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Theoretical Foundations for Understanding Students' Misconceptions in Chemistry

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Abstract

Misconceptions in chemistry remain a significant obstacle to students' conceptual understanding and academic success. The increasing misconceptions needs investigative research efforts for developing targeted interventions to improve students' learning and conceptual clarity in chemistry. This paper highlights a theoretical framework which includes the pre-existing theory, concepts, and definitions of the origins and nature of these misconceptions that researchers will need to collect relevant data for their research and offer meaningful empirical findings. The paper integrates several theories like threshold theory, zone of proximal development, constructivist framework, cognitive load theory, cognitive conflict theory and alternative concept framework examine how students develop, reinforce, and resist modifications to their preconceived notions as students' previous knowledge, intuitive reasoning, and life experiences can conflict with formal scientific concepts, leading to robust but scientifically inaccurate understandings.

Key words: *Misconceptions, Alternative Concepts, Chemistry, Theoretical Foundations*

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Introduction

Misconceptions in chemistry have become the focus of research in the literature, embracing a wide range of topics in chemical education. Despite this enormous amount of knowledge, efforts to properly conceptualize the nature, origins, and treatment of such errors are still scattered. The lack of an overarching theoretical paradigm stifles both instructional efficacy and research progress in chemistry education. The theoretical framework provides a concrete view of the topic, acting as a bridge between the theoretical perspectives with data collection and data analysis strategy, also offering a structure to organize & interpret the data. The theoretical framework acts as a contextualized guide in forming the research questions and objectives. By determining the theories that are specified for the research, the theoretical framework shapes the nature and direction of the study. Particular variables or concepts that the researcher examines in his study. It articulates a strategic framework that aligns the requirement of data a researcher needs to collect and serves a structure to interpret the collected data. Theoretical frameworks connect the study to the base of knowledge and specify the key terms. It also helps to identify the research gaps of the study. In essence, careful and thorough outlining of structure of the theoretical frameworks, help the researcher to effectively utilize the data in the research which ensures a solid foundation for the research study. Misconceptions are prevalent issue in chemistry education, significantly hindering student's ability to grasp fundamental concepts (Johnstone, 2000). The abstract nature of chemistry subject is a considerable challenge for many students as it requires them to visualize and understand phenomena that are not really visible ((Nufus & Silfianah, 2023). Addressing misconceptions can lead to improved learning outcomes and a deeper grasp of chemistry

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(Islamiyah et al., 2022). Many theoretical frameworks have been found to study misconceptions in chemistry. Constructivism provides a useful theoretical framework for understanding how students develop their knowledge in chemistry. Constructivist theory states that students actively construct their own understanding of the world based on their previous experiences and interactions with their surroundings (Taber, 2000). Conceptual change theories highlight the need to restructure old knowledge to accommodate new information (Treagust & Duit, 2008). Ausubel's idea of meaningful learning emphasizes the importance of relating new concepts to existing knowledge (Mossi & Júnior, 2022). According to Ausubel, learning is meaningful when students can apply new information to their existing cognitive framework. Considering students' mental models and thinking processes is crucial in understanding and addressing misconceptions in chemistry ((Lin & Chiu, 2007; Lajium, 2013). Mental models are mental representations of reality that people employ to reason and predict. Students' mental models of chemical concepts may be incomplete, erroneous or inconsistent with scientific principles (Coll, 2006). These incorrect mental models can lead to misunderstandings and hinder comprehension (Chittleborough, 2004). In the present study, several theories which are related to misconceptions are exemplified. As mentioned in Figure 1, this is classified into six types as (i) Threshold Theory (ii) Zone of Proximal Development (iii) Constructivist Framework (iv) Cognitive Load Theory (v) Cognitive Conflict Theory and (vi) Alternative Concept Framework.

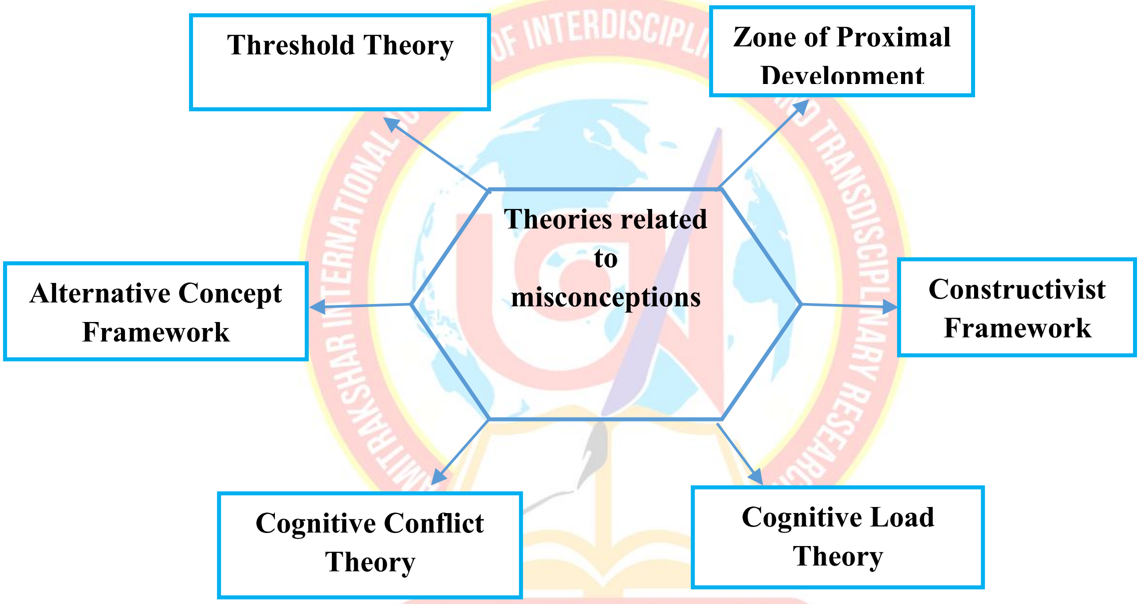

Figure 1. Theories Related to Misconceptions

Objectives of the Study

The objectives of the study are:

1. To examine the theoretical foundations providing the origins and persistence of students' misconceptions in chemistry.

2. To explore how the integration of theoretical foundations help developing instructional strategies to eradicate the common misconceptions of the students in chemistry.

Methodology

In this study a META (Merging Evidences To Aggregate) framework of diverse theories have been undertaken to understand the misconceptions of students in chemistry. The different theories explaining the nature of misconceptions is presented in the subsequent sections.

Learning Theories for Identifying Misconceptions

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Threshold Theory

A new perspective on students' conceptual understanding has been introduced through recent works in the area of 'threshold concepts. The perception of threshold concept was introduced by Meyer and Land (2003). A theory argues that the belief of a threshold concept may act as a catalyst, drawing together a variety of fields of research in a productive educative framework. To illustrate these arguments, the case of introductory accounting to draw on prior research can be established and educational practices can be considered to review within a threshold concept framework (Lucas & Mladenovic, 2007). Meyer & Land (2006) found five main aspects of the threshold concept tentatively related to misconception were proposed. Firstly, it is transformative. In other words, it signifies a vital shift in the perception of a subject. Secondly, it is probably irreversible, and it cannot be unlearned. Thirdly, it is integrative in that it exposes the previously hidden interrelatedness of a context. Fourthly, it may represent a point at which the student would move generally outside of the discipline. Lastly, it may be troublesome to the students sometimes as counter-intuitive or incoherent (lacking an obvious organizing principle) nature. Theories propose over threshold concepts which are the essential ideas which must be grasped for students to advance their understanding of particular topics. On the other hand, troublesome knowledge is that the knowledge which students find counter-intuitive and which stands as a barrier to their ability to grasp threshold concepts and thus lead to formation of misconceptions (Bampton, 2011). It has been proved to be a fruitful and generative idea that it has rapidly led to a lively discussion on the nature of a threshold concept within a variety of disciplines. This debate is evidenced in a publication (Meyer & Land, 2006). It can easily be understood that arriving at a clear view of a concept may involve a process of working through a range of misconceptions about a particular phenomenon or experience that may or may not create a threshold experience in a learner. The journey through conceptual change and thresholds requires a more nuanced stress on liminal spaces, where misconceptions and thresholds may reside together (Lewis et al., 2018). Some theories introduced the basic idea that in certain contexts there are 'conceptual gateways' or 'portals' that lead to a transformed view of something especially when such thresholds have been crossed. Or it may be that one sees features in a familiar landscape that were previously not discernible (Meyer & Land, 2006).

Zone of Proximal Development

In 1978, Vygotsky stated the socio-historical approach to cognitive development which provides the underpinning for social constructivism. Vygotsky is known as the father of the "Zone of Proximal Development (ZPD)" theory who asserts about a student who can do with the presence of helping aids or assistance (Silalahi, 2019). Traditionally, a child's ZPD is defined as the gap between their current level of development and their ability to do tasks independently (Figure. 2). The level of a child's potential development is assessed by its ability to complete tasks under adult supervision (Vygotsky, 1991).

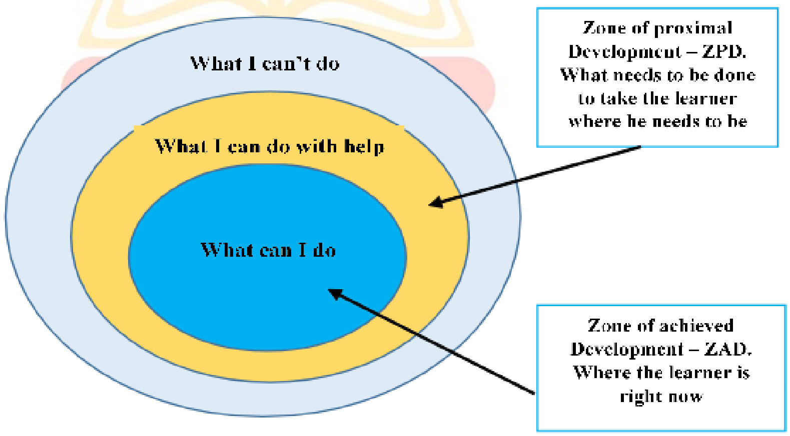

Figure 2. Schematic diagram of ZPD

According to Hausfather, (1996), the work of Vygotsky on ZPD in relation to students' alternative concepts is mainly distinguished by three themes: (1) the best possible way to understand a context is to look at how it changes (2) higher mental functions have their origins in social activity and (3) higher mental functions are mediated by tools and signs.

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Cognitive changes can take place in the Zone of Proximal Development given a shared purpose and focus. Three main Vygotskian ideas are explored in relation to young children's learning of proper concepts of science through the ZPD. All of the ideas highlight the importance of including a contextual framework in which to situate children's early learning of science, much of which currently consists of experiential manipulation. Vygotsky's ideas specifically aim at improving both children's conceptions in primary science and their development of misconceptions along with scientific concepts (Murphy, 2012). The major reason for the development-generating effect of properly organized school instruction relates to students' acquisition of "scientific concepts," which can be contradicted with "spontaneous concepts" of students (Vygotsky, 1978, 1986). Vygotsky also emphasized that learning in the ZPD is enhanced by helping the students' decontextualized concepts within a specific discipline (Zeuli, 1986). A theory proposes a computational approach to model the ZPD using almost predicted probabilities of correctness about a particular topic. The concept of the "Grey Area" has been introduced here, i.e., the area of uncertainty in which the students are unpredictable with acceptable accuracy that whether a student is able to give a correct answer without support or not (Chounta, et al., 2017). It has been observed that the problem of misconceptions has become more crucial when it comes to acquire scientific concepts. According to this theory on ZPD in relation to misconceptions of students, science students are found to use complex content and technical terms in the presence of a more knowledgeable person and thus to identify their misconceptions in a certain part becomes easier (Akram, 2016).

Constructivist Framework

Constructivism according to Piaget (1971) is a system of explanation of how learners as individuals adapt and refine knowledge. Constructivism is a learning theory found in psychology which explains how people might acquire knowledge and learn. Conceptual understanding of the theory is needed as the basic characteristic of constructivists learning environment (Bada & Olusegun, 2015). The latest catchword in educational circles is "constructivism," applied both to learning theory and to epistemology on how people learn, and on the nature of knowledge (Hein, 1991). Many teachers assume that new learning will occur if new information is imparted and the student is paying attention and is motivated. In other words, learning is the result of teaching. Sewell (2002), in his study stated that the constructivist learning theory maintains that learning is not the result of teaching rather it is the result of what students do with the new information they are presented with. Students have often been viewed as holding flawed ideas that are strongly held, that interfere with learning, and that instruction must confront and replace. A constructivist theory of learning that interprets students' prior conceptions as resources for cognitive growth within a complex systems view of knowledge which might lead to formation of misconceptions sometimes (Smith et al., 1994). If we take the example of chemistry, electrochemistry has been considered as a difficult topic for students to learn. It developed research to generate a constructivist model to encounter hindrances in conceptualizing this as language misconceptions, prior knowledge overgeneralizations and visualization errors after identifying electrochemistry misconceptions (Akram, 2016). According (Panasuk & Lewis, 2012), some found it "radical" whereas some called it a "power model", but some expressed concern about it as the most dangerous intellectual tendency of this framework Much of the works related to constructivist framework have focused on the school sectors, where there have been major projects such as LISP (Learning in Science Project) in New Zealand (Osborne & Freyberg, 1985) and in the U.K., CLISP (Children's Learning in Science Project), and SPACE (Science Processes and Concept Exploration). These projects have examined a range of topics: for example, SPACE (focusing on primary school science) has produced a report on pupils' misconceptions about materials (Klahr, 2001) has looked at the understanding along with misconceptions of elementary ideas in chemistry (Windschitl et al., 2008).

Cognitive Load Theory

Cognitive Load Theory (CLT) is considered as one of the most important theories in educational psychology, a highly effective guide for the design of research related to several aspects including misconceptions and alternative conceptions. Cognitive load theory has been very significant framework in educational psychology during the last decade which provides guidelines for instructional designs. Lots of empirical studies have used it as a theoretical framework (Schnotz & Kürschner, 2007). Cognitive Load Theory is based on the model of human information processing. This model describes memory as having three main parts: sensory, working, and long-term. Sensory memory filters out most of what is going on around us, passing selective information on to our working memory for additional processing. Working memory can typically process 5-9 pieces, or chunks, of information at any given time. Our working memory either discards the information or categorizes it for storing in our long-term memory (Atkinson

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& Shiffrin, 1968). The theory assumes that knowledge can be divided into biologically primary knowledge that we have evolved to acquire and biologically secondary knowledge that is important for cultural reasons. Secondary knowledge, unlike primary knowledge, is the subject of instruction (Sweller, 2011). Whereas numerous empirical studies have used it as a theoretical framework, a closer analysis reveals some fundamental conceptual problems within the theory. Various generalizations of empirical findings become questionable because the theory allows different and contradicting possibilities to explain some empirical results (Schnotz & Kürschner, 2007). It has been outlined how CLT is evolved and presented a synthesis of current-day CLT principles in a holistic model for designing the identification of wrong scientific concepts among learners. This model distinguishes three dimensions - task fidelity: from literature i.e. lowest through simulated learners to real learners i.e. highest, task complexity: the number of information elements; and instructional support: from worked examples i.e. highest through completion tasks to autonomous task performance i.e. lowest (Leppink & Van Den Heuvel, 2015).

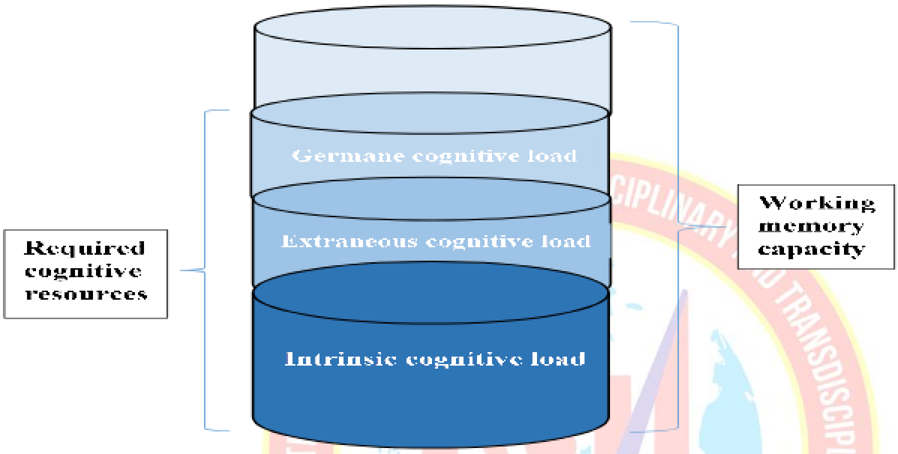

Figure 3. Schematic Diagram of Cognitive Load Theory

According to cognitive load theory, instructions can be imposed three types of cognitive load on the learner: intrinsic load, extraneous load, and germane load (Figure.3). Proper measurement of these different types of cognitive load can help us to understand why the effectiveness and efficiency of learning may differ as a function of instructional formats and learner characteristics which leads to formation of misconceptions among learners (Sweller et al, 1988; Leppink et al., 2013 and Krieglstein et al., 2022). Some studies reveal new insights into learning about natural selection by outlining the complex interplay between situated learning, cognitive load, clarification of misconceptions, and contextual reasoning. Additionally, it advises researchers and educators on potential instructional strategies (Aptyka et al., 2022).

Cognitive Conflict Theory

The "Cognitive Conflict (CC)" theory was given by Festinger in 1952. According to CC theory (Festinger, 1957) "If one belief, knowledge, or attitude needs the opposite of another belief, knowledge, or attitude that a person holds, there is a CC between those two beliefs, knowledge, or attitude". In accordance with this theory, the person will be motivated to eliminate this conflict on the basis of CC (Kaya, 2011). Cognitive Conflict is based on the theory of the constructivist approach. One of the explorers of cognitive structuralism, Piaget, elaborates learning in adaptation, assimilation, and balancing processes. If the new information does not conflict with the individual's previous knowledge, it is accepted, and a new cognitive balance is established. If the new information contradicts previous knowledge, confusion, an imbalance happens due to the new information cannot be merged into the existing structure. The individual tugs to eradicate this imbalance. By adapting to this situation, one understands that he is confronted with new learning and creates a new cognitive structure (Powell & Kalina, 2009). CC is regarded as one of the traditional models of conceptual change strategies (Hewson & Hewson, 1984). CC is a vital stage of conceptual change. The student experiences dissatisfaction when the student observes that the information which the student

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believes to be true is incompatible with scientific knowledge (Posner et al., 1982). Nonetheless, the students' intentions to deal with CC and finding a solution are not uniform. It is difficult for all students to reach a remarkable Cognitive Conflict state (Chan et al., 1997). As each student's alternative conceptions are different, and the self-management and diversity limit of students gets transitioned from one body of knowledge to another, i.e., conceptual change. To overcome misconceptions, conceptual change strategies should make students understand that they are having misconceptions. For this reason, creating Cognitive Conflict is a very important condition to go through conceptual changes (Lee et al., 2003). The first step in learning a context with CC is always to find and identify followed by activating alternative concepts among students (Başer, 2006). A misconception is the most important aspect in science learning activities and Cognitive Conflict is the condition where there is a mismatch between the cognitive structures that a person regarding information. The signs of Cognitive Conflict can be stated as uncertainty, doubt, confusion, contradiction, contrary and conflict (Haryono et al., 2021). Cognitive Conflicts that occur amongst students are included in the high and very high categories, and some theories show that students' experience and some thought processes while dealing with Cognitive Conflict approach. This helps students to change their conceptions from initially formed misconceptions to understanding right scientific concepts (Makhrus & Busyairi, 2022). The implications of a research theory have been found as this has smart syntaxes. For e.g., like activation of previous misconception along with presentation of Cognitive Conflict which are having advantages to identify misconceptions. Besides it can enhance the students' conceptual understanding (Mufit et al., 2023).

Alternative Concept Framework

An alternative conceptual framework is a type of conceptual framework or a topic that is judged as being alternative to (inconsistent with) canonical accounts of a topic-often because it includes one or more alternative concepts. The term 'framework' suggests a basic structure which supports and gives shape (Muradian et al., 2010). The term alternative framework has been used as the organization of alternate ideas rather than the ideas generated by themselves, so that alternative frameworks are considered as just the under girders that anchor ideas (Abimbola, 1988). The terms "alternative framework" and "misconceptions" are commonly used interchangeably (Seligin, 2012). As illustrated in Figure 4, their meanings differ slightly.

Figure 4. Alternative Framework (AF) Position and Misconceptions.

The idea of alternative concept framework is well established particularly since the appearance of two seminal papers published one-and-a-half decades ago (Driver & Erickson, 1983). However, this theory has more recently found objects questioning the existence of such frameworks (Kuiper, 1994). The term alternative frameworks were specified for particular situation in which learners have well developed autonomous frameworks to conceptualize their different kinds of experience regarding the physical world (Driver & Easley, 1978). Later, it was also explained that the ACFs are alternative in true sense in those cases where "the accepted theory may be counter-intuitive with students' own beliefs and expectations which differ in significant ways from those to be taught" (Driver, 1983). Figure 5. illustrates how students process new information by forming alternative concept based on their prior knowledge. According to Davy Seligin (2012), students' knowledge of scientific concepts is influenced by their acceptance, rejection, or modification of new information.

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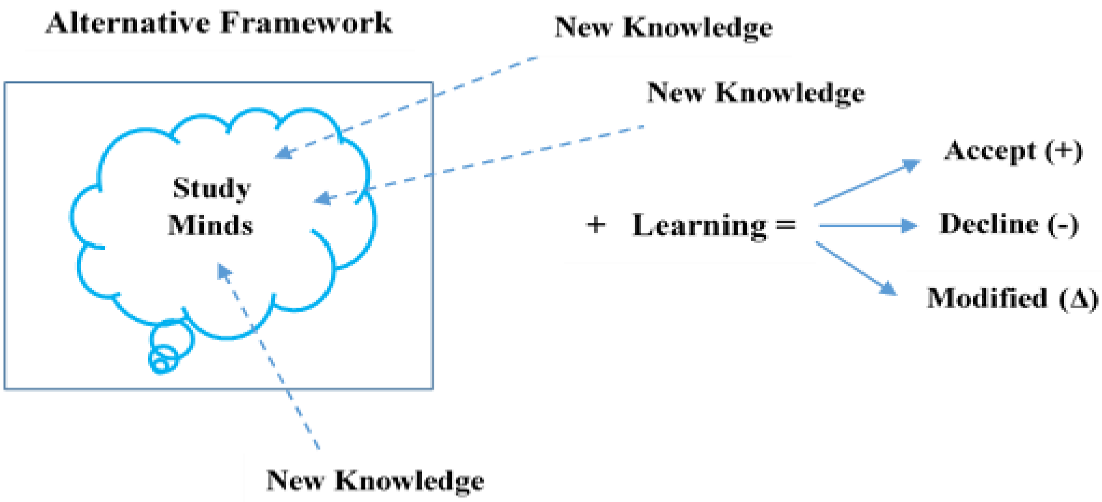

Figure 5. Alternative Framework Imagination and its Position

The conviction of "alternative concept frameworks" could be related closely to George Kelly's (Kelly,1970) "personal construct theory" where the principal emphasis is given upon the distinctiveness of each person's construction along with the construct systems which will continue to evolve in order to bring in meanings of the experiences they have acquired. They considered that alternative frameworks "would be seen as sensible coherent expressions of this cognitive activity" (Pope & Gilbert, 1983). While discussing about learners' concepts in science one needs to distinguish between an individual's cognitive structure (which can only be conjectured), and the researcher's own hypothesis (which can be formally represented in words and diagrams). Dominant difference between cognitive structure and the representation is noticed in theory of conclusion that is a product of the research of a study (Ault et al., 1984). The necessity to differentiate between an individual's psychological, personal, knowledge structure was also emphasized in a theory of alternative concept framework (Gilbert & Watts, 1983). The difference between the structures through which classification in misconception formation and external occurrences as a chief significant distinction takes place, was also observed in study (Lakoff & Johnson, 1980). The identification of misconceptions with schemes seems to reflect students' thought processes as the term "conception" is used usually to indicate a functional unit of thought (Novak, 1985). It has observed that teachers' opinions about Alternative Conceptual Frameworks amongst learners in science have diversity and variations. They seem to accept the changeable nature of science. It is also accepted that the ACFs are the ideas that do not coincide with the scientific views sometimes (Kumar, 2014). A theory has also possessed on making no distinction between conceptions and ideas and using the terms interchangeably while comparing misconceptions with alternative frameworks (Strike & Posner, 1985). In accordance with these, Alternative Conceptual Framework is sometimes thought to be consistent with an approach to investigate the framework in specific research studies elicited by students where misconceptions found to be occurred (Viennot, 1985). An article examined the conceptual framework of some specific theories including its original contextual concepts. This form of representation is a barrier to extending or replacing existing theory as it confuses conceptual and empirical matters. An alternative conceptual framework is proposed to avoid these problems which are more favourable to an integrated systems view of this kind of research study (Noble, 2015).

Discussion

This study presents a comprehensive theoretical foundation to analyse and address students' misconceptions in chemistry by incorporating various educational theories such as threshold theory, zone of proximal development, constructivist framework, cognitive load theory, cognitive conflict theory and alternative concept framework- it provides a comprehensive perspective on how misconceptions develop, endure, and can be changed. Students often arrive in the classroom with intuitive reasoning and past experiences that influence their preliminary comprehensive of chemical process. These preconceptions although significant to learners in context, may contradict established scientific understanding. This study highlights that misconceptions are not merely false beliefs but are frequently logical and resistant to alteration because of cognitive and emotional influences. Each theory makes a distinct

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contribution to understanding this complexity. For example, cognitive conflict theory explains how challenging existing beliefs can lead to conceptual change while cognitive load theory cautions against overwhelming students with too much information at once. Constructivist approaches promote learning environment where students actively engage with knowledge and reconstruct their understanding. Meanwhile threshold theory finds conceptual gateways once grasped, significantly shift student understanding. The zone of proximal development provides a social and developmental lens through which instruction can be tailored to student's capabilities with guidance. By integrating these viewpoints, the framework provides researchers with the means to gather detailed data and deliver richer empirical insights into the processes of learning and unlearning in chemistry among students.

Conclusion

This paper establishes a robust theoretical foundation for understanding students' misconceptions in chemistry by integrating different learning theories. Analysing the roles of students' previous knowledge, intuitive reasoning, and life experiences reveals that misunderstandings are not merely errors, but firmly held, often rational views from the learner's point of view. The integration of multiple educational theories offers a holistic approach to understanding and addressing these misconceptions. Each theory makes a distinct contribution to understanding how students develop, reinforce, and sometime resist changes to their conceptual understanding. Furthermore, the foundations presented in this paper highlights how theoretical ideas can inform practical instructional strategies. Finally, this theoretical foundation researchers and practitioners with useful tools for encouraging deeper learning and facilitating conceptual development in chemistry education.

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