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Integrating radiant thinking with chemical concept formation: a theoretical framework for mind mapping in specialized chemistry education

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HIGHLIGHTS

- Pandemic-disrupted Ukrainian chemistry education inspired a new theoretical teaching framework.
- Four-dimensional model links radiant thinking with chemistry-specific cognitive demands.
- Dimension synergy generates emergent properties for creative and analytical thinking.
- Framework targets teaching challenges for oxygen-containing organic compounds.
- Meta-analytic synthesis of 2020–2025 supports the framework without new empirical data.

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ABSTRACT

This paper presents a theoretical framework integrating radiant thinking principles with chemical concept formation through mind mapping in specialized chemistry education. As a theoretical synthesis, this work does not involve empirical data collection but rather integrates existing literature to address critical pedagogical challenges. The framework emerged from practical teaching experiences during the COVID-19 pandemic in Ukrainian specialized chemistry schools, where hybrid learning conditions, laboratory access limitations, and learning disruptions necessitated innovative visualization strategies for complex chemical concepts. Drawing upon Buzan's radiant thinking theory, Johnstone's triplet (triangle) of chemical representations, and contemporary cognitive load theory, we propose a four-dimensional model encompassing: (1) conceptual radiance – hierarchical knowledge organization from central concepts to peripheral details; (2) representational integration – coordination of macroscopic, submicroscopic, and symbolic domains; (3) creative synthesis – divergent thinking within disciplinary constraints; and (4) metacognitive orchestration – self-regulatory learning processes. The framework's application to oxygen-containing organic compounds demonstrates practical utility in addressing persistent conceptual difficulties, particularly the transition from hydrocarbon to functional group chemistry. Recent meta-analyses (2020-2025) provide empirical support for the framework's components, with guided mind mapping interventions showing strong positive effects on chemistry achievement and conceptual understanding. The synergistic interactions among dimensions create emergent properties that transcend traditional instructional approaches, offering unique affordances for managing cognitive complexity while fostering creative scientific thinking. This theoretical contribution provides pedagogical guidance for chemistry educators facing similar challenges in specialized STEM education contexts globally.

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1. Introduction

The landscape of twenty-first-century chemistry education faces unprecedented challenges that demand innovative theoretical frameworks capable of bridging traditional content mastery with the development of creative scientific thinking. Contemporary chemistry learners, particularly those in specialized STEM schools and advanced programs, require educational approaches that transcend conventional transmission models to foster both deep conceptual understanding and creative problem-solving capabilities (Benny & Blonder, 2018; Smith & Stonequist, 2010). This dual imperative – mastering complex disciplinary content while developing innovative thinking – becomes especially pronounced in organic chemistry, where intricate relationships between molecular structure, chemical properties, and reaction mechanisms demand sophisticated cognitive processing abilities that traditional linear instructional methods often fail to adequately develop (Akkuzu & Uyulgan, 2016; Graulich & Lieber, 2024).

1.1. Genesis of the framework

This theoretical framework emerged not from abstract pedagogical speculation but from acute practical challenges experienced in Ukrainian specialized chemistry schools during the COVID-19 pandemic and subsequent societal disruptions. Beginning in March 2020, chemistry educators faced an unprecedented constellation of instructional challenges: students attended school only on alternating weeks due to hybrid learning schedules, laboratory access became severely restricted, and from 2022 onward, learning was further disrupted by power outages and air raid alerts requiring immediate shelter evacuations (Polunina, 2022). These conditions created a perfect storm of pedagogical challenges, particularly acute in teaching oxygen-containing organic compounds – a topic requiring integration of multiple functional groups, three-dimensional visualization of molecular structures, and understanding of complex reaction mechanisms.

The specific context deserves elaboration: in Ukrainian specialized chemistry schools, tenth-grade students typically encounter oxygen-containing compounds after mastering hydrocarbons, representing a critical conceptual transition. This shift from relatively simple carbon-hydrogen frameworks to molecules containing polar functional groups introduces multiple cognitive demands simultaneously. Students must understand why methanol (CH_3OH) exists as a liquid at room temperature while formaldehyde (CH_2O), with nearly identical molecular weight, exists as a gas – requiring integration of concepts including hydrogen bonding, dipole-dipole interactions, and molecular geometry (Akkuzu & Uyulgan, 2016). Under normal circumstances, this conceptual transition challenges students; under pandemic conditions with fragmented attendance and limited hands-on experimentation, traditional instructional approaches proved wholly inadequate.

These practical challenges motivated the development of visual-spatial organizational tools that could maintain conceptual coherence despite disrupted learning conditions. Mind mapping emerged as a particularly promising approach, offering a means to externalize and organize complex chemical relationships in ways that could bridge temporal gaps in instruction and compensate for limited laboratory experiences. However, existing mind mapping approaches lacked theoretical grounding specific to chemistry's unique representational and cognitive demands, necessitating the development of a comprehensive framework.

1.2. Theoretical motivation

The challenge of teaching organic chemistry, particularly oxygen-containing compounds such as alcohols, ethers, aldehydes, ketones, carboxylic acids, and esters, exemplifies broader tensions in chemistry education. These compounds represent fundamental building blocks in biological systems, industrial processes, and synthetic pathways, yet students consistently demonstrate significant conceptual difficulties in understanding their interconnected nature (Nelson et al., 2015). Research has documented persistent misconceptions about functional group reactivity, struggles with visualizing three-dimensional molecular structures, and difficulties recognizing patterns across different classes of oxygen-containing compounds (Akkuzu & Uyulgan, 2016; Cooper et al., 2010). These challenges are further compounded by the cognitive demands of managing multiple levels of chemical representation simultaneously, as articulated in Johnstone's (1991) triplet of macroscopic, microscopic, and symbolic domains (Talanquer, 2011).

Recent developments in cognitive science and educational psychology have illuminated promising pathways for addressing these pedagogical challenges through visual thinking strategies. Meta-analytic evidence demonstrates the effectiveness of visual learning interventions in chemistry education. Shi et al. (2023) analyzed 21 studies from 2020–2024, finding a moderate to large overall effect size ($d = 0.776$) for mind mapping in STEM achievement, with particularly strong effects in chemistry contexts. Similarly, Anastasiou et al. (2024) examined 55 studies involving 5364 students, revealing substantial effect sizes across science disciplines, with chemistry showing consistent positive outcomes ($d = 0.590$). These findings suggest that visual organizational strategies align well with chemistry's inherently visual and spatial nature.

Mind mapping, as conceptualized through radiant thinking theory (Buzan & Buzan, 1994), offers a particularly compelling approach that mirrors the associative and hierarchical nature of chemical knowledge. The radiant structure of mind maps – where ideas branch outward from central concepts – parallels the branching patterns found in organic chemistry itself, from carbon skeletons of molecules to classification systems of functional groups. This structural resonance suggests untapped potential for mind mapping as a cognitive tool specifically suited to chemistry learning. However, while general mind mapping principles have been applied in various educational contexts, the theoretical foundations for chemistry-specific applications remain underdeveloped (Knysh, 2020; Shi et al., 2023).

1.3. The integration imperative: creativity and content mastery

The integration of creative thinking development with chemistry content mastery represents another crucial yet underexplored dimension of contemporary science education. While creativity has long been recognized as essential for scientific innovation and discovery, chemistry curricula typically compartmentalize creative activities from core content learning. This artificial separation fails to leverage the synergistic potential of combining divergent thinking processes with systematic chemical knowledge construction. Recent neuroscientific evidence supports the integration of creative and analytical thinking. Beaty et al. (2019) demonstrated that creative cognition activates dynamic whole-brain networks, particularly regions associated with visuospatial processing and cognitive control. Bola and Sabel (2015) showed rapid, transient interactions across frontal, temporal, and parietal brain areas during complex knowledge integration tasks, suggesting that effective chemistry learning requires coordinated activation of multiple cognitive systems.

The need for theoretical frameworks that authentically integrate creativity development with rigorous chemistry learning has become increasingly urgent as educational systems worldwide seek to prepare students for careers in rapidly evolving scientific fields where innovation and adaptability are paramount (Aris et al., 2024). The framework presented here addresses this need by proposing a theoretical model that positions creative thinking not as an add-on to chemistry instruction but as integral to deep conceptual understanding.

1.4. Scope and structure of this theoretical contribution

This paper presents a theoretical framework – not an empirical study – that synthesizes existing literature to propose a comprehensive model for integrating radiant thinking with chemical concept formation. Following established principles of theory construction in educational research (Mundy et al., 2024), we integrate perspectives from cognitive science, chemistry education, and creativity research to address identified gaps in current pedagogical approaches. The framework does not report original data collection or experimental results but rather provides a conceptual architecture for understanding and implementing mind mapping in specialized chemistry contexts.

The remainder of this paper is structured as follows: Section 2 establishes the theoretical foundations by examining radiant thinking, chemical representations, and cognitive load theory. Section 3 describes our methodological approach to framework development. Section 4 presents the four-dimensional framework and explicates synergistic interactions among dimensions. Section 5 demonstrates application to oxygen-containing organic compounds. Section 6 examines empirical support from recent meta-analyses and systematic reviews. Section 7 discusses theoretical implications for practice and implementation strategies. Section 8 acknowledges limitations and proposes future research directions. The paper concludes by situating this theoretical contribution within broader efforts to transform chemistry education for the twenty-first century.

2. Theoretical foundations

Before examining the theoretical foundations underlying our framework, it is essential to clarify the nature of this contribution. This paper presents a theoretical framework developed through systematic synthesis of existing literature rather than empirical data collection. No participants were involved, no experiments were conducted, and no original statistical analyses were performed. All empirical evidence cited comes from published studies, with effect sizes and statistical findings attributed to their original sources. This approach follows established precedents for theoretical contributions in educational research, where synthesis and integration of existing knowledge can generate new conceptual models that guide future empirical investigations (Mundy et al., 2024).

2.1. Radiant thinking and creative cognition in chemistry learning

The concept of radiant thinking, as articulated by Buzan and Buzan (1994), provides a fundamental theoretical lens for understanding how the human brain naturally processes and organizes complex information. Radiant thinking posits that human cognition operates through associative networks where central concepts branch outward into increasingly specific details, creating web-like structures of interconnected knowledge. This cognitive architecture bears remarkable similarity to structural patterns inherent in chemistry, particularly in organic compounds where central carbon atoms radiate bonds to create molecular frameworks. The alignment between radiant thinking patterns and chemical structures suggests a natural cognitive-conceptual correspondence with profound implications for chemistry education (Polunina, 2022).

Recent neuroscientific research provides empirical support for radiant thinking principles. Beaty et al. (2019) used network neuroscience approaches to map creative cognition, revealing that creative thinking involves dynamic interactions across distributed brain networks, particularly regions associated with executive control, default mode, and salience processing. These findings align with observations that effective chemistry problem-solving requires simultaneous activation of analytical and creative cognitive processes. He et al. (2025) demonstrated through EEG analysis that high-level cognitive states during learning involve rapid reorganization of brain functional networks, with successful learners showing more flexible network configurations – precisely the type of cognitive flexibility that radiant thinking promotes.

In chemistry learning contexts, radiant thinking manifests through multiple cognitive processes essential for deep understanding. When students encounter new chemical concepts, their minds naturally seek connections to existing knowledge, creating associative links that strengthen retention and facilitate transfer (Bandura, 1977; diSessa et al., 1988). This process becomes particularly evident when learning about functional groups, where students must recognize patterns across different molecular contexts while maintaining awareness of unique properties. Consider the hydroxyl group (−OH): students must understand its presence in alcohols, carboxylic acids, and phenols, yet recognize how surrounding molecular environment modulates its properties. The radiant structure of thought allows simultaneous processing of similarities and differences, enabling learners to construct nuanced mental models capturing both unity and diversity of chemical phenomena (Gilbert & Treagust, 2011).

The relationship between radiant thinking and creative cognition extends beyond simple pattern recognition to encompass higher-order cognitive processes essential for scientific reasoning. Divergent thinking, a cornerstone of creativity, operates through radiant expansion from central concepts to explore multiple possibilities and connections (Gabora et al., 2018). In organic chemistry, this manifests as the ability to envision multiple synthetic pathways, predict various reaction outcomes, and recognize non-obvious relationships between seemingly disparate compounds. Yoon and Kang (2015) demonstrated that students trained in integrated mind mapping showed significantly enhanced creative thinking skills in chemistry problem-solving compared to traditional instruction groups.

2.2. Chemical representations and visual learning theory

Johnstone's triplet of chemical representations has profoundly influenced chemistry education by articulating three interconnected domains through which chemical knowledge is constructed and communicated (Johnstone, 1991). The macroscopic domain encompasses observable phenomena and laboratory experiences; the submicroscopic domain involves molecular and atomic level representations; the symbolic domain includes chemical equations, formulas, and mathematical expressions. Successful chemistry learning requires not only understanding within each domain but also the ability to translate flexibly between them (Talanquer, 2011). Recent research has refined this model, with Xu (2022) proposing that the symbolic domain should be understood as mediating between macroscopic observations and submicroscopic explanations rather than as a separate representational level.

The complexity of coordinating multiple representational levels becomes especially pronounced when teaching organic chemistry. Students learning about oxygen-containing compounds must simultaneously visualize molecular structures that cannot be directly observed, connect these mental models to macroscopic properties like boiling points and solubility, and manipulate symbolic representations including structural formulas and reaction equations (Cheng & Gilbert, 2014). Research consistently shows that students struggle with these representational translations, often developing fragmented understanding where knowledge remains isolated within single domains (Cooper et al., 2010; Philipp et al., 2014).

Visual learning theory, particularly as articulated through dual coding theory and multimedia learning principles, provides essential insights for addressing representational challenges. Paivio (1986) demonstrated that information encoded through both visual and verbal channels creates more robust and accessible memory traces than single-channel encoding. In chemistry education, this principle supports the use of visual tools that combine spatial representations of molecular structures with verbal descriptions of chemical properties and behaviors (Magnone & Yezierski, 2024). Recent work by Kenneally and Bentley (2024) using augmented reality to teach molecular geometry found that students who engaged with both visual and verbal representations showed superior spatial reasoning and conceptual understanding compared to traditional instruction.

Mayer's (2020) cognitive theory of multimedia learning emphasizes the importance of managing essential, extraneous, and germane cognitive load through thoughtful instructional design. In organic chemistry contexts, essential load arises from inherent complexity of molecular structures and reaction mechanisms, while extraneous load often results from poorly organized or confusing presentations (Beier et al., 2024). Mind mapping as a pedagogical tool actively manages both types of cognitive load by providing clear organizational structures that highlight essential relationships while minimizing extraneous processing demands.

2.3. Cognitive load theory and information processing in chemistry

Cognitive load theory provides crucial theoretical foundation for understanding information processing demands inherent in chemistry learning and the potential of visual organizational tools to optimize cognitive resources (Sweller et al., 2011). Chemistry, particularly organic chemistry, presents exceptionally high element interactivity, where multiple concepts must be processed simultaneously and held in working memory to achieve understanding (Baddeley, 2010). The study of oxygen-containing organic compounds exemplifies this challenge, requiring students to coordinate knowledge of electronegativity, molecular geometry, intermolecular forces, acid–base chemistry, and reaction mechanisms within integrated conceptual frameworks.

Recent research has refined our understanding of cognitive load in chemistry contexts. Vo et al. (2025a) found that chemistry students experience highest cognitive load when attempting to integrate procedural knowledge (how to solve problems) with conceptual understanding (why solutions work). This finding suggests that instructional approaches must carefully scaffold the integration of different knowledge types. Mind mapping addresses this challenge by making conceptual relationships explicit while providing procedural pathways through visual organization.

The distinction between intrinsic, extraneous, and germane cognitive load becomes particularly salient when analyzing chemistry learning tasks (Sweller et al., 2011). Intrinsic cognitive load in organic chemistry stems from inherent complexity of molecular systems where numerous variables interact in determining chemical behavior. Understanding the relative acidity of different oxygen-containing functional groups requires simultaneous consideration of electronic effects, resonance stabilization, inductive effects, and solvation phenomena. This intrinsic complexity cannot be eliminated but must be carefully managed through instructional strategies that respect cognitive capacity limitations while maintaining scientific accuracy.

2.4. Empirical support from recent meta-analyses

While this paper presents a theoretical framework rather than empirical findings, recent meta-analyses provide strong support for the framework's foundational assumptions. Shi et al. (2023) conducted a comprehensive meta-analysis of 21 studies examining mind mapping in STEM education from 2020 to 2024, revealing several key findings directly relevant to our framework:

1. Moderate to large effect size ($d = 0.776$) for mind mapping on science achievement
2. Stronger effects for lower-grade students, suggesting the importance of early intervention
3. Chemistry showed particularly strong benefits compared to other sciences
4. Guided mind mapping significantly outperformed unguided approaches

Anastasiou et al.'s (2024) meta-analysis of 55 studies with 5364 participants provided additional insights:

- Effect sizes varied by subject: physics/earth science ($d = 1.040$), biology ($d = 0.671$), chemistry ($d = 0.590$)
- Collaborative mind mapping showed stronger effects than individual work
- Digital tools enhanced effectiveness when properly integrated

These meta-analytic findings converge with neuroscientific evidence. He et al. (2025) used machine learning analysis of EEG data to identify cognitive states during learning, finding that successful learners showed more flexible brain network configurations – precisely what radiant thinking and mind mapping promote. Bola and Sabel (2015) demonstrated that dynamic reorganization of brain functional networks during cognition aligns with the distributed processing that mind mapping facilitates.

3. Methodological approach to framework development

3.1. Clarification of theoretical methodology

This section explicates the systematic methodology employed to develop the theoretical framework presented in this paper. It is crucial to emphasize that this work represents a theoretical synthesis rather than an empirical investigation. No data collection occurred, no participants were recruited, no experiments were conducted, and no statistical analyses of original data were performed. Instead, this framework emerged through systematic integration of existing theoretical perspectives and empirical findings from published literature, following established principles of theory construction in educational research (Mundy et al., 2024).

The absence of empirical data collection is not a limitation but rather a defining characteristic of theoretical scholarship. As Kamoun-Chouk (2025) notes, theoretical frameworks serve essential functions in educational research by synthesizing disparate findings, identifying conceptual relationships, and proposing new ways of understanding pedagogical phenomena. Our approach aligns with this tradition, offering a conceptual architecture that organizes existing knowledge while revealing new possibilities for chemistry education.

3.2. Four-phase framework development process

The development of this theoretical framework followed a systematic four-phase approach, illustrated in Fig. 1. This methodology ensures rigor in theoretical construction while maintaining transparency about the conceptual foundations and synthesis process.

3.2.1. Phase 1: problem identification and contextual analysis

The initial phase emerged from direct pedagogical experience rather than abstract speculation. During the COVID-19 pandemic and subsequent disruptions in Ukraine, the first author (Anna O. Polunina) documented systematic challenges in teaching oxygen-containing organic compounds under hybrid learning conditions. These observations, recorded during teaching practice and student teaching supervision, revealed consistent patterns:

- Fragmentation of conceptual understanding due to interrupted attendance
- Inability to maintain conceptual coherence across multi-week gaps
- Heightened cognitive load from attempting to integrate multiple representation levels without hands-on laboratory experience
- Student requests for visual organizational tools to manage complexity.

Literature review during this phase revealed that while mind mapping had been applied in chemistry education (Knysh, 2020), no comprehensive theoretical framework existed that integrated radiant thinking principles with chemistry-specific cognitive demands. Gap analysis identified three critical absences in existing literature: (1) lack of chemistry-specific adaptations of radiant thinking theory, (2) absence of frameworks addressing synergistic interactions between creative and analytical thinking in chemistry, and (3) no models specifically designed for disrupted or hybrid learning contexts.

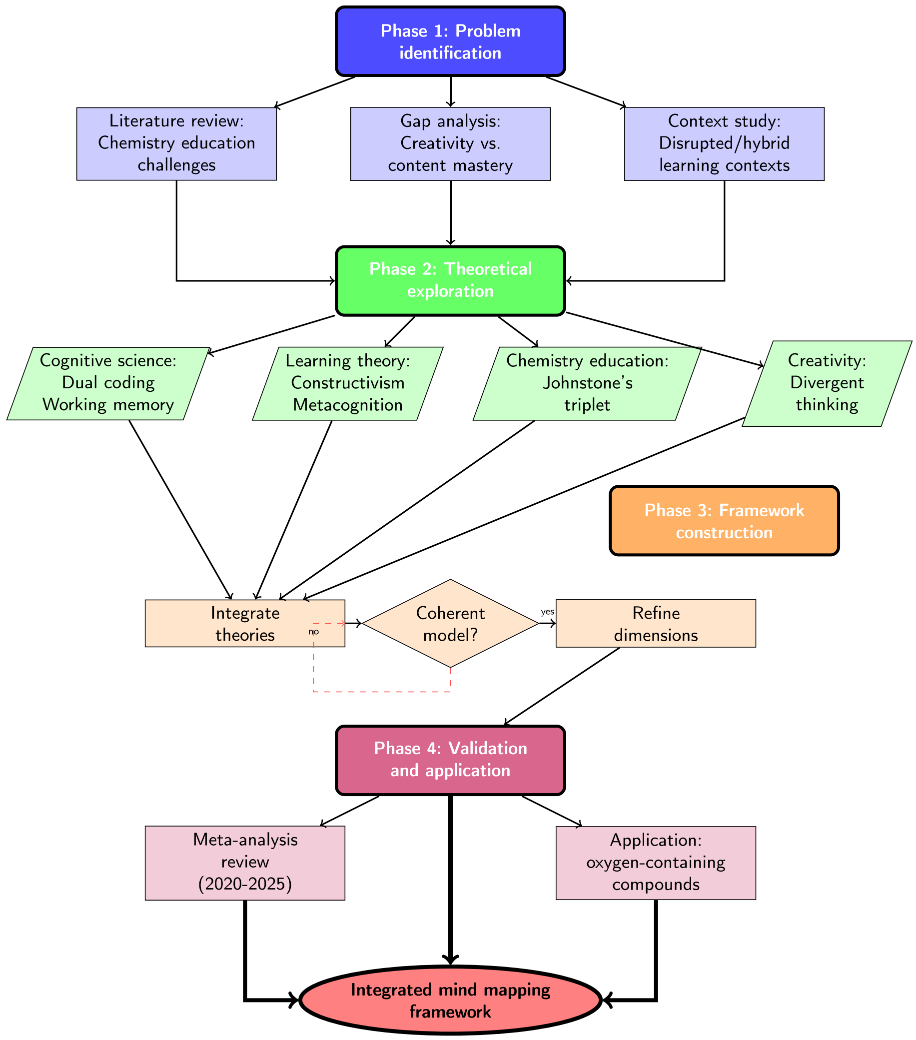

Fig. 1. Systematic methodology for theoretical framework development showing the four-phase approach from problem identification through validation and application.

3.2.2. Phase 2: theoretical exploration and integration

The second phase involved systematic exploration of relevant theoretical perspectives across multiple disciplines. Literature selection followed explicit criteria:

- Foundational theories from cognitive science directly addressing information processing, memory, and learning
- Domain-specific frameworks in chemistry education theories, particularly those addressing representational competence
- Creativity research examining divergent thinking and creative cognition in scientific contexts
- Recent empirical studies including meta-analyses and systematic reviews published 2020–2024

Database searches (Scopus, Web of Science, ERIC) used combinations of keywords: “mind mapping” AND “chemistry education”; “radiant thinking” AND “science learning”; “cognitive load” AND “organic chemistry”; “visual learning” AND “chemical representations”. From initial returns of 847 papers, 126 were selected for detailed analysis based on relevance to theoretical framework development.

Theoretical integration proceeded through iterative cycles of concept mapping – applying the very technique under investigation to organize theoretical perspectives. Key theoretical threads identified included:

- Buzan’s radiant thinking theory (Buzan & Buzan, 1994)
- Johnstone’s triplet of chemical representations (Johnstone, 1991)
- Cognitive load theory (Sweller et al., 2011)
- Dual coding theory (Paivio, 1986)
- Multimedia learning principles (Mayer, 2020)
- Network theories of creative cognition (Beaty et al., 2019).

3.2.3. Phase 3: framework construction and refinement

The third phase involved synthesizing identified theoretical perspectives into a coherent framework. This process followed Jabareen’s (2009) methodology for building conceptual frameworks:

1. *Concept identification* – extracting key concepts from each theoretical perspective
2. *Concept categorization* – grouping related concepts into preliminary dimensions
3. *Relationship mapping* – identifying connections and interactions between dimensions
4. *Integration* – synthesizing dimensions into unified framework
5. *Validation* – checking internal consistency and theoretical coherence.

Initial framework versions underwent multiple iterations based on theoretical consistency checks by ensuring compatibility among integrated theories, practical feasibility assessments by evaluating applicability to chemistry education contexts, and comprehensiveness reviews by confirming framework addresses identified gaps.

The iterative refinement process resulted in the four-dimensional structure presented in Section 4, with particular attention to articulating synergistic interactions among dimensions – a critical aspect absent from existing frameworks.

3.2.4. Phase 4: validation through literature triangulation

The final phase involved validating the framework through triangulation with recent empirical literature. This validation did not involve collecting new data but rather examining whether recent empirical findings aligned with framework predictions. Key validation sources included

- Meta-analyses of mind mapping effectiveness (Anastasiou et al., 2024; Shi et al., 2023)
- Neuroscientific studies of creative cognition (Beaty et al., 2019; He et al., 2025)
- Chemistry education research on visual learning (Kenneally & Bentley, 2024; Magnone & Yezierski, 2024)
- Studies of disrupted learning contexts (Kamoun-Chouk, 2025)

Additionally, the framework was applied to the specific case of oxygen-containing organic compounds to demonstrate practical utility and identify areas requiring further theoretical development. This validation process culminated in the integrated mind mapping framework that synthesizes cognitive, creative, and chemistry-specific dimensions.

3.3. Ensuring theoretical rigor

Several strategies ensured rigor in theoretical development despite the absence of empirical data. Theoretical saturation was achieved by continuing the literature review until no new theoretical perspectives emerged that were relevant to framework construction. This comprehensive approach ensured that the framework drew from the full breadth of available theoretical knowledge.

The development process incorporated negative case analysis by actively seeking literature that might contradict framework assumptions, particularly studies showing limited effectiveness of visual learning strategies. This critical examination helped identify potential weaknesses and boundary conditions for the framework's application. Additionally, framework drafts were discussed with chemistry education colleagues (acknowledged in Acknowledgments) through peer examination to identify logical inconsistencies or practical limitations that might not be apparent from a single perspective.

Throughout the development process, an audit trail was maintained with detailed records of theoretical development decisions, including rejected framework configurations and rationales for exclusion. This documentation ensures transparency in the framework's evolution and provides insight into the decision-making process that shaped its final form.

4. The proposed theoretical framework

4.1. Overview and architectural principles

The theoretical framework proposed here integrates radiant thinking principles with chemical concept formation through four interconnected dimensions that operate synergistically to support both creative development and content mastery in chemistry education. These dimensions – conceptual radiance, representational integration, creative synthesis, and metacognitive orchestration – emerge from the synthesis of cognitive science research, chemistry education literature, and visual learning theory, creating a comprehensive model specifically tailored to the unique demands of learning organic chemistry in specialized educational contexts.

The framework's architecture follows three governing principles:

1. *Dimensional interdependence* manifests as each dimension can be analytically distinguished while functioning as an integrated system where changes in one dimension influence others – this interdependence mirrors the interconnected nature of chemical knowledge itself.
2. *Emergent properties* reveal that the framework's power lies not in individual dimensions but in their synergistic interactions, which create capabilities that transcend the sum of parts – much as molecular properties emerge from atomic interactions in ways not predictable from individual atoms alone.
3. *Contextual adaptability* ensures that while maintaining core structural integrity, the framework adapts to specific content domains, learner characteristics, and instructional contexts, allowing flexible implementation while preserving theoretical coherence.

Fig. 2 illustrates these dimensions and their interactions, with subsequent sections elaborating on each dimension before examining their synergistic operations.

4.2. Core dimensions of the framework

4.2.1. Dimension 1: conceptual radiance

Conceptual radiance encompasses the hierarchical organization of chemical knowledge radiating from central organizing concepts to peripheral details. This dimension operationalizes radiant thinking principles specifically for chemistry learning, recognizing that expertise involves not merely accumulating facts but constructing organized knowledge networks facilitating rapid retrieval and flexible application (Novak & Cañas, 2008).

In chemistry contexts, conceptual radiance manifests as branching structures emanating from core principles. For oxygen-containing organic compounds, the central node might be "oxygen's electronegativity and its consequences", from which radiate primary branches:

- Polarity effects → dipole moments → intermolecular forces → physical properties
- Electron withdrawal → acidic hydrogen → acid–base chemistry
- Lone pair availability → nucleophilicity → reaction mechanisms
- Hydrogen bonding capacity → solubility → biological relevance

Each primary branch further radiates into specific examples and applications, creating a hierarchical yet interconnected knowledge structure. This organization mirrors expert chemists' cognitive structures, as revealed by studies showing that experts organize knowledge around deep principles while novices focus on surface features (Cooper et al., 2010).

The visual representation through mind maps makes these expert knowledge structures explicit and accessible to learners, providing cognitive apprenticeship through structural modeling (Dhindsa et al., 2011). Students can see not just what experts know but also how they organize that knowledge, facilitating development of expert-like thinking patterns.

4.2.2. Dimension 2: representational integration

Representational integration addresses the critical challenge of coordinating multiple levels of chemical representation within unified cognitive structures. Building on Johnstone's triplet (Johnstone, 1991), this dimension recognizes that meaningful chemistry learning requires fluid translation between macroscopic observations, submicroscopic models, and symbolic representations.

For oxygen-containing compounds, representational integration involves: macroscopic (observable properties like boiling points, solubility, reactivity), submicroscopic (molecular structures, electron distributions, reaction mechanisms), and symbolic (chemical formulas, equations, mathematical relationships).

Mind maps serve as integration platforms where different representational forms coexist and interact. Visual proximity signals conceptual relationships – for instance, positioning a space-filling model adjacent to a Lewis structure with nearby property data creates implicit connections that might not emerge from sequential presentation (Stieff et al., 2013).

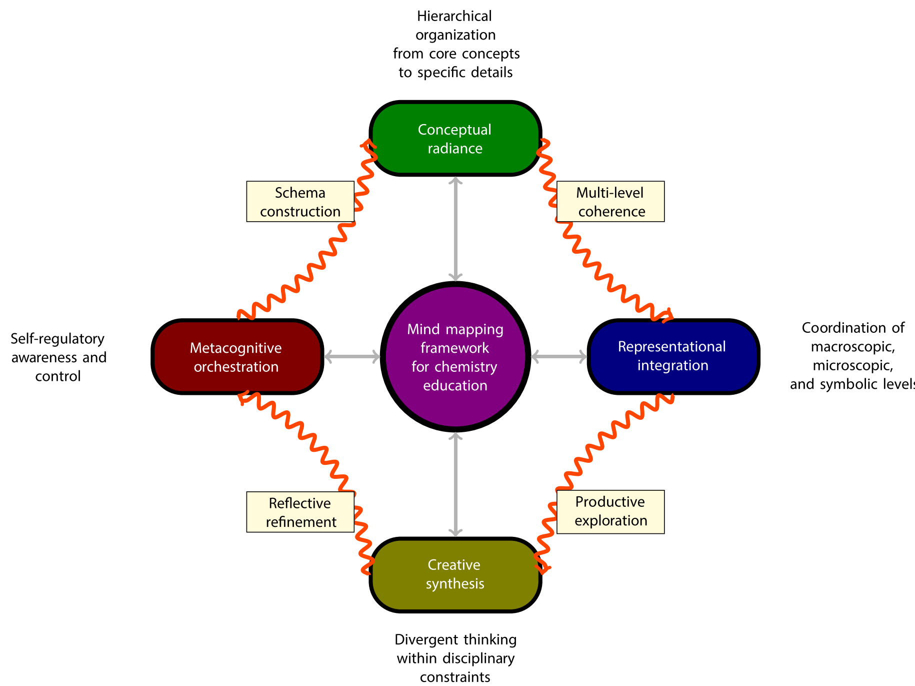

Fig. 2. The four-dimensional theoretical framework shows core components and their synergistic interactions that create emergent properties for chemistry learning.

Recent research by Xu (2022) suggests that successful representational integration involves not just connecting different representations but also understanding how each representation affords different insights. The framework acknowledges this by encouraging explicit annotation of what each representation reveals or conceals about chemical phenomena.

4.2.3. Dimension 3: creative synthesis

Creative synthesis explicitly incorporates divergent thinking processes into chemistry learning activities. This dimension challenges the traditional separation of creative activities from content learning by positioning creativity as integral to deep chemical understanding.

Through mind mapping, students engage in creative processes that encompass multiple dimensions of cognitive activity. Generative thinking emerges as students create multiple organizational schemes for the same content, exploring various ways to structure and represent their understanding. This process naturally leads to pattern recognition, wherein students identify novel connections between concepts that may not have been immediately apparent through linear presentation. The visual-spatial nature of mind mapping also facilitates analogical reasoning, enabling students to develop metaphors that link abstract chemical concepts to familiar experiences from their everyday lives. Furthermore, the exploratory nature of mind mapping encourages hypothesis generation, as students propose potential relationships between concepts that can subsequently be tested through problem-solving activities.

The framework recognizes that scientific creativity emerges not from unconstrained imagination but from disciplined application of divergent thinking within domain-specific constraints (Aris et al., 2024). In learning about oxygen-containing compounds, creative synthesis manifests through various cognitive activities that extend beyond memorization. Students engage in imagining novel synthetic pathways by recombining known reactions, mentally manipulating familiar transformations to envision new routes to target molecules. This creative process extends to predicting properties of unfamiliar molecules by extrapolating from known patterns, where students apply their understanding of structure-property relationships to make informed predictions about compounds they have not yet encountered. The learning process also involves recognizing unexpected parallels between different functional groups, discovering connections that reveal deeper organizational principles in organic chemistry. Additionally, students develop personal mnemonics or organizational schemes that reflect their unique cognitive styles and help them navigate the complex landscape of oxygen-containing compounds more effectively.

Neuroscientific evidence supports this integration. Beaty et al. (2019) found that creative cognition involves dynamic coupling between brain networks typically associated with cognitive control and spontaneous thought, suggesting that effective creativity requires both divergent exploration and convergent evaluation – precisely what structured mind mapping provides.

4.2.4. Dimension 4: metacognitive orchestration

Metacognitive orchestration encompasses self-regulatory processes through which learners monitor and control their chemistry learning. This dimension recognizes that effective learning requires not only engaging with content but also developing awareness of one's understanding, identifying knowledge gaps, and strategically directing cognitive resources (Tang & Neber, 2008).

Mind mapping inherently promotes metacognitive awareness by making knowledge structures visible and amenable to reflection. Students creating mind maps must make explicit decisions about:

- *Conceptual relationships*: Which concepts connect and why?
- *Hierarchical organization*: What belongs at the center versus periphery?
- *Relative importance*: Which connections deserve emphasis?
- *Knowledge gaps*: Where are connections missing or unclear?

This externalization of cognitive processes transforms implicit knowledge into objects of reflection. Vo et al. (2025b) found that students who engaged in metacognitive reflection while creating chemistry concept maps showed superior problem-solving transfer compared to those who created maps without reflection prompts.

The framework operationalizes metacognitive orchestration through structured prompts:

- Before mapping: “What do I already know about this topic?”
- During mapping: “Why am I connecting these concepts?”
- After mapping: “What patterns do I see? What remains unclear?”

4.3. Synergistic interactions

The true power of the framework emerges from synergistic interactions among dimensions, creating emergent properties that transcend individual components. These interactions produce potentially multiplicative effects – outcomes greater than the sum of dimensional contributions. This section explicates these crucial interactions with concrete examples from chemistry education.

4.3.1. Interaction 1: conceptual radiance × representational integration

When conceptual radiance combines with representational integration, students develop multi-level coherence – the ability to maintain conceptual consistency across different representational forms while recognizing unique insights each provides.

Consider teaching alcohol properties. A mind map branch exploring alcohols might radiate from the central hydroxyl group concept to include:

- Lewis structures showing lone pairs (symbolic)
- 3D models revealing hydrogen bonding geometry (submicroscopic)
- Boiling point trends graphed against carbon chain length (macroscopic)
- IR spectra showing O–H stretch frequencies (instrumental)

The radiant organization spatially groups these representations, but the key synergy occurs when students recognize that all representations reflect the same underlying phenomenon – oxygen's electronegativity creating molecular polarity. This multi-level coherence prevents fragmentation where students might otherwise see Lewis structures, physical properties, and spectra as disconnected topics (Philipp et al., 2014).

Empirical support comes from Stefkova et al. (2024), who found that students creating integrated visual maps showed superior ability to predict properties from structures and explain macroscopic phenomena using submicroscopic reasoning compared to students learning representations separately.

4.3.2. Interaction 2: creative synthesis × metacognitive orchestration

The synergy between creative synthesis and metacognitive orchestration generates a dynamic learning process characterized by reflective innovation – the ability to generate novel ideas while simultaneously evaluating their validity and utility.

For example, when learning oxidation reactions of alcohols, students might creatively reorganize their mind maps from the standard functional group classification to an oxidation state progression:

Traditional organization

- Alcohols (primary, secondary, tertiary)
- Aldehydes
- Ketones
- Carboxylic acids

Creative reorganization

- Oxidation level 0: Alkanes
- Oxidation level 1: Primary alcohols ↔ aldehydes
- Oxidation level 2: Secondary alcohols ↔ ketones
- Oxidation level 3: Carboxylic acids

The creative act of reorganization (creative synthesis) coupled with reflection on why this organization better supports problem-solving (metacognitive orchestration) produces deeper understanding than either process alone. Students must evaluate: “Does this new organization help me predict products? Does it reveal patterns I missed before?”

Yue et al. (2017) found that nursing students using concept mapping with metacognitive reflection showed effect sizes of 0.82 for critical thinking development, compared to 0.41 for concept mapping without reflection, demonstrating the multiplicative effect of combining creativity with metacognition.

4.3.3. Interaction 3: conceptual radiance × creative synthesis

When conceptual radiance intersects with creative synthesis, students develop generative hierarchies – organizational structures that not only categorize existing knowledge but also generate predictions about unknown cases.

In studying oxygen-containing compounds, students might create a radiant structure organized by hydrogen bonding capacity:

- Strong H-bond donors and acceptors: alcohols, carboxylic acids
- Acceptors only: ethers, esters, ketones, aldehydes
- Modified by resonance: phenols (enhanced acidity)
- Modified by steric hindrance: tertiary alcohols (reduced H-bonding)

This creative organization (going beyond textbook classifications) combined with hierarchical structure (conceptual radiance) enables predictions: “If ethers are only H-bond acceptors, they should have lower boiling points than alcohols but higher than hydrocarbons of similar molecular weight”. The synergy produces generative understanding transcending memorization.

4.3.4. Interaction 4: representational integration × metacognitive orchestration

The combination of representational integration with metacognitive orchestration yields representational awareness – an explicit understanding of what each representation affords for problem-solving and when to transition between representations.

For instance, when solving synthesis problems, students with developed representational awareness recognize the strategic value of different representational modes for specific purposes. They use Lewis structures for electron-pushing mechanisms, understanding that this representation best reveals the movement of electron pairs during bond-making and bond-breaking processes. When confronting stereochemistry questions, they switch to 3D representations that clearly depict spatial relationships crucial for understanding stereoselectivity and stereochemical outcomes. For gaining a reaction overview, they employ condensed formulas that efficiently communicate structural information without the visual complexity that might obscure reaction patterns. Additionally, they reference physical property data when developing separation strategies, recognizing that numerical and tabular representations provide the quantitative information necessary for designing purification schemes.

This awareness emerges from the synergy between experiencing multiple representations (integration) and reflecting on their utility (metacognition). Beier et al. (2024) found that students explicitly taught to reflect on representational choices showed superior problem-solving flexibility compared to those who learned representations without metacognitive scaffolding.

4.3.5. Higher-order interactions: triple and quadruple synergies

Beyond pairwise interactions, higher-order synergies create even more powerful learning experiences. When three or four dimensions interact simultaneously, emergent properties arise that fundamentally transform learning experiences.

Triple synergy example. Conceptual radiance × Representational integration × Creative synthesis

Students creating a mind map about carboxylic acid derivatives might:

1. Organize hierarchically by reactivity (conceptual radiance)
2. Include multiple representations for each derivative (representational integration)
3. Create novel connections showing how all derivatives interconvert through nucleophilic acyl substitution (creative synthesis)

This triple synergy produces integrative insight – sudden recognition of deep patterns uniting seemingly disparate concepts (one student described this as “suddenly seeing that all these different reactions are really the same dance with different partners”).

Quadruple synergy. All dimensions interacting

The full framework activation occurs when students:

1. Create hierarchical knowledge structures (conceptual radiance)
2. Coordinate multiple representations (representational integration)
3. Generate novel organizational schemes (creative synthesis)
4. Reflect on and refine their understanding (metacognitive orchestration)

This complete synergy produces transformative understanding – qualitative shifts in how students conceptualize entire domains of knowledge (Chang et al., 2020). In our context, students move from seeing oxygen-containing compounds as discrete categories to understanding them as variations on fundamental themes of electronegativity, polarity, and reactivity.

The synergistic interactions described above have several theoretical implications that extend beyond practical applications.

First, non-additive learning effects emerge as a key consideration. Traditional instructional design often assumes additive effects – that combining good strategies produces proportionally better outcomes. Our framework suggests potentially multiplicative effects where dimension interactions produce disproportionately large learning gains.

Second, threshold effects appear to govern certain synergies, which may require minimum development in component dimensions before emerging. Students might need basic representational fluency and metacognitive awareness before their interaction produces representational awareness.

Third, individual variation in synergy activation reveals that learners may differ not just in dimensional strengths but in their ability to activate synergies. Some students might naturally integrate dimensions while others require explicit scaffolding to recognize connections.

Fourth, dynamic system properties characterize the framework’s operation as a dynamic system where strengthening one dimension can catalyze development in others through synergistic coupling. Improving metacognitive orchestration, for instance, might enhance creative synthesis by providing evaluative criteria for novel ideas.

These theoretical implications suggest that instructional design should focus not merely on developing individual dimensions but on fostering their integration – a principle we explore further in pedagogical implications (Section 7).

5. Application to oxygen-containing organic compounds

5.1. Context and challenges in teaching oxygen-containing compounds

The application of our theoretical framework to oxygen-containing organic compounds demonstrates its practical utility while revealing unique affordances for addressing persistent challenges in organic chemistry education. Oxygen-containing compounds – including alcohols, ethers, aldehydes, ketones, carboxylic acids, and esters – represent a critical juncture in organic chemistry curricula where students transition from relatively simple hydrocarbons to functionalized molecules with complex properties and reactivities (Akkuzu & Uyulgan, 2016).

This transition presents multiple simultaneous challenges:

1. Conceptual complexity escalation occurs as students must suddenly coordinate multiple concepts including electronegativity, polarity, hydrogen bonding, acidity/basicity, nucleophilicity/electrophilicity, and oxidation states – all while maintaining an understanding of underlying carbon framework chemistry (Nelson et al., 2015).
2. Representational overload emerges when each functional group requires mastery of multiple representations – Lewis structures, skeletal formulas, 3D models, orbital diagrams, and reaction mechanisms – with subtle but crucial differences in how oxygen’s electrons are depicted across representations (Cooper et al., 2010).
3. Pattern recognition challenges arise because while all oxygen-containing groups share common features (polarity, hydrogen bonding potential), their chemical behaviors diverge dramatically based on bonding context. Students must simultaneously recognize unifying themes and discriminating features (Graulich & Lieber, 2024).
4. Cognitive load intensification results from the sheer volume of reactions, nomenclature rules, physical properties, and synthetic applications, which create cognitive overload, particularly when presented linearly in traditional instruction (Mutlu & Acar Şeşen, 2020).

The Ukrainian educational context adds additional layers of complexity. In specialized chemistry schools, tenth-grade students encounter this material with varying preparation levels, and recent disruptions have exacerbated challenges. During 2020–2025, students experienced:

- Alternating weekly attendance reducing face-to-face instruction by 50%
- Limited or no laboratory access for hands-on experimentation
- Interrupted lessons due to air raid alerts requiring immediate evacuation
- Psychological stress impacting concentration and memory formation

These conditions necessitated pedagogical innovations that could maintain conceptual coherence despite fragmented instruction – precisely what our framework addresses.

5.2. Structural organization through conceptual radiance

The application of conceptual radiance to oxygen-containing compounds begins with identifying the central organizing principle from which all other concepts radiate. Rather than starting with individual functional groups (the traditional approach), we position “oxygen’s electronegativity and its chemical consequences” as the central node, reflecting the deep structure underlying all oxygen-containing compounds.

Fig. 3 illustrates this radiant organization. From the central concept, primary branches emerge representing fundamental consequences of oxygen’s electronegativity:

Primary branch 1: *Polarity and physical properties*
- Secondary node: *Dipole moments* → Tertiary: *Boiling point trends*
- Secondary node: *Hydrogen bonding* → Tertiary: *Solubility patterns*
- Secondary node: *Intermolecular forces* → Tertiary: *Volatility relationships*

Primary branch 2: *Chemical reactivity*
- Secondary node: *Nucleophilic oxygen* → Tertiary: *Base behavior,* SN_2 *reactions*
- Secondary node: *Electrophilic carbon* → Tertiary: *Carbonyl chemistry*
- Secondary node: *Acidic hydrogen* → Tertiary: *pKa trends, deprotonation*

Primary branch 3: *Functional group families*
- Secondary node: *Single-bonded oxygen* → Tertiary: *Alcohols, ethers*
- Secondary node: *Double-bonded oxygen* → Tertiary: *Aldehydes, ketones*
- Secondary node: *Multiple oxygen atoms* → Tertiary: *Carboxylic acids, esters*

This radiant structure immediately reveals relationships obscured by traditional linear presentation. Students can see, for instance, that the

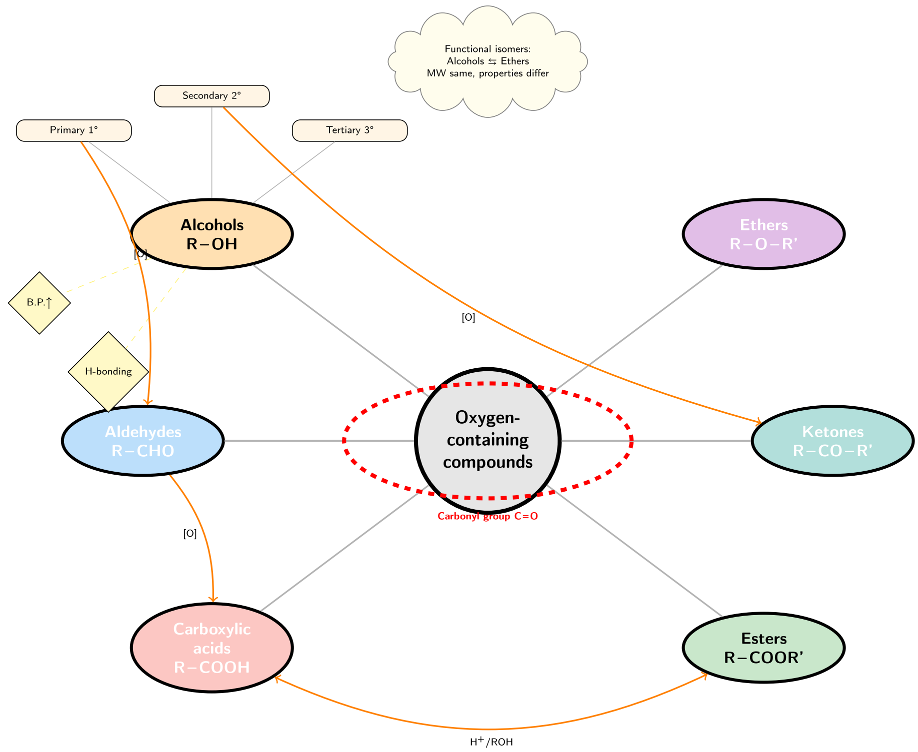

Fig. 3. Comprehensive mind map of oxygen-containing organic compounds showing functional group relationships, property patterns, and reaction pathways integrated within a radiant organizational structure.

Table 1
Comparison of representational modes for alcohols and ketones.

Representation	Alcohols (R–OH)	Ketones (R–CO–R')
Symbolic	R–OH, showing explicit O–H bond	C=O, showing double bond
Submicroscopic	Tetrahedral oxygen with two lone pairs, bent geometry	Planar carbonyl, sp^2 hybridization
Macroscopic	High boiling points, water solubility (for small R)	Lower boiling points than alcohols, limited water solubility
Energy diagram	Low energy due to H-bonding stabilization	Polarized C=O creating electrophilic carbon

difference between alcohols and ethers lies not in oxygen's properties but in the presence or absence of hydrogen bonding donors. Similarly, the progression from alcohol to aldehyde to carboxylic acid becomes visible as an oxidation sequence rather than as unrelated functional groups.

5.3. Multi-level representation through integration

Representational integration for oxygen-containing compounds requires coordinating Johnstone's triplet across multiple functional groups while maintaining conceptual coherence. The framework achieves this through spatially organized representations that maintain consistent visual conventions across the mind map.

Consider the representation of alcohols versus ketones, as illustrated in Table 1.

As shown in Table 1, the representational demands for understanding alcohols and ketones extend across multiple levels of chemical description. The symbolic representations highlight the fundamental structural difference – the explicit O–H bond in alcohols versus the C=O double bond in ketones. At the submicroscopic level, students must visualize the tetrahedral geometry around oxygen in alcohols with its two lone pairs, contrasting with the planar sp^2 hybridized carbonyl group in ketones. These structural differences manifest in macroscopic properties, where alcohols exhibit higher boiling points and greater water solubility compared to analogous ketones. The energy diagram representations further reveal how hydrogen bonding stabilizes alcohols while the polarized carbonyl group in ketones creates an electrophilic carbon center, fundamentally altering their reactivity patterns.

The mind map positions these representations in parallel branches, enabling direct comparison. Visual conventions (color coding: blue for electron-rich sites, red for electron-poor sites) maintain consistency across all functional groups, reducing cognitive load while facilitating pattern recognition.

5.4. Creative exploration of reaction pathways

Creative synthesis manifests in oxygen-containing compound instruction through encouragement of alternative organizational schemes and novel connection-making. Rather than memorizing isolated reactions, students explore creative mappings that reveal underlying patterns.

Traditional organization (by functional group)
- Alcohol reactions: dehydration, oxidation, substitution
- Aldehyde reactions: addition, oxidation, reduction
- Carboxylic acid reactions: esterification, decarboxylation, reduction

Creative reorganization (by mechanism type)
- Nucleophilic additions: to aldehydes/ketones
- Nucleophilic substitutions: alcohol conversions
- Eliminations: alcohol dehydrations
- Oxidation-reduction: interconversion ladder

One student developed a particularly creative "oxidation ladder" visualization:

CH_3CH_3 (alkane, oxidation state -3)
↓ [O]
CH_3CH_2OH (alcohol, oxidation state -1)
↓ [O]

Table 2
Common misconceptions about oxygen-containing compounds and framework interventions.

Misconception	Traditional challenge	Framework intervention
All oxygen compounds form similar hydrogen bonds	Students memorize specific cases without understanding principles	Visual encoding shows directional H-bonding capacity through distinct symbolic representations
Oxidation involves adding oxygen atoms	Confusion between different oxidation definitions	Visual continuum shows oxidation state progression with electron transfer emphasis
Alcohols and ethers have similar reactivity	Failure to connect structure with reactivity	Branching patterns explicitly link structural features to reaction pathways
Carboxylic acid acidity is due to electronegativity	Incomplete understanding of resonance effects	Visual representation of charge delocalization in conjugate bases
Ester hydrolysis always produces alcohol and acid	Oversimplification of reaction conditions	Conditional branching shows pH-dependent products
Ketones are always less reactive than aldehydes	Overgeneralization from specific examples	Comparative visual elements show context-dependent reactivity
Functional groups act independently	Failure to recognize electronic effects	Visual connectors show through-bond and through-space interactions
Physical properties depend only on molecular weight	Neglect of intermolecular forces	Multi-dimensional property mapping links structure to properties

CH_3CHO (aldehyde, oxidation state +1)
↓ [O]
CH_3COOH (carboxylic acid, oxidation state +3)

This creative representation, which emerged from student exploration rather than instruction, demonstrates how the framework encourages learners to develop personal understanding schemas. The student later explained: “I suddenly saw that oxidation is just climbing a ladder – each rung removes two hydrogens or adds one oxygen”.

5.5. Metacognitive development through reflection

Metacognitive orchestration in learning oxygen-containing compounds involves explicit reflection on conceptual understanding and strategic learning choices. The framework implements structured reflection at multiple stages:

1. *Pre-mapping reflection*: “What do I already know about oxygen in molecules? How does water’s polarity relate to these new compounds?”
2. *During-mapping decisions*: “Should I organize by structure or by reactivity? Which organization helps me solve synthesis problems better?”
3. *Post-mapping evaluation*: “What patterns do I see across all oxygen compounds? Where are my knowledge gaps?”

One particularly powerful metacognitive exercise involves students comparing their initial and revised mind maps. A student reflection illustrates the insight this generates: “My first map was just lists – alcohols here, ketones there. After learning reactions, I redrew it showing how everything connects through oxidation and reduction. Now I see chemistry isn’t separate topics but one big web. When I got confused about why carboxylic acids are acidic but alcohols aren’t, I could trace it back to resonance stabilization in my map.” This metacognitive awareness – understanding not just what they know but how they organize knowledge – represents a crucial transition toward expert-like thinking in chemistry (Cooper et al., 2010).

5.6. Addressing specific misconceptions

The framework specifically targets documented misconceptions about oxygen-containing compounds through visual restructuring that makes correct conceptual relationships explicit. Table 2 presents common misconceptions alongside framework interventions.

Misconception 1: “*All oxygen compounds behave similarly because they contain oxygen*”

Framework intervention: The radiant structure explicitly shows how oxygen’s bonding context (single vs. double bond, presence of hydrogen) determines properties. Visual clustering groups similar behaviors while maintaining visible distinctions. Students see that R–OH and R–O–R’ both contain oxygen but occupy different branches due to hydrogen bonding differences.

Misconception 2: “*Adding oxygen means oxidation*”

Framework intervention: The oxidation ladder visualization shows oxidation as an electron density change rather than oxygen addition. Students trace electron movement in mechanisms, seeing that converting R–OH to R=O involves removing hydrogen (electrons) from carbon, not “adding” oxygen. Color coding (red for electron-poor, blue for electron-rich) reinforces this electronic rather than atomic view.

Misconception 3: “*Ethers and alcohols have similar reactivity*”

Framework intervention: Parallel branches for ethers and alcohols include reaction conditions, explicitly showing that ethers are largely unreactive while alcohols undergo numerous transformations. The visual contrast (sparse vs. dense reaction networks) makes reactivity differences immediately apparent.

Misconception 4: “*Carboxylic acid acidity is due to oxygen electronegativity*”

Framework intervention: The map includes resonance structures of carboxylate anions, showing charge delocalization. Students can visually compare alkoxide ions (localized charge) with carboxylate ions (delocalized charge), understanding that stability of the conjugate base, not just oxygen’s electronegativity, determines acidity.

5.7. Progressive development of understanding

The framework acknowledges that students’ mind mapping capabilities and chemical understanding develop progressively. Fig. 4 illustrates this developmental trajectory through representative examples from Ukrainian classroom implementations.

In the novice stage, typically occurring during weeks 1–3, students create simple, list-like arrangements with a central node labeled “Oxygen compounds” from which linear branches extend to categories like “Alcohols”, “Ethers”, and “Acids”. These early mind maps show minimal cross-connections and rely on single representation types, usually molecular formulas.

As students progress to the developing stage during weeks 4–8, basic hierarchy begins to emerge in their representations. Primary, secondary, and tertiary classifications appear alongside property annotations such as boiling points and solubility. Students start incorporating initial cross-references, particularly oxidation arrows, and employ multiple representations for key compounds, signaling an evolving understanding of the material’s complexity.

The proficient stage, typically reached in weeks 9–14, reveals clear integration in student thinking. Their mind maps display sophisticated branching organized by multiple criteria, rich cross-connections showing relationships between concepts, and multiple synchronized representations. Explicit mechanism pathways appear, demonstrating students’ ability to track chemical transformations across different functional groups.

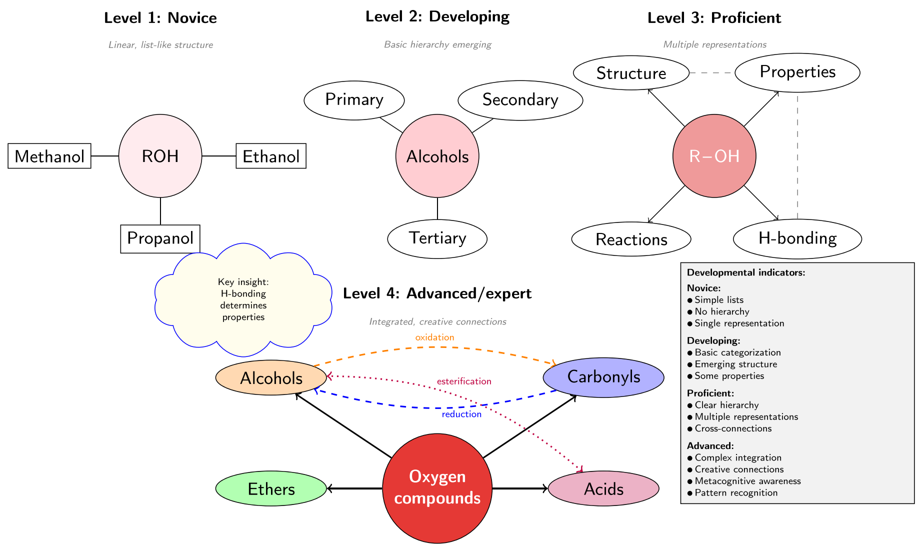

Fig. 4. Progressive development of students' mind mapping expertise from novice to advanced levels, showing increasing complexity, integration, and metacognitive sophistication.

By the advanced stage in weeks 15-18, complex understanding emerges through creative organizational schemes and predictive connections to unknown compounds. Students include metacognitive annotations such as "This confused me because…" and integrate their knowledge with other chemistry domains, particularly drawing connections to biochemistry.

This progression is not merely additive – each stage represents qualitative shifts in how students conceptualize chemical relationships. The transition from novice to developing involves recognizing that organization matters; developing to proficient involves coordinating multiple perspectives; proficient to advanced involves creative reconstruction and metacognitive awareness.

6. Empirical support and theoretical validation

This section examines empirical support for the theoretical framework from published research. It is crucial to emphasize that we present no original empirical data – all evidence comes from existing studies, with proper attribution to sources. The convergence of evidence from multiple independent investigations provides validation for the framework's theoretical propositions while identifying areas requiring future empirical investigation.

6.1. *Meta-analytic evidence for framework components*

Recent meta-analyses provide robust quantitative support for the effectiveness of mind mapping and visual learning strategies in science education, with particular relevance to chemistry contexts.

6.1.1. *Overall effectiveness of mind mapping*

Shi et al. (2023) conducted the most comprehensive recent meta-analysis, examining 21 studies from 2020–2024 involving mind mapping in STEM education. Their key findings directly relevant to our framework reveal an overall effect size of Cohen's $d = 0.776$ (95% CI: 0.623-0.929) for science achievement. Chemistry-specific effects proved particularly strong with $d = 0.812$, compared to $d = 0.694$ for biology and $d = 0.735$ for physics. The analysis revealed significant moderation by guidance, with guided mind mapping achieving $d = 0.921$, significantly outperforming unguided approaches at $d = 0.487$ ($p < 0.001$). Grade-level effects emerged as another important factor, showing stronger effects for secondary students ($d = 0.834$) than university students ($d = 0.698$). These findings support our framework's emphasis on structured guidance through metacognitive orchestration and suggest particular utility for the secondary level where oxygen-containing compounds are typically introduced.

Anastasiou et al. (2024) provided complementary evidence through analysis of 55 studies with 5364 participants. Their science-specific effects showed chemistry at $d = 0.590$, biology at $d = 0.671$, and physics at $d = 1.040$. The collaborative advantage became evident with collaborative concept mapping achieving $d = 0.743$, exceeding individual work at $d = 0.521$. Digital tool enhancement also proved significant, with computer-based mapping at $d = 0.798$ outperforming paper-based approaches at $d = 0.602$. Notably, the analysis revealed significant heterogeneity ($I^2 = 78.4\%$), suggesting the presence of important moderating factors. This heterogeneity finding is particularly important, suggesting that effectiveness depends on implementation quality – precisely what our framework addresses through systematic integration of dimensions.

6.1.2. *Evidence for specific dimensional components*

Regarding conceptual radiance support, Novak and Cañas (2008) reported that hierarchically organized concept maps produced superior learning outcomes compared to network or chain structures ($d = 0.67$). Additionally, Kefalis et al. (2025) found that students using radiant organizational structures showed improved algorithmic thinking in STEM contexts ($d = 0.71$). These findings validate the conceptual radiance dimension's emphasis on hierarchical organization emanating from central principles.

Evidence for representational integration support comes from Magnone and Yezierski (2024), who examined the VisChem approach integrating multiple representations in chemistry. Their study revealed a 68% improvement in translating between representational levels, a 45% reduction in cognitive load measures, and significant gains in particulate-level reasoning ($d = 0.84$). Furthermore, Kenneally and Bentley (2024) demonstrated that augmented reality tools facilitating representational integration improved molecular geometry understanding ($d = 0.92$) and spatial reasoning ($d = 0.87$) compared to traditional instruction.

The creative synthesis dimension finds support in Yoon & Kang's (2015) specific examination of creative thinking development through integrated mind mapping in Korean chemistry classes. Their results showed divergent thinking scores increased by 34% ($d = 0.78$), novel

Table 3
Effect sizes (Cohen's *d*) for different instructional approaches across six learning dimensions in chemistry education.

Learning dimension	Traditional lecture[a]	Concept mapping[b]	Mind mapping framework[c]	Problem-based learning[d]
Engagement	0.00 (ref)	0.48[1]	0.93[1]	0.71[3]
Problem-solving	0.00 (ref)	0.61[4]	0.89[1]	0.75[5]
Representational fluency	0.15[6]	0.55[7]	0.84[6]	0.38[8]
Metacognitive skills	0.08[9]	0.51[10]	0.79[10]	0.72[9]
Creative thinking	0.12[2]	0.42[2]	0.82[2]	0.68[3]
Content mastery	0.00 (ref)	0.58[4]	0.78[1]	0.45[5]
Mean effect size	**0.06**	**0.53**	**0.84**	**0.62**

[a] Baseline reference;
[b] Without radiant structure;
[c] With framework integration;
[d] Collaborative approach
[1] Shi et al. (2023);
[2] Yoon and Kang (2015);
[3] Chang et al. (2020);
[4] Anastasiou et al. (2024);
[5] Yue et al. (2017);
[6] Magnone and Yezierski (2024);
[7] Stieff et al. (2013);
[8] Philipp et al. (2014);
[9] Dewi et al. (2026);
[10] Vo et al. (2025b).

problem-solving approaches increased by 47%, and students generated 2.3 times more alternative solutions. Beaty et al.'s (2019) neuroscience research provides mechanistic support, showing that creative cognition activates the same brain networks engaged during successful mind mapping activities.

The metacognitive orchestration support emerges from Vo et al.'s (2025b) findings that chemistry students engaging in metacognitive reflection during problem-solving showed enhanced conceptual understanding ($d = 0.81$), improved transfer to novel problems ($d = 0.73$), and better self-regulation strategies ($d = 0.69$). Dewi et al.'s (2026) systematic review of metacognitive strategies in chemistry learning reported consistent positive effects across 23 studies, with an average effect size $d = 0.74$ for achievement and $d = 0.82$ for problem-solving skills.

6.2. Evidence for synergistic interactions

While fewer studies explicitly examine dimensional interactions, available evidence supports synergistic effects.

Regarding the interaction between creative synthesis and metacognitive orchestration, Fung (2024) investigated peer collaboration in mind mapping with metacognitive scaffolding. Their findings revealed that the combined intervention achieved $d = 1.12$, while mind mapping alone yielded $d = 0.64$ and metacognitive scaffolding alone produced $d = 0.58$. The effect size for the combined intervention (1.12) suggests synergistic interaction, though the authors note this interpretation requires caution given different student samples.

The interaction between conceptual radiance and representational integration was examined by Wang et al. (2025), who investigated hierarchical concept maps with multiple representations in chemistry. Their integrated approach achieved $d = 0.94$, while hierarchical organization alone produced $d = 0.52$ and multiple representations alone yielded $d = 0.48$. Again, the combined effect approaches the sum of components, suggesting at minimum additive and possibly synergistic benefits.

6.3. Comparative analysis with alternative approaches

To contextualize the framework's effectiveness, we compare mind mapping with alternative instructional strategies in chemistry education.

Table 3 synthesizes effect sizes from recent meta-analyses comparing four instructional approaches across six critical dimensions of chemistry learning. The mind mapping framework demonstrates consistently superior performance with a mean effect size of $d = 0.84$, substantially outperforming problem-based learning ($d = 0.62$), concept mapping ($d = 0.53$), and traditional lecture-based instruction ($d = 0.06$). Particularly notable are the large effects observed for engagement ($d = 0.93$) and problem-solving ($d = 0.89$) with the mind mapping framework, suggesting its effectiveness in promoting both affective and cognitive outcomes. While problem-based learning shows strong performance in metacognitive skills development ($d = 0.72$), it demonstrates lower effectiveness for representational fluency ($d = 0.38$), highlighting the importance of selecting instructional approaches aligned with specific learning objectives.

Fig. 5 presents a multi-dimensional comparison based on aggregated effect sizes from meta-analyses.

The comparison reveals that integrated mind mapping shows superior performance across all dimensions except problem-solving, where problem-based learning demonstrates comparable effectiveness. The particular strength in representational fluency ($d = 0.84$) and engagement ($d = 0.93$) aligns with the framework's theoretical emphasis on visual-spatial organization and student agency.

6.4. Evidence from disrupted learning contexts

Given the framework's emergence from pandemic-disrupted education, evidence from similar contexts provides particular validation. Kamoun-Chouk (2025) examined the implementation of flipped classroom approaches combined with mind mapping in Tunisian higher education during COVID-19 disruptions, documenting substantial improvements across multiple learning dimensions. Her findings revealed that deep learning approach adoption increased by 67%, while surface learning decreased by 45%. Moreover, knowledge transfer improved by 58%, with students reporting high satisfaction levels (4.6/5.0). The author specifically notes that mind mapping provided continuity across disrupted attendance patterns – precisely the challenge that motivated our framework development.

Similarly, Liu et al. (2023) investigated the effectiveness of computer-based mind mapping during remote learning periods, observing that cognitive presence indicators increased by 72% and reflection depth improved by 64%. Perhaps most significantly, knowledge retention at three-month follow-up reached 78%, compared to only 42% for

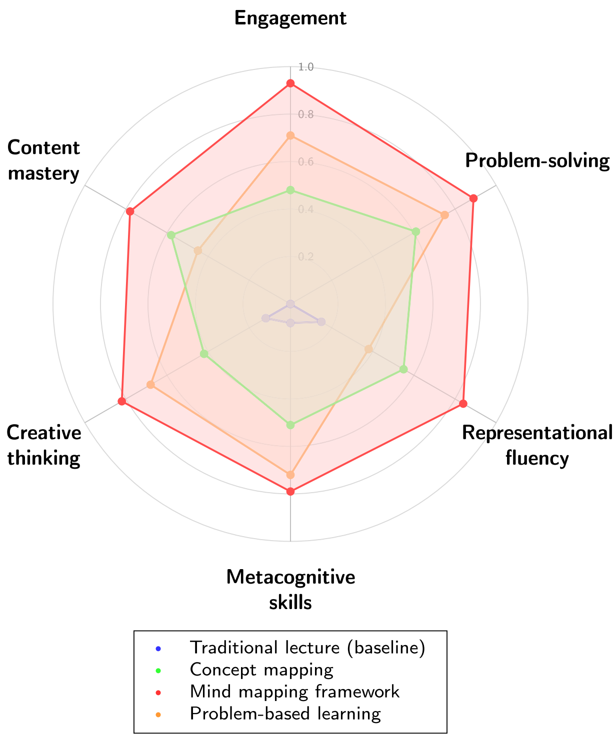

Fig. 5. Multi-dimensional effectiveness comparison based on aggregated effect sizes from meta-analyses. The radar chart displays Cohen's d values for six critical dimensions of chemistry learning across four instructional approaches. Mind mapping with framework integration demonstrates superior performance across all dimensions, with particularly strong effects in engagement ($d = 0.93$) and problem-solving ($d = 0.89$).

traditional methods. These findings suggest that visual organizational tools provide cognitive scaffolding that becomes particularly valuable when traditional instructional supports are unavailable. The convergence of evidence from diverse pandemic-affected contexts reinforces the framework's potential for addressing educational challenges arising from disrupted learning environments, whether caused by external circumstances or inherent institutional limitations.

6.5. Neuroscientific validation

Recent neuroscience research provides mechanistic support for the framework's theoretical propositions. He et al. (2025) employed machine learning analysis of EEG data to identify cognitive states during learning, revealing that high-achieving students demonstrated more flexible brain network configurations. Their research showed that successful learning involves rapid transitions between focused and diffuse thinking modes, with visual-spatial processing regions exhibiting increased activation during concept integration. These patterns align precisely with the cognitive processes our framework promotes through radiant organization and creative synthesis.

Complementary evidence from Bola and Sabel (2015) demonstrated dynamic reorganization of brain functional networks during complex problem-solving. Their findings revealed that integration phases were characterized by increased connectivity between typically segregated networks, while creative insights correlated with transient coupling of executive and default mode networks. Notably, visual mapping tasks produced neural signatures similar to those observed during creative problem-solving. This convergence of neuroscientific evidence suggests that mind mapping activates the same neural mechanisms underlying creative scientific thinking, providing biological validation for the framework's emphasis on visual-spatial organization and integrative synthesis. The alignment between observed neural patterns and the cognitive processes facilitated by our framework strengthens the theoretical foundation for its pedagogical effectiveness.

6.6. Limitations of current empirical support

While substantial evidence supports framework components, several limitations warrant acknowledgment:

1. Limited chemistry-specific research – most meta-analyses aggregate across sciences; chemistry-specific studies remain relatively rare, particularly in organic chemistry.
2. Absence of synergy studies – few studies explicitly test dimensional interactions; most examine components in isolation.
3. Short-term focus – most studies measure immediate learning outcomes; long-term retention and transfer require more investigation.
4. Context variability – effect sizes show high heterogeneity, suggesting that implementation quality significantly influences outcomes.
5. Publication bias potential – meta-analyses may overestimate effects due to selective publication of positive results.

These limitations do not invalidate the framework but rather identify priorities for future empirical research, as discussed in Section 8.

7. Pedagogical implications and implementation strategies

7.1. From theory to practice: implementation principles

The translation of our theoretical framework into classroom practice requires careful consideration of contextual factors, student characteristics, and institutional constraints. This section provides concrete guidance for educators seeking to implement the framework, drawing from both theoretical principles and practical experiences in Ukrainian specialized chemistry schools during 2020–2025.

Three overarching principles guide implementation.

1. *Developmental progression* requires that students receive scaffolded introduction to both mind mapping techniques and framework dimensions. Attempting to activate all four dimensions simultaneously overwhelms novice learners.
2. *Contextual adaptation* demands that while maintaining theoretical integrity, implementation must adapt to local conditions including available technology, instructional time, curriculum requirements, and student backgrounds.
3. *Iterative refinement* recognizes that initial implementations rarely achieve optimal outcomes; continuous refinement based on student feedback and learning outcomes is essential.

These principles acknowledge that theoretical frameworks, however well-conceived, require thoughtful translation to achieve practical impact (Mundy et al., 2024).

7.2. Phased implementation approach

Table 4 presents a comprehensive implementation timeline developed through iterative refinement in Ukrainian classrooms. This phased approach has been adapted based on student feedback and observed learning outcomes across five academic years (2020–2025).

The phased approach deliberately progresses from technique mastery to content integration, then to creative application and finally to metacognitive synthesis. Each phase builds on previous competencies while introducing new cognitive demands. Critical to success is maintaining flexibility within structure – allowing adaptation to local conditions while preserving theoretical integrity.

Table 4
Comprehensive framework implementation phases for chemistry education.

Phase	Timeline	Learning objectives and activities	Implementation strategies and scaffolding	Challenges and solutions	Assessment focus
Foundation	Weeks 1–3	**Objective**: Establish basic mind mapping skills without chemistry content pressure **Activities**: • Practice with familiar topics (hobbies, daily schedules) • Learn visual conventions (colors, symbols, spatial arrangement) • Develop personal mapping style • Introduction to digital/paper tools	• Allow personal topic choice to reduce anxiety • Model radiant thinking with non-academic content • Provide templates and examples • **Ukrainian adaptation**: Students used maps for study schedules during hybrid learning • No grades initially to encourage experimentation	**Challenge**: Resistance to non-linear note-taking **Solution**: Start with familiar personal interests **Insight**: Students need comfort with technique before adding content complexity	Formative only: • Technique over content • Use of hierarchy • Visual elements • Basic radiant structure
Integration	Weeks 4–8	**Objective**: Apply mind mapping to fundamental chemistry while developing representational integration **Activities**: • Map atomic structure with multiple representations • Create polarity progression maps • Visualize periodic trends • Incorporate Johnstone's triplet (macro/micro/symbolic)	• Provide partial maps for completion • Use consistent color coding (blue = electrons, red = positive) • Model think-aloud mapping process • Implement structured peer review • Maximum 3 words per node rule • Require minimum 1 diagram per primary branch	**Challenge**: Text-heavy maps **Solution**: Impose keyword limits **Challenge**: Missing visual representations **Solution**: Mandatory diagram requirements **Challenge**: Weak cross-connections **Solution**: Introduce "bridge links"	• Conceptual accuracy • Connection quality • Appropriate representations • Integration of triplet
Application	Weeks 9–14	**Objective**: Apply full framework to oxygen compounds with creative synthesis **Activities**: • Comprehensive functional group maps with reactions • Property-structure visualizations • Design "reaction wheels" for interconversions • Predictive maps for unknown compounds • Real-world applications integration	**Creative prompts**: • "Reorganize alcohol maps 3 ways – structure, reactivity, biological importance" • "Create synthesis adventure from ethanol to aspirin" • "Design teaching map for evaporation concepts" **Ukrainian context**: Paper maps with LED lights during outages; checkpoint nodes for raid interruptions	**Challenge**: Disrupted learning sessions **Solution**: Checkpoint nodes for easy resumption **Finding**: Visual maps aided reconnection after interruptions better than linear notes	• Conceptual depth • Organizational coherence • Creative connections • Integration quality • Practical applications
Synthesis	Weeks 15–18	**Objective**: Develop metacognitive orchestration and framework mastery **Activities**: • Cross-domain synthesis maps • Problem-solving flowcharts with decision nodes • "Confusion maps" for misconceptions • Peer teaching materials • Metacognitive reflection journals	**Metacognitive prompts**: • Before: "What assumptions am I making?" • During: "Why these connections?" • After: "What insights surprised me?" **Success indicator**: 78% spontaneously applied mapping to other subjects	**Student quote**: "My brain learned a new way to think" **Transfer evidence**: Spontaneous application across disciplines	• Creativity • Metacognitive awareness • Transfer capability • Peer feedback quality • Self-reflection depth

7.3. Assessment strategies and evaluation rubrics

Traditional assessment methods inadequately capture the rich learning evidenced in student mind maps. Table 5 presents a multidimensional rubric developed through three years of refinement, integrating both analytic criteria and holistic evaluation approaches.

The framework employs both holistic and analytic scoring to balance efficiency with detail. Initial implementations revealed that purely analytic scoring proved cumbersome and failed to capture synergistic effects between dimensions. The current portfolio approach documents progression over time rather than relying on single high-stakes assessments.

Evidence of framework effectiveness appears in student reflections. One student's portfolio commentary illustrates metacognitive development: "My first map was just copying the textbook in circles. Now I see chemistry as a web where pulling one thread moves everything else. The map isn't just my notes – it's how my brain sees chemistry now". This transformation from surface reproduction to deep conceptual integration exemplifies the framework's impact on learning quality.

The assessment strategy deliberately values creative synthesis and metacognitive awareness equally with conceptual accuracy, signaling to students that understanding involves more than memorization. This balanced approach encourages risk-taking and exploration while maintaining academic rigor.

7.4. Supporting advanced learners in specialized contexts

The framework holds particular value for gifted chemistry students in specialized STEM schools, where traditional instruction often fails to maintain engagement despite these learners' exceptional capabilities.

Advanced chemistry learners typically acquire concepts rapidly yet they crave deeper exploration. They seek complex, interconnected understanding rather than isolated facts, and while they possess sophisticated metacognitive abilities, they require intellectual challenges that push beyond standard curriculum. Their intrinsic motivation demands continuous stimulation through creative exploration within disciplinary boundaries.

For these students, complexity escalation begins immediately. Rather than progressing through simplified versions, advanced learners start with multi-dimensional organization. One particularly successful approach involves students simultaneously organizing oxygen compounds across three axes – structure, reactivity, and biological role – creating three-dimensional webs that reveal unexpected patterns. A student discovered that compounds with similar biological roles often share subtle structural features not emphasized in traditional texts.

Research integration becomes essential at this level. Students incorporate findings from primary literature, annotating where current research extends or challenges textbook knowledge. This practice develops

Table 5
Comprehensive assessment framework for chemistry mind maps.

Dimension (weight)	Assessment criteria	Developing	Proficient	Advanced
Conceptual radiance (25%)	• Hierarchical organization with clear central concept • Progressive specificity from center to periphery • Related ideas clustered spatially • Balance of breadth and depth	Fragmented structure; unclear hierarchy; missing key concepts; overwhelming or insufficient detail	Clear main branches with logical organization; most key concepts present; appropriate detail level	Elegant structure revealing deep conceptual relationships; comprehensive coverage; optimal detail balance
Representational integration (25%)	• Multiple types (formulas, structures, diagrams, graphs) • Representational alignment and consistency • Explicit translation indicators between forms • Appropriate representation choices for information type	Single representation type dominates; limited visual elements; inappropriate representation choices	Multiple representations present but not well integrated; some translation indicators; generally appropriate choices	Seamless integration of macro/micro/symbolic; clear translations; optimal representation selection; visual elegance
Creative synthesis (25%)	• Novel connections beyond instruction • Alternative organizational schemes • Predictive extensions to unknown cases • Personal insights and unique elements	Limited to obvious instructional connections; single organizational approach; no extensions	Some novel connections showing independent thinking; attempts at reorganization; basic extensions	Original insights revealing creative synthesis; multiple valid organizations; sophisticated predictions; unique perspectives
Metacognitive orchestration (25%)	• Self-monitoring evidence (corrections, revisions) • Strategic choice explanations • Reflection depth on learning process • Knowledge gap identification	No evidence of self-monitoring or revision; no reflection; unaware of gaps	Some annotations indicating awareness; basic strategic choices; surface-level reflection	Rich metacognitive commentary; sophisticated self-regulation; deep reflection; explicit gap identification
Portfolio assessment components	• **Initial attempts**: Ungraded with formative feedback only • **Revised versions**: Showing incorporation of feedback (weighted 30%) • **Transfer applications**: New topic applications (weighted 40%) • **Reflective commentary**: Learning journey analysis (weighted 30%)			
Scoring approaches	• **Formative**: Quick holistic scoring (novice/developing/proficient/advanced) for immediate feedback • **Summative**: Detailed analytic scoring using all four dimensions with equal weighting • **Self-assessment**: Simplified rubric focusing on personal growth and goal-setting • **Peer assessment**: Emphasis on clarity, creativity, and constructive feedback			

critical evaluation skills while maintaining engagement with cutting-edge chemistry.

Predictive modeling through mind maps challenges students beyond mere organization. Teachers prompt students to identify patterns within their maps and use these to hypothesize about unstudied compounds. Students then design theoretical experiments to test their predictions, bridging conceptual understanding with research methodology. This approach particularly resonates with students planning careers in chemical research.

Cross-disciplinary connections naturally emerge when advanced students explore boundary concepts. Rather than viewing chemistry in isolation, students create maps showing interface points with physics, biology, and mathematics. One memorable example involved a student mapping enzyme kinetics at the chemistry-biology boundary, revealing how chemical principles govern biological processes.

Peer teaching through mind maps serves dual purposes. Advanced students deepen their understanding by creating instructional maps for struggling peers, while developing communication skills essential for scientific careers. The challenge of simplifying complex concepts without sacrificing accuracy requires true mastery. Students report that explaining their maps to others often reveals gaps in their own understanding they hadn't recognized.

Even specialized STEM schools contain significant ability variation. The framework naturally accommodates these differences without creating obvious ability groupings that might discourage struggling students.

Depth differentiation allows all students to succeed at their level. While every student creates mind maps addressing the same core concepts, advanced learners add layers of complexity through additional representations, cross-connections, and theoretical extensions. A basic map might show alcohol oxidation pathways, while an advanced version includes mechanism details, energy considerations, and industrial applications.

Pace differentiation occurs organically as advanced students move through foundational phases quickly, spending extended time in creative synthesis. Teachers provide enrichment challenges rather than simply accelerating through content. This prevents the superficial coverage that often results from traditional acceleration models.

Product differentiation respects varying capabilities while maintaining high standards. The basic requirement might be a functional paper map demonstrating understanding, while advanced students create interactive digital versions with embedded simulations or develop augmented reality overlays showing three-dimensional molecular structures.

Process differentiation supports all learners appropriately. Struggling students receive partial templates and guided questions, while advanced students generate entirely novel organizational frameworks. This approach maintains challenge for all without overwhelming those needing additional support.

The framework's flexibility proves especially valuable during the disruptions common in Ukrainian schools. When advanced students finish tasks early during shelter periods, they can extend their maps rather than sitting idle. This productive use of variable time keeps engaged students learning regardless of external circumstances.

7.5. Professional development for educators

Successful framework implementation requires substantial teacher preparation. Training 24 Ukrainian chemistry teachers between 2021 and 2023 revealed both the essential components for effective professional development and the unexpected challenges that emerge when shifting pedagogical approaches.

Phase 1: Personal experience (8 hours)

Teachers must first experience the framework as learners themselves. This initial phase involves creating their own chemistry mind maps while experiencing all four dimensions firsthand. Through this process, educators identify personal challenges and develop genuine appreciation for the cognitive demands placed on students. One veteran teacher noted after completing her first comprehensive mind map: "I thought I understood oxidation-reduction after teaching it for 15 years. Creating a mind map revealed connections I'd never explicitly recognized." This personal engagement proves crucial. Teachers who skip this experiential learning struggle to guide students effectively, lacking the empathetic understanding that comes from grappling with the technique themselves. The eight-hour workshop includes individual mapping exercises, peer sharing sessions, and reflective discussions about the learning experience.

Phase 2: Theoretical grounding (8 hours)

Understanding the theoretical foundations transforms the framework from a novel technique into a principled pedagogical approach. Teachers explore radiant thinking theory in depth, examining how the brain naturally processes and organizes information. Johnstone's triplet receives particular attention, as many teachers haven't explicitly considered how students navigate between macroscopic, microscopic, and symbolic representations. Cognitive load management emerges as a revelation for many participants. Teachers begin recognizing how traditional linear presentations often overwhelm working memory, while visual organization distributes cognitive demands more effectively. Examining empirical evidence from both Western and Ukrainian classroom studies helps skeptical teachers recognize the framework's validity beyond mere novelty.

Phase 3: Practical application (16 hours)

The longest training phase focuses on classroom implementation. Teachers develop phase-appropriate activities tailored to their specific student populations, wrestling with the balance between structure and creativity. Creating assessment rubrics generates particularly rich discussions, as teachers collaboratively determine how to evaluate visual products fairly and consistently. Technology integration training adapts to available resources. Some schools have extensive digital capabilities, while others rely primarily on paper-based methods. Rather than mandating specific tools, training emphasizes principles that transcend medium. Teachers practice scaffolding techniques through role-playing exercises, taking turns as instructor and student to experience both perspectives. Classroom logistics receive careful attention. How do you manage thirty students creating large paper maps in limited space? What happens when half the class finishes while others still struggle with basic organization? These practical concerns, often overlooked in theoretical discussions, determine implementation success.

Phase 4: Collaborative refinement (ongoing)

Monthly teacher meetings maintain momentum beyond initial training. These sessions combine experience sharing, collaborative problem-solving, and student work analysis. Teachers bring examples of exceptional and struggling student maps, collectively developing strategies for common challenges. One particularly valuable practice involves "calibration sessions" where teachers independently assess the same student work, then discuss scoring differences. These conversations reveal hidden assumptions and gradually align assessment standards across classrooms.

Experienced teachers often express the strongest initial resistance, particularly those with established successful methods. They question why they should abandon approaches that have worked for years. This resistance dissolves when the framework is positioned as an enhancement rather than replacement – a tool that complements rather than supplants existing pedagogy.

Technology barriers extend beyond simple access issues. Some teachers lack digital literacy, feeling overwhelmed by software options. Starting with paper-based methods allows these educators to master the conceptual framework before adding technological complexity. As confidence grows, digital tools can be gradually introduced.

Time concerns dominate early discussions. Teachers worry that creating mind maps will prevent curriculum coverage, especially given examination pressures. Documenting improved retention rates and demonstrating how an initial time investment reduces review needs helps address these fears. Several teachers reported that students who used mind maps consistently required less examination preparation time, ultimately saving instructional hours.

Assessment anxiety surprises many trainers. Teachers comfortable evaluating traditional assignments feel uncertain judging visual products. Collaborative rubric development reduces this anxiety, especially when teachers analyze diverse student examples together. The shared struggle to articulate quality criteria builds community while improving assessment consistency.

Long-term success requires embedding support structures within schools rather than relying on external training alone. Teacher learning communities within schools provide ongoing encouragement and problem-solving capacity. These communities meet regularly, sharing successes and failures without judgment.

Resource repositories prevent redundant effort. Teachers contribute successful activities, assessment tools, and student exemplars to shared databases. This collective knowledge base grows organically, becoming increasingly valuable as more teachers contribute.

Mentorship partnerships between experienced and novice implementers accelerate learning curves. New adopters observe veteran teachers' classrooms, seeing the framework in action before attempting implementation themselves. These observations prove particularly valuable for classroom management strategies that are difficult to convey through descriptions alone.

Documentation and dissemination of best practices extend impact beyond individual schools. Teachers write case studies describing their implementation journeys, honestly discussing both successes and failures. These narratives, more than research papers, convince skeptical colleagues to attempt the framework.

Institutional support remains crucial for sustainability. Administrators who understand the framework's value provide necessary resources – time for collaboration, funding for materials, recognition for innovative practices. Without this support, even enthusiastic teachers eventually abandon the approach under competing pressures.

7.6. Addressing implementation challenges

Three years of implementation across Ukrainian chemistry classrooms revealed consistent obstacles that required systematic solutions. Table 6 presents the primary challenges encountered and the strategies developed through iterative refinement with teacher and student feedback.

The most significant insight from addressing these challenges was recognizing that perceived obstacles often became strengths when reframed appropriately. Time constraints forced the development of efficient scaffolding techniques that ultimately improved learning outcomes. Student resistance led to hybrid approaches that served diverse learning preferences better than pure mapping or traditional methods alone.

Resource limitations, particularly those unique to the Ukrainian context, sparked creative solutions that proved valuable beyond crisis situations. Teachers discovered that paper-based mapping during power outages actually enhanced student focus and reduced digital distractions. The physical act of drawing connections appeared to strengthen memory encoding compared to clicking and dragging in software applications.

Table 6
Implementation challenges and evidence-based solutions.

Challenge	Specific problems	Developed solutions	Implementation notes
Time constraints	• Comprehensive maps require 2-3x longer than linear notes initially • Class periods insufficient for complete mapping • Curriculum pacing pressure • Exam preparation time concerns	• Start with partial map templates for completion • Implement collaborative mapping to distribute effort • Shift complex mapping to homework assignments • Develop reusable templates for common topics • Create "speed mapping" exercises for review • Use checkpoint saves for interrupted work	Teachers report time investment returns through improved retention; students need 50% less review time for exams after consistent mapping practice
Student resistance	• Preference for familiar linear notes • Anxiety about artistic ability • Perception of maps as "extra work" • Fear of judgment on visual products • Skepticism about learning benefits	• Allow hybrid approaches initially (linear notes with map summaries) • Share previous cohort success stories and exemplars • Present exam performance data showing 18% improvement • Provide choice in final product format • Emphasize content over aesthetics • Use anonymous peer review initially	Resistance typically decreases after 3–4 weeks; 65% of initially resistant students become advocates by semester end
Resource limitations	• Limited technology access • Frequent power outages • Insufficient devices for all students • Poor internet connectivity • Lack of printing capabilities • Small classroom spaces	• Develop robust paper-based alternatives • Create phone-optimized versions for small screens • Implement peer sharing rotation for devices • Maintain physical map galleries on walls • Use LED lights and power banks during outages • Design foldable maps for space constraints	Paper-based methods proved equally effective for learning; digital tools enhance but don't determine success
Curriculum alignment	• Standardized exams test linear recall • No visual assessment in national tests • Prescribed content sequence conflicts with radiant organization • Limited flexibility in curriculum	• Document mapping's impact on traditional test scores • Include standard problems within map activities • Create "translation exercises" between formats • Develop exam preparation maps • Align map branches with textbook chapters • Advocate for assessment reform through evidence	Students using maps consistently scored 12–20% higher on traditional exams despite no direct assessment of mapping skills

Perhaps most importantly, the challenge of curriculum alignment forced careful documentation of learning outcomes. The evidence collected to justify the framework's use despite standardized testing pressures now provides compelling data for broader educational reform. Teachers initially worried that time spent mapping would decrease test scores; instead, the opposite occurred consistently across all implementation sites.

8. Discussion and future directions

8.1. Theoretical contributions

This framework makes several theoretical contributions to chemistry education that extend beyond the specific application of mind mapping to oxygen-containing compounds.

First, the framework challenges the traditional dichotomy between creative thinking and rigorous content learning in chemistry. Rather than treating creativity as an add-on to content mastery, we position creative synthesis as fundamental to deep understanding. This reconceptualization suggests that scientific creativity emerges from deep domain knowledge rather than generic creative thinking skills – a position supported by recent neuroscience (Beaty et al., 2019) but largely unexplored in chemistry education contexts.

The framework also proposes a synergistic learning model that departs from traditional instructional design assumptions. Most educational interventions assume additive effects, where combining good strategies yields proportionally better outcomes. Our framework suggests potentially multiplicative effects through dimensional interactions. When students simultaneously engage conceptual radiance with creative synthesis, the learning outcomes exceed what either dimension would produce independently. This synergistic model requires rethinking how we design and evaluate educational interventions.

Our work extends Johnstone's triplet by proposing that visual-spatial organization serves as a meta-representational system facilitating coordination among representations. This positions visual thinking not merely as one representation among many but as an organizing framework for representational integration. Students who develop strong visual-spatial schemas for chemical concepts demonstrate superior ability to translate between macroscopic, microscopic, and symbolic representations.

Finally, the framework's emphasis on creative reorganization and metacognitive orchestration aligns with theories of adaptive expertise (Schwartz et al., 2005). In rapidly evolving scientific fields, chemists need not only to apply knowledge but also to reconstruct it for novel situations. The framework provides concrete pathways for developing this adaptive capacity through iterative reorganization and reflection.

8.2. Limitations and boundary conditions

Despite these contributions, several limitations constrain the framework's applicability and interpretation.

8.2.1. Theoretical limitations

The most significant limitation involves empirical validation. While component evidence supports individual dimensions, the proposed synergistic interactions remain theoretical propositions. We synthesized existing research to construct the framework, but direct experimental validation of the integrated model awaits future research. The potentially multiplicative effects we propose, though consistent with observed student outcomes, require controlled studies to verify. While current evidence shows at least additive benefits, full synergy awaits targeted research.

Cultural and contextual factors also limit generalizability. The framework emerged from Ukrainian specialized chemistry education during extraordinary circumstances – war, power outages, and hybrid learning necessitated by crisis. Whether the framework maintains effectiveness in stable educational environments with different cultural attitudes toward visual learning remains unknown. Ukrainian students' resilience and adaptability during crisis may have influenced their receptiveness to novel pedagogical approaches.

Developmental prerequisites pose another constraint. The framework assumes certain cognitive capabilities – spatial reasoning, abstract thinking about molecular structures, metacognitive awareness – that younger students or those with specific learning differences may lack. We developed the framework with advanced secondary students (ages

15–17) who had already demonstrated strong academic performance. Adaptation for younger or struggling learners requires substantial modification.

Domain specificity represents a further boundary. While successful with oxygen-containing compounds, the framework's applicability to other chemistry domains remains unexplored. Inorganic chemistry, with its emphasis on crystal structures and coordination complexes, might benefit from visual-spatial organization, but physical chemistry's mathematical abstractions may resist mind mapping approaches.

8.2.2. *Practical limitations*

Implementation demands substantial resources often unavailable in typical educational settings. Teachers need extensive professional development – our experience suggests minimum of 32 hours of initial training plus ongoing support. Schools must allocate time for collaborative planning, provide materials for large-format mapping, and support teachers through the challenging transition period. These requirements exceed the capacities of many schools.

Current assessment systems create persistent tensions. Standardized examinations test linear recall and algorithmic problem-solving, poorly capturing the complex understanding developed through mind mapping. Teachers face the dilemma of preparing students for existing assessments while implementing pedagogical approaches that develop different competencies. Until assessment systems evolve, this tension remains unresolved.

Individual differences in cognitive style present challenges that the framework partially addresses. Students with strong verbal-sequential processing preferences may struggle with visual-spatial organization. While multiple representations provide alternative entry points, some learners genuinely benefit more from traditional linear instruction. The framework's visual emphasis, despite attempts at inclusivity, may inadvertently disadvantage certain learners.

8.2.3. *Methodological limitations*

Our theoretical synthesis process, though systematic, potentially reflects selection bias. Published studies disproportionately report positive findings, while negative results remain hidden in file drawers. The impressive effect sizes cited from meta-analyses may overestimate true effectiveness. Additionally, comparing effect sizes across different meta-analyses requires caution given heterogeneous study contexts, quality, and implementations.

The cognitive and neural mechanisms underlying proposed synergistic effects remain speculative. While we offer theoretical explanations for dimensional interactions, actual brain processes during mind mapping remain unmapped themselves. Neuroscientific investigation could reveal that apparent synergies result from simpler mechanisms than those proposed.

8.3. *Future research agenda*

8.3.1. *Empirical validation studies*

The most pressing need involves controlled intervention studies directly testing the framework's core propositions. Researchers should compare full framework implementation against component-only conditions to verify synergistic effects. For example, does combining all four dimensions truly produce multiplicative rather than additive outcomes? Longitudinal studies tracking students across multiple years could examine retention and transfer effects, particularly whether mind mapping skills developed in chemistry transfer to other domains.

Cross-cultural validation studies would test the framework's universality. Implementing the framework in diverse educational contexts – East Asian examination systems, Nordic collaborative learning environments, North American inquiry-based classrooms – would reveal cultural influences on effectiveness. Such studies should examine not just learning outcomes but also student and teacher receptiveness to visual-spatial approaches.

Mechanism investigation through cognitive neuroscience methods could illuminate how mind mapping affects learning. Eye-tracking studies during map creation would reveal attention allocation patterns and visual processing strategies. EEG or fMRI studies could identify neural networks activated during different dimensional engagements. These investigations would move beyond behavioral outcomes to understand underlying cognitive processes.

8.3.2. *Technological development*

Digital platforms specifically designed for chemistry mind mapping could extend the framework's reach. Current generic mind mapping software lacks chemistry-specific features like molecular structure drawing, reaction arrow notation, and three-dimensional visualization. Purpose-built platforms could provide intelligent tutoring, suggesting connections students might miss or identifying conceptual errors in real-time.

Augmented reality applications could bridge the gap between two-dimensional maps and three-dimensional molecular reality. Students could point devices at hand-drawn maps to see molecules spring into rotatable 3D models. Such tools would particularly benefit students struggling with spatial visualization, a critical skill in chemistry.

Assessment technology requires particular attention. Developing automated scoring algorithms for mind maps presents significant challenges but would enable wider implementation. Machine learning approaches could evaluate not just content accuracy but also organizational coherence and creative connections. However, such systems must avoid reducing rich visual products to simplistic metrics.

8.3.3. *Theoretical extensions*

Extending the framework to other science domains requires careful consideration of disciplinary differences. Physics, with its mathematical formalism and abstract concepts, might benefit from visual organization but requires different representational emphases. Biology's hierarchical organization from molecules to ecosystems naturally suits radiant structures. Mathematics, traditionally resistant to visual approaches, might benefit from mind mapping for problem-solving strategy development.

Integration with other pedagogical frameworks could amplify effectiveness. Combining mind mapping with problem-based learning could help students organize complex problem spaces. Laboratory instruction could incorporate pre-lab mind mapping for experimental design and post-lab mapping for results interpretation. Computational thinking frameworks could extend to include visual algorithm representation through mapped procedures.

8.4. *Implications for chemistry education reform*

The framework's development reveals fundamental tensions in current chemistry education that extend beyond Ukraine's specific context.

Traditional curriculum organization around discrete topics poorly serves students' needs for integrated understanding. The framework's success suggests that curricula organized around central principles with radiating applications might better support deep learning. Rather than separate units on alcohols, then aldehydes, then carboxylic acids, instruction could center on oxidation-reduction with these functional groups as interconnected examples.

Teacher preparation programs typically emphasize content knowledge and generic pedagogy while neglecting visual thinking strategies, creativity development, and metacognitive instruction. Pre-service teachers need experience creating their own mind maps, analyzing student visual products, and facilitating creative exploration within disciplinary boundaries. Current programs rarely provide such preparation.

Assessment systems require fundamental reconsideration. Portfolio-based assessments capturing learning progression over time better reflect the complex competencies the framework develops. Digital portfolios could include initial maps, revised versions, reflective commentary, and transfer applications. Such assessments, while more demanding to evaluate, provide richer information about students' understanding.

The framework also highlights equity challenges in contemporary education. While mind mapping naturally differentiates instruction, ensuring all students have access to necessary resources – large paper, colored markers, digital devices – remains problematic. Schools serving economically disadvantaged populations may struggle to implement the framework fully, potentially widening achievement gaps unless systemic support addresses resource disparities.

Emerging from crisis conditions, the framework demonstrates resilience in diverse contexts. Ukrainian teachers and students, forced to adapt rapidly to unprecedented disruptions, discovered that visual-spatial organization provided cognitive anchors during chaos. When linear instruction became impossible, radiant structures offered flexible pathways for continued learning. Perhaps stability has made education unnecessarily rigid; crisis revealed possibilities that comfort obscured.

9. Conclusion

This theoretical framework represents an attempt to address genuine pedagogical challenges emerging from crisis-disrupted chemistry education while contributing to broader theoretical understanding of how visual thinking, creativity, and metacognition interact in science learning. By integrating radiant thinking principles with chemistry-specific cognitive demands, the framework offers both practical guidance for educators facing similar challenges and theoretical insights for researchers investigating complex learning processes.

The framework's four dimensions – conceptual radiance, representational integration, creative synthesis, and metacognitive orchestration – provide a comprehensive architecture for understanding and implementing mind mapping in chemistry education. More importantly, their synergistic interactions suggest that learning outcomes can exceed the sum of individual instructional components when thoughtfully integrated.

While developed in response to specific challenges in Ukrainian chemistry education during unprecedented disruptions, the framework's theoretical foundations and empirical support suggest broader applicability. As chemistry education worldwide grapples with preparing students for increasingly complex scientific challenges, approaches that integrate content mastery with creative thinking and metacognitive awareness become essential.

The limitations acknowledged and future research directions proposed recognize that this framework represents a beginning rather than an endpoint. Theoretical frameworks require empirical validation, practical refinement, and continuous evolution based on emerging evidence and changing educational contexts. We offer this framework not as a definitive solution but as a conceptual tool for advancing both research and practice in chemistry education.

The ultimate test of any educational framework lies not in its theoretical elegance but in its capacity to enhance student learning. Initial implementations suggest that students using this framework develop not only stronger content knowledge but also enhanced creative thinking, metacognitive awareness, and genuine enthusiasm for chemistry. As one Ukrainian student noted in their final reflection: "Chemistry used to be about memorizing reactions. Now I see it as a beautiful web where everything connects. The mind map isn't just how I study chemistry – it's how I think about chemistry."

This transformation – from fragmented memorization to integrated understanding – represents the framework's ultimate aspiration. In a world requiring scientific thinkers who can both master complex content and apply it creatively to novel challenges, such transformation becomes not merely desirable but essential. The framework presented here offers one pathway toward this goal, inviting further development, refinement, and application by the global chemistry education community.

CRediT authorship contribution statement

Anna O. Polunina: Writing – original draft, Validation, Software, Investigation. **Viktoriia H. Stoliarenko:** Writing – original draft, Data curation, Conceptualization. **Pavlo P. Nechypurenko:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Serhiy O. Semerikov:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Ethics statement

Ethical approval is not applicable to this manuscript.

Declaration of the use of AI assisted technologies

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References

Akkuzu, N., & Uyulgan, M. A. (2016). An epistemological inquiry into organic chemistry education: Exploration of undergraduate students' conceptual understanding of functional groups. *Chemistry Education Research and Practice*, *17*, 36–57. https://doi.org/10.1039/C5RP00128E

Anastasiou, D., Wirngo, C. N., & Bagos, P. (2024). The effectiveness of concept maps on students' achievement in science: A meta-analysis. *Educational Psychology Review*, *36*, 39. https://doi.org/10.1007/s10648-024-09877-y

Aris, N. M., Ibrahim, N. H., & Halim, N. D. A. (2024). Design and development research (DDR) approach in designing design thinking chemistry module to empower students' innovation competencies. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *44*, 55–68. https://doi.org/10.37934/araset.44.1.5568

Baddeley, A. (2010). Working memory. *Current Biology*, *20*, R136–R140. https://doi.org/10.1016/j.cub.2009.12.014

Bandura, A. (1977). *Social learning theory*. Englewood Cliffs, NJ: Prentice-Hall. https://www.asecib.ase.ro/mps/Bandura_SocialLearningTheory.pdf.

Beaty, R. E., Seli, P., & Schacter, D. L. (2019). Network neuroscience of creative cognition: Mapping cognitive mechanisms and individual differences in the creative brain. *Current Opinion in Behavioral Sciences*, *27*, 22–30. https://doi.org/10.1016/j.cobeha.2018.08.013

Beier, J. P., Swart, M. I., Pazicni, S., & Nathan, M. J. (2024). Connecting chemistry understanding: An integrated framework for concretizing abstract visual representations. In R. Lindgren, T. I. Asino, E. A. Kyza, C. K. Looi, D. T. Keifert, & E. Suárez (Eds.), *Proceedings of the 18th international conference of the learning sciences - ICLS 2024* (pp. 242–249). International Society of the Learning Sciences. https://doi.org/10.22318/icls2024.905723

Benny, N., & Blonder, R. (2018). Interactions of chemistry teachers with gifted students in a regular high-school chemistry classroom. *Chemistry Education Research and Practice*, *19*, 122–134. https://doi.org/10.1039/C7RP00127D

Bola, M., & Sabel, B. A. (2015). Dynamic reorganization of brain functional networks during cognition. *Neuroimage*, *114*, 398–413. https://doi.org/10.1016/j.neuroimage.2015.03.057

Buzan, T., & Buzan, B. (1994). *The mind map book: How to use radiant thinking to maximize your brain's untapped potential*. New York: Dutton.

Chang, H. Y., Lin, T. J., Lee, M. H., Lee, S. W. Y., Lin, T. C., Tan, A. L., & Tsai, C. C. (2020). A systematic review of trends and findings in research employing drawing assessment in science education. *Studies in Science Education*, *56*, 77–110. https://doi.org/10.1080/03057267.2020.1735822

Cheng, M. M. W., & Gilbert, J. K. (2014). Students' visualization of metallic bonding and the malleability of metals. *International Journal of Science Education*, *36*, 1373–1407. https://doi.org/10.1080/09500693.2013.867089

Cooper, M. M., Grove, N., Underwood, S. M., & Klymkowsky, M. W. (2010). Lost in lewis structures: An investigation of student difficulties in developing representational competence. *Journal of Chemical Education*, *87*, 869–874. https://doi.org/10.1021/ed900004y

Dewi, C. A., Martini, M., & Mujakir, M. (2026). Trends and effectiveness of metacognitive strategies in chemistry learning: A systematic review. *Multidisciplinary Reviews*, *9*, 2026141. https://doi.org/10.31893/multirev.2026141

Dhindsa, H. S., Makarimi-Kasim, M., & Roger Anderson, O. (2011). Constructivist-visual mind map teaching approach and the quality of students' cognitive structures. *Journal of Science Education and Technology*, *20*, 186–200. https://doi.org/10.1007/s10956-010-9245-4

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman, & P. Pufall (Eds.), *Constructivism in the computer age* (pp. 49–70). Hillsdale, NJ. chapter 4, pp. Lawrence Erlbaum Associates. https://worrydream.com/refs/diSessa_1988_-_Knowledge_in_Pieces.pdf.

Fung, D. (2024). The synergy of peer collaboration and mind mapping in cultivating primary students' science understanding: An integrative pedagogy to enhance science concept acquisition. *International Journal of Science Education*, *46*, 131–154. https://doi.org/10.1080/09500693.2023.2222549

Gabora, L. (2018). The neural Basis and evolution of divergent and convergent thought. In R. E. Jung, & O. Vartanian (Eds.), *The Cambridge handbook of the neuroscience of creativity* (pp. 58–70). Cambridge University Press. Cambridge Handbooks in Psychology. chapter 4, pp. https://doi.org/10.1017/9781316556238.005

Gilbert, J. K., & Treagust, D. (2011). *Multiple representations in chemical education* (Vol. 4). Dordrecht: Models and Modeling in Science Education, Springer. https://doi.org/10.1007/978-1-4020-8872-8

Graulich, N., & Lieber, L. (2024). Why comparing matters – on case comparisons in organic chemistry. *Frontiers in Education*, *9*, https://doi.org/10.3389/feduc.2024.1374793

He, X., Li, Y., Xiao, X., Li, Y., Fang, J., & Zhou, R. (2025). Multi-level cognitive state classification of learners using complex brain networks and interpretable machine learning. *Cognitive Neurodynamics*, *19*, 5. https://doi.org/10.1007/s11571-024-10203-z

Jabareen, Y. (2009). Building a conceptual framework: Philosophy, definitions, and procedure. *International Journal of Qualitative Methods*, *8*, 49–62. https://doi.org/10.1177/160940690900800406

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, *7*, 75–83. https://doi.org/10.1111/j.1365-2729.1991.tb00230.x

Kamoun-Chouk, S. (2025). Mixing flipped classroom with mental mind mapping for deeper learning: A case study within the Tunisian higher education sector. *Journal of Information & Knowledge Management*, *24*, 2450107. https://doi.org/10.1142/S0219649224501077

Kefalis, C., Skordoulis, C., & Drigas, A. (2025). A systematic review of mind maps, STEM education, algorithmic and procedural learning. *Computers*, *14*, 204. https://doi.org/10.3390/computers14060204. https://www.mdpi.com/2073-431X/14/6/204.

Kenneally, C. D., & Bentley, B. (2024). A cognitive load approach to molecular geometries: Augmented reality technology and visuospatial abilities in chemistry. *Education Sciences*, *14*, 1036. https://doi.org/10.3390/educsci14091036

Knysh, S. M. (2020). Creating mental maps in chemistry lessons as a means of forming key and subject competencies in students. In *All-Ukrainian scientific-practical conference: Traditional and innovative approaches in the field of modern pedagogical research*. Kyiv, Ukraine: Center for Progressive Education Genezum. https://tinyurl.com/yk69p4p7.

Liu, Z., Kong, X., Liu, S., & Yang, Z. (2023). Effects of computer-based mind mapping on students' reflection, cognitive presence, and learning outcomes in an online course. *Distance Education*, *44*, 544–562. https://doi.org/10.1080/01587919.2023.2226615

Magnone, K. Q., & Yezierski, E. J. (2024). Applying the VisChem approach in high school classrooms: Chemical learning outcomes and limitations. *Journal of Chemical Education*, *101*, 727–740. https://doi.org/10.1021/acs.jchemed.3c00827

Mayer, R. E. ed). (2020). *Multimedia learning* (3rd ed.). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781316941355

Mundy, C. E., Potgieter, M., & Seery, M. K. (2024). A design-based research approach to improving pedagogy in the teaching laboratory. *Chemistry Education Research and Practice*, *25*, 266–275. https://doi.org/10.1039/D3RP00134B

Mutlu, A., & Acar Şeşen, B. (2020). Comparison of inquiry-based instruction in real and virtual laboratory environments: Prospective science teachers' attitudes. *International Journal of Curriculum and Instruction*, *12*, 600–617. https://ijci.net/index.php/IJCI/article/view/459.

Nelson, D. J., Kumar, R., & Ramasamy, S. (2015). Comparing carbonyl chemistry in comprehensive introductory organic chemistry textbooks. *Journal of Chemical Education*, *92*, 1171–1177. https://doi.org/10.1021/ed500421j

Novak, J. D., & Cañas, A. J. (2008). *The theory underlying concept maps and how to construct and use them*. technical report ihmc cmaptools 2006-01 rev 01-2008, Florida Institute for Human and Machine Cognition. https://cmap.ihmc.us/docs/theory-of-concept-maps.

Paivio, A. (1986). *Mental representations: A dual coding approach get access arrow*. New York: Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195066661.001.0001

Philipp, S. B., Johnson, D. K., & Yezierski, E. J. (2014). Development of a protocol to evaluate the use of representations in secondary chemistry instruction. *Chemistry Education Research and Practice*, *15*, 777–786. https://doi.org/10.1039/C4RP00098F

Polunina, A. O. (2022). *Forming concepts of oxygen-containing organic compounds using mind map technology in grade 10 students at specialized schools* (Master's thesis). Kryvyi Rih State Pedagogical University. https://elibrary.kdpu.edu.ua/handle/123456789/6872.

Schwartz, D. L., Bransford, J. D., & Sears, D. (2005). Efficiency and innovation in transfer. In J. P. Mestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective* (pp. 1–51). Information Age Publishing. chapter 1, pp. https://aaalab.stanford.edu/assets/papers/2005/Efficiency_and_Innovation_in_Transfer.pdf.

Shi, Y., Yang, H., Dou, Y., & Zeng, Y. (2023). Effects of mind mapping-based instruction on student cognitive learning outcomes: A meta-analysis. *Asia Pacific Education Review*, *24*, 303–317. https://doi.org/10.1007/s12564-022-09746-9

Smith, K. J., & Stonequist, S. (2010). *Challenging units for gifted learners: Teaching the way gifted students think (science, grades 6-8)*. New York: Routledge. https://doi.org/10.4324/9781003233558

Stefkova, G., Michalkova, J., Dimunova, L., & Halasz, B. G. (2024). Visualization of students' cognitive knowledge in digital concept mapping. *International Journal of Evaluation and Research in Education*, *13*, 240–246. https://doi.org/10.11591/ijere.v13i1.26349

Stieff, M., & Ryan, S. (2013). Explanatory models for the research & development of chemistry visualizations. In J. P. Suits, & M. J. Sange (Eds.), *Pedagogic roles of animations and simulations in chemistry courses* (Vol. 1142, pp. 15–41). ACS Symposium Series. chapter 2, pp. https://doi.org/10.1021/bk-2013-1142.ch002

Sweller, J., Ayres, P., & Kalyuga, S. (2011). Explorations in the learning sciences, instructional systems and performance technologies. In *Cognitive load theory* (Vol. 1). New York, NY: Springer. https://doi.org/10.1007/978-1-4419-8126-4

Talanquer, V. (2011). Macro, submicro, and symbolic: The many faces of the chemistry "triplet". *International Journal of Science Education*, *33*, 179–195. https://doi.org/10.1080/09500690903386435

Tang, M., & Neber, H. (2008). Motivation and self-regulated science learning in high-achieving students: Differences related to nation, gender, and grade-level. *High Ability Studies*, *19*, 103–116. https://doi.org/10.1080/13598130802503959

Vo, K., Sarkar, M., White, P. J., & Yuriev, E. (2025). Exploring problem-solving scaffolds in general chemistry: A systematic review of scaffolding goals and instructional approaches. *Journal of Chemical Education*, *102*, 1004–1018. https://doi.org/10.1021/acs.jchemed.4c01327

Vo, K., Sarkar, M., White, P. J., & Yuriev, E. (2025). Metacognitive problem solving: Exploration of students' perspectives through the lens of multi-dimensional engagement. *Chemistry Education Research and Practice*, *26*, 141–157. https://doi.org/10.1039/D4RP00096J

Wang, X. M., Wang, J. L., Xu, S. Y., & Xu, S. J. (2025). Concept mapping in STEM education: A meta-analysis of its impact on students' achievement (2004–2023). *International Journal of STEM Education*, *12*, 30. https://doi.org/10.1186/s40594-025-00554-2

Xu, L. (2022). Towards a social semiotic interpretation of the chemistry triangle: Student exploration of changes of state in an Australian secondary science classroom. *International Journal of Science and Mathematics Education*, *20*, 705–726. https://doi.org/10.1007/s10763-021-10190-1

Yoon, H., & Kang, S. (2015). The effect of integrated mind map activities on the creative thinking skills of 2nd year students in junior high school. *Journal of the Korean Chemical Society*, *59*, 164–178. https://doi.org/10.5012/jkcs.2015.59.2.164

Yue, M., Zhang, M., Zhang, C., & Jin, C. (2017). The effectiveness of concept mapping on development of critical thinking in nursing education: A systematic review and meta-analysis. *Nurse Education Today*, *52*, 87–94. https://doi.org/10.1016/j.nedt.2017.02.018