mi, Q. (2021). Cognitive diagnosis of high school set content based on DINA model. Doctoral dissertation, Central China Normal University. China. https://doi.org/10.27159/d.cnki.ghzsu.2021.001781

Mi, S., Lu, S., & Bi, H. (2020). Trends and foundations in research on students' conceptual understanding in science education: a method based on the structural topic model. *Journal of Baltic Science Education*, *19*(4), 551–568. https://dx.doi.org/10.33225/jbse/20.19.551

Mintzes, J. J., Wandersee, J. H., & Novak, J. D. (Eds.). (2005). *Assessing science understanding: A human constructivist view*. Academic Press.

Morgan, D. L., Krueger, R. A., & King, J. A. (1998). *The focus group guidebook*. Sage.

Nakiboglu, C. (2008). Using word associations for assessing non major science students' knowledge structure before and after general chemistry instruction: the case of atomic structure. *Chemistry Education Research and Practice*, *9*(4), 309–322. https://doi.org/10.1039/B818466F

O. Nyumba, T., Wilson, K., Derrick, C. J., & Mukherjee, N. (2018). The use of focus group discussion methodology: Insights from two decades of application in conservation. *Methods in Ecology and Evolution*, *9*(1), 20–32. https://doi.org/10.1111/2041-210X.12860

Ortiz Nieves, E. L., Barreto, R., & Medina, Z. (2012). JCE classroom activity# 111: Redox reactions in three representations. *Journal of Chemical Education*, *89*(5), 643–645. https://doi.org/10.1021/ed100694m

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), 825–838.
https://doi.org/10.1002/tea.3660200905

Osborne, R. J., & Gilbert, J. K. (1980). A method for investigating concept understanding in science. *European Journal of Science Education*, *2*(3), 311–321. https://doi.org/10.1080/0140528800020311

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*(3), 182–192. https://doi.org/10.1039/C005467B

Øyehaug, A. B., & Holt, A. (2013). Students' understanding of the nature of matter and chemical reactions–a longitudinal study of conceptual restructuring. *Chemistry Education Research and Practice*, *14*(4), 450–467. https://doi.org/10.1039/C3RP00027C

Pearl, J. (1988). *Probabilistic reasoning in intelligent systems: networks of plausible inference*. Morgan kaufmann.

Plummer, J. D., & Krajcik, J. (2010). Building a learning progression for celestial motion: Elementary levels from an earth-based perspective. *Journal of Research in Science Teaching*, *47*(7), 768–787. https://doi.org/10.1002/tea.20355

Primastuti, M., & Priyambodo, E. (2018). Profile of students' cognitive ability in chemistry learning using chemistry systemic multiple choice questions (CSMCQs). *EDUCATUM Journal of Science, Mathematics and Technology*, *5*(2), 57–64. https://doi.org/10.37134/ejsmt.vol5.2.7.2018

Rosenthal, D. P., & Sanger, M. J. (2013). How does viewing one computer animation affect students' interpretations of another animation depicting the same oxidation–reduction reaction?. *Chemistry Education Research and Practice*, *14*(3), 286–296. https://doi.org/10.1039/C3RP00006K

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. https://doi.org/10.1039/C2RP20048A

Schroeder, N. L., Nesbit, J. C., Anguiano, C. J., & Adesope, O. O. (2018). Studying and constructing concept maps: A meta-analysis. *Educational psychology review*, *30*, 431–455. https://doi.org/10.1007/s10648-017-9403-9

Şekerci, A. R., & Erdem, A. R. (2022). The development and implementation of a two-tier multiple choice test related to the concepts of oxidation-reduction reactions and galvanic cells. *Journal of Educational Sciences & Psychology*, *12*(1). https://doi.org/10.51865/jesp.2022.1.05

Sen, S., & Cohen, A. S. (2021). Sample size requirements for applying diagnostic classification models. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.621251

Shi, G. (2024). Research on the chemistry curriculum content system and learning progressions of the big ideas of matter in middle school. Doctoral dissertation, Shandong Normal University, China. https://doi.org/10.27280/d.cnki.gsdsu.2024.000006

Silaban, L. P., Riris, I. D., Muchtar, Z., Ginting, E., & Nasution, H. A. (2024). Analysis of student misconceptions using a web-based diagnostic test on redox material. *Jurnal Teknologi Pendidikan: Jurnal Penelitian dan Pengembangan Pembelajaran*, *9*(2), 185–192. https://doi.org/10.33394/jtp.v9i2.11102

Silverstein, T. P. (2011). Oxidation and reduction: too many definitions? *Journal of Chemical Education*, *88*(3), 279–281. https://doi.org/10.1021/ed100777q


https://doi.org/10.33225/jbse/24.23.1243

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Singh, A., & Babbar, S. (2018). Detecting internet addiction disorder using Bayesian networks. In *Data Science and Analytics: 4th International Conference on Recent Developments in Science, Engineering and Technology, REDSET 2017, Gurgaon, India, October 13-14, 2017, Revised Selected Papers 4* (pp. 80–95). Springer Singapore. https://doi.org/10.1007/978-981-10-8527-7_8

Snow, R. E., & Lohman, D. F. (1989). *Implications of cognitive psychology for educational measurement*. American Council on Education.

Sorrel, M. A., Escudero, S., Nájera, P., Kreitchmann, R. S., & Vázquez-Lira, R. (2023). Exploring approaches for estimating parameters in cognitive diagnosis models with small sample sizes. *Psych*, *5*(2), 336–349. https://doi.org/10.3390/psych5020023

Stains, M., & Talanquer, V. (2008). Classification of chemical reactions: Stages of expertise. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *45*(7), 771–793. https://doi.org/10.1002/tea.20221

Tang, W., Qian, Y., Wang, H., Wen, J., Huang, J., Zhu, X., & Wang, Y. (2024). Students' conceptual structures regarding redox reaction: combining multidimensional scaling and hierarchical cluster analysis approaches. *Journal of Baltic Science Education*, *23*(1), 164–174. https://doi.org/10.33225/jbse/24.23.164

Tang, W., Zhu, X., & Qian, Y. (2022). Applying factor analysis for assessing knowledge structure of students in Grade 10: The subject of redox reaction. *Journal of Baltic Science Education*, *21*(4), 680–693. http://dx.doi.org/10.33225/jbse/22.21.680

Tasci, G., & Yurdugul, H. (2017). Biology teaching through self-regulated learning and cognitive structure: An analysis of the effect of learning strategies for cognitive development via latent growth model. *Journal of Baltic Science Education*, *16*(1), 20–31. http://dx.doi.org/10.33225/jbse/17.16.20

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education*, *2*, 53. https://doi.org/10.5116/ijme.4dfb.8dfd

Todd, A., Romine, W., Sadeghi, R., Cook Whitt, K., & Banerjee, T. (2022). How do high school students' genetics progression networks change due to genetics instruction and how do they stabilize years after instruction? *Journal of Research in Science Teaching*, *59*(5), 779–807. https://doi.org/10.1002/tea.21744

Treagust, D. F. (2006). Diagnostic assessment in science as a means to improving teaching, learning and retention. In *Proceedings of The Australian Conference on Science and Mathematics Education*. https://openjournals.library.sydney.edu.au/IISME/article/view/6375

Trnova, E., & Trna, J. (2015). Formation of science concepts in pre-school science education. *Procedia-Social and Behavioral Sciences*, *197*, 2339–2346. https://doi.org/10.1016/j.sbspro.2015.07.264

Von Soest, C. (2023). Why do we speak to experts? Reviving the strength of the expert interview method. *Perspectives on Politics*, *21*(1), 277–287. https://doi.org/10.1017/S1537592722001116

Wafa, M. N., Hussani, S. A. M., & Pazhman, J. (2020). Evaluation of students' mathematical ability in afghanistan's schools using cognitive diagnosis models. *Eurasia Journal of Mathematics, Science and Technology Education*, *16*(6). https://doi.org/10.29333/ejmste/7834

Wang, C., & Gierl, M. J. (2011). Using the attribute hierarchy method to make diagnostic inferences about examinees' cognitive skills in critical reading. *Journal of Educational Measurement*, *48*(2), 165–187. https://doi.org/10.1111/j.1745-3984.2011.00142.x

Wang, L. L., Jian, S. X., Liu, Y. L., & Xin, T. (2023). Using Bayesian networks for cognitive assessment of student understanding of buoyancy: A granular hierarchy model. *Applied Measurement in Education*, *36*(1), 45–59. https://doi.org/10.1080/08957347.2023.2172014

Wong, C. L., Chu, H. E., & Yap, K. C. (2020). A framework for defining scientific concepts in science education. *Asia-Pacific Science Education*, 6(2), 615–644. https://doi.org/10.1163/23641177-BJA10010

Zou, X., & Yue, W. L. (2017). A bayesian network approach to causation analysis of road accidents using netica. *Journal of Advanced Transportation*, *2017*(1), 1–18. https://doi.org/10.1155/2017/2525481

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

**Appendix**

Two-way Checklist of the Test Instrument

| Item explore patterns | Item |
|---|---|
| $I_2$ | 1、2 |
| $I_3$ | 3、4、5 |
| $I_4$ | 6、7、8 |
| $I_5$ | 9、10、11 |
| $I_6$ | 12、13、14 |
| $I_7$ | 15、16、17、18 |
| $I_8$ | 19、20、21、22 |
| $I_9$ | 23 |
| $I_{10}$ | 24、25 |

Additionally, since the test items were sourced from multiple literatures, when the researcher sought authorization to employ the scale, the authors offered the following elucidation on the usage prerequisites through a subsequent email response:

**Declaration on the Use of ROXCI**

(1) Neither the scale nor any of the items in the scale can be placed on the website without being secured to prevent downloading or printing by unauthorised means.
(2) Students are not allowed to keep copies during the test-taking process.
(3) No items or answers are allowed to be mailed over the Internet.
(4) If the instrument or any of the items are shared, students will find it and our work will be wasted because none of us want to measure students on a test they have taken.

Therefore, the full test items for this study are not available at this time. They can be obtained by contacting the authors if required.

Received: *September 14, 2024* Revised: *October 02, 2024* Accepted: *December 04, 2024*

Cite as: Qi, M., Hu, X., & Bi, H. (2024). Using Bayesian networks for cognitive diagnosis assessment of upper-secondary school students understanding in redox reaction. *Journal of Baltic Science Education*, *23*(6), 1243–1265. https://doi.org/10.33225/jbse/24.23.1243

***Min Qi***
Master of Pedagogy Student, Shandong Normal University, No.88, East Wenhua Road, Lixia District, Jinan City, Shandong Province, P. R. China.
E-mail: coconut726@126.com
ORCID: https://orcid.org/0009-0002-4811-5694

***Xinyang Hu***
PhD, Assistant Professor, Shandong Normal University, No.88, East Wenhua Road, Lixia District, Jinan City, Shandong Province, P. R. China.
E-mail: huxinyang_sdnu@163.com
ORCID: https://orcid.org/0000-0002-8861-2567

***Hualin Bi***
*(Corresponding author)*
PhD, Professor, Shandong Normal University, No.88, East Wenhua Road, Lixia District, Jinan City, Shandong Province, P. R. China.
E-mail: bihualin@sdnu.edu.cn
ORCID: https://orcid.org/0000-0002-2244-4839