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Conceptual reframing in action: how students build and revise predictions about a simple chemical reaction

Onyinye Joy Ikenyirimba * and Vicente Talanquer

Predicting the outcome of a chemical reaction requires selecting and coordinating structural, thermodynamic, and kinetic ideas, yet little is known about how students activate and integrate these conceptual resources in real time. In this study, 25 undergraduate and graduate chemistry students completed think-aloud interviews while reasoning about a simple reaction presented through symbolic, particulate, and thermodynamic representations. Analysis of students' predictions across successive prompts revealed three initial interpretative frames: stoichiometric completion, surface equilibrium, and temperature-feasibility, each cued by surface features of the representations. As new thermodynamic information was introduced, students frequently reframed their thinking, although in partial ways, including the emergence of an energetic-favorability frame and instances of frame collapse. Coordinated use of structural, thermodynamic, and kinetic concepts was rare. These findings highlight the central role of context-sensitive framing in chemistry reasoning and point to the need for instruction that supports frame recognition, conceptual reframing, and coordination across conceptual domains.

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Introduction

Solving and understanding chemistry problems often requires not only recalling relevant concepts but also coordinating multiple conceptual frames—mental lenses through which individuals interpret information, decide what to focus on, and determine which ideas are most relevant (Gordon and Tannen, 2023). For example, when predicting the outcome of a chemical reaction, chemists may adopt several different frames (Talanquer, 2018; 2021):

• A *structural frame* that focuses on how chemical composition and bonding patterns affect stability.

• A *thermodynamic frame* that evaluates energetic and entropic factors, such as ΔH and ΔS, that influence reaction favorability.

• A *kinetic frame* that emphasizes activation barriers and rates for forward and reverse processes.

Experts routinely integrate diverse disciplinary perspectives, shifting fluidly among them depending on the explanatory goals of the task (Chi *et al.*, 1988; Slominski *et al.*, 2020).

However, students often struggle to make such shifts. A substantial body of educational research has documented that students may possess relevant knowledge yet fail to activate or apply it productively when solving problems (Hammer *et al.*, 2005; Wagner, 2006; Goodhew *et al.*, 2021). These difficulties may arise not only from gaps in conceptual understanding but from framing failures, such as relying on a single interpretive lens, overlooking important information, or being unable to coordinate multiple representations and ideas. In chemistry, for example, a student might correctly build a structural interpretation of a reaction but fail to integrate thermodynamic or kinetic considerations or fail to recognize when these frames would be more informative.

The present study examines these challenges through a chemical-reaction prediction task designed to probe students' capacity to shift and coordinate conceptual frames. Undergraduate and graduate chemistry students were asked to predict the outcome of a generic chemical reaction, $A + B \rightleftharpoons AB$, taking place at a given temperature, and presented both symbolically and through a particulate-level diagram. Additional information (thermodynamic data, an energy diagram, and new temperature conditions) was introduced sequentially, enabling us to analyze how students activated, revised, or maintained their interpretations in response to new cues.

By tracing how students responded to changing information, we sought to better understand (1) the conceptual frames students default to when making predictions, (2) how new information shapes their reasoning and whether it triggers reframing, and (3) the extent to which they coordinate structural, thermodynamic, and kinetic ideas. The findings reveal systematic patterns in students' reasoning, highlight barriers to frame shifting and coordination, and suggest instructional strategies that may

Department of Chemistry and Biochemistry, University of Arizona, Tucson, AZ 85721, USA. E-mail: ikenyirimbajoy@arizona.edu

more effectively support integrated knowledge structures and productive conceptual framing in chemistry problem-solving.

Literature review

A central finding in the learning sciences is that possessing normative disciplinary knowledge does not guarantee that it will be used productively (National Research Council, 2000). Learners must also be able to activate relevant knowledge in response to contextual cues (Hammer *et al.*, 2005; Förster and Liberman, 2007). According to resource-based models of cognition, knowledge is organized as a set of fine-grained cognitive resources that are selectively triggered by situational features (Hammer, 2000; Redish, 2004; Taber, 2008a, 2008b). From this perspective, students' difficulties in chemistry may reflect failures of activation rather than conceptual absence: they may have learned about Gibbs free energy or activation energy but fail to recognize when those ideas are relevant to a problem.

The concept of framing provides a powerful lens for understanding such challenges (Hammer *et al.*, 2005; Gordon and Tannen, 2023). Framing refers to the learner's implicit sense of "what kind of activity is this?", which shapes the knowledge, strategies, and representations they see as relevant. In chemistry problem-solving, students may frame a task as requiring algorithmic calculation rather than causal explanation or may adopt a macroscopic frame when a submicroscopic one is more meaningful (Sevian and Couture, 2018).

Closely related to this perspective, Data-Frame Theory (Klein *et al.*, 2006; Klein *et al.*, 2007) conceptualizes sensemaking as an iterative interaction between interpretive frames and incoming data. In this account, frames function as working mental models that guide attention and interpretation, while new data are evaluated in relation to those frames. Learners may elaborate or preserve an existing frame when new information appears consistent with expectations, or reframe when persistent anomalies render the current frame untenable. Recent chemistry education research drawing on Data-Frame Theory has examined how students interpret experimental data (Berg and Moon, 2023; Zhou and Moon, 2023; Hamilton *et al.*, 2025). These studies suggest that students often strive to preserve their initial frame, assimilating new data into existing interpretations rather than replacing them. Reframing, in this context, is typically triggered by sustained inconsistencies that challenge the adequacy of *a prior* interpretation.

These different perspectives on the role of framing highlight that reasoning difficulties may arise not simply from incorrect knowledge but from how learners interpret the situation and manage evolving information. Their prior applications in chemistry education have focused on how students approach problem-solving (Sevian and Couture, 2018) and data analysis and interpretation (Berg and Moon, 2023). Less attention has been given to how students shift among coexisting disciplinary lenses, such as structural, thermodynamic, or kinetic frameworks, when reasoning about a single conceptual phenomenon. The present study builds on this broader framing literature by examining how students activate, revise, and coordinate disciplinary frames in response to changing representational and informational cues.

Expert reasoning depends on epistemic control—the ability to monitor and shift frames when a chosen lens no longer serves explanatory goals (Greene *et al.*, 2016; Hofer, 2018). Without such control, students often remain "stuck" in a single frame even when they possess relevant alternative knowledge. Thus, failures in chemical reasoning may stem not from insufficient knowledge or persistent alternative conceptions, but from inappropriate framing and limited metacognitive awareness of alternative frames.

Many chemistry problems require not only activating a productive frame but also coordinating multiple conceptual frameworks and representations. Research on representational competence has shown that students struggle to translate or reconcile information across symbolic, particulate, graphical, and mathematical forms (Kozma and Russell, 1997; Kozma and Russell, 2005; Rau, 2018). However, most of this work has focused on representational formats rather than conceptual frameworks.

Recent scholarship emphasizes the importance of conceptual coordination in chemistry learning: the ability to link structural, energetic, mechanistic, and statistical explanations, and to understand how different explanatory lenses map onto one another (Talanquer, 2021). This type of coordination is critical in chemistry because many phenomena can be productively interpreted through multiple theoretical models, causal mechanisms, and analytical perspectives (Chang, 2014; Schummer, 2015; Ruthenberg and Mets, 2020). When students do not coordinate such frames, their reasoning remains fragmented and brittle, limiting conceptual transfer and preventing the development of expert-like understanding.

The ability to choose, shift, and coordinate conceptual frames is closely tied to research on metacognition and adaptive expertise (Hofer, 2018). Adaptive experts are not only efficient in routine contexts but also demonstrate cognitive flexibility, enabling them to reinterpret problems and revise their thinking when conditions change. Recent reconceptualization of adaptive expertise highlights three interrelated capacities: (1) coordination of cognitive and material resources, (2) reframing of problems and goals, and (3) navigational foresight in planning and justification (Martin and Dixon, 2024).

Empirical studies that examine how students dynamically adapt their ideas and shift conceptual frames in response to changing information remain scarce (Goodhew *et al.*, 2021). The present work contributes to this gap by analyzing frame activation and coordination in real time as students revise predictions about a simple chemical reaction. In doing so, we aim to clarify the cognitive challenges that limit flexible reasoning and inform the design of curricula and instruction that better support frame awareness and conceptual integration.

Theoretical framework

Chemistry is a fundamentally pluralistic science: the same phenomenon can be legitimately conceptualized through multiple theories, models, causal mechanisms, and analytical frameworks, each grounded in distinct ontologies, explanatory goals, and representational systems (Taber, 2008a, 2008b; Chang, 2014; Schummer, 2015; Ruthenberg and Mets, 2020; Talanquer, 2025). Bonding may be framed through Lewis structures, molecular orbital theory, or valence bond theory; chemical change may be interpreted using particulate models, reaction mechanisms, or thermodynamics. Expert reasoning in chemistry, therefore, depends not only on conceptual knowledge but on the ability to select, shift among, and coordinate multiple conceptual frames, each offering partial but useful insights into a given problem.

In this paper, we use the term *conceptual frame* to refer to a locally coherent configuration of conceptual resources, representational tools, and explanatory commitments that becomes activated in response to a task. The term *lens* is used more metaphorically to emphasize that such frames selectively foreground certain entities, relationships, and causal mechanisms while backgrounding others. When we refer to structural, thermodynamic, or kinetic "lenses," we are describing disciplinary frames that differ in ontological focus and explanatory goals. These lenses are not individual concepts but organized patterns of resource activation that exhibit internal coherence.

We refer to the capacity to deliberately reorganize one's reasoning across such frames as conceptual reframing (Talanquer, 2026): the deliberate reorganization of one's conceptual resources to align with a different explanatory lens when new information, goals, or constraints make an existing frame insufficient. Conceptual reframing is related to, but distinct from, the reframing processes described in Data-Frame Theory (Klein *et al.*, 2006; Klein *et al.*, 2007). In Data-Frame Theory, reframing occurs when incoming data can no longer be assimilated within a working interpretive model, prompting revision or replacement of that model. In contrast, the form of conceptual reframing examined here arises not primarily from anomalous data but from the coexistence of multiple legitimate disciplinary lenses that can be applied to the same phenomenon. These lenses may all be valid yet emphasize different explanatory aims and representational systems. Reframing in this context does not necessarily require abandoning an incorrect interpretation; rather, it involves recognizing the limits of a currently activated lens and adopting or coordinating an alternative one better suited to the problem's goals. Conceptual reframing, as defined here, is therefore grounded in disciplinary pluralism rather than solely in anomaly resolution.

Although similar in some aspects, conceptual reframing is not simply conceptual change in the sense of learning to prioritize a scientific idea over an intuitive one (Potvin, 2023), nor is it merely representational fluency (Daniel, 2018). Instead, it reflects a metacognitive and epistemic capacity to evaluate the purposes and limits of different frameworks and to adapt reasoning accordingly. As such, conceptual reframing constitutes a core condition for transfer in chemistry, where movement across levels of representation (*e.g.*, submicroscopic *vs.* macroscopic), across subdisciplines (*e.g.*, physical *vs.* organic chemistry), and across explanatory logics (*e.g.*, energetic *vs.* structural arguments) is routinely required.

Drawing on prior work, we propose that conceptual reframing depends primarily on two interacting mechanisms (Talanquer, 2026):

1. *Context-sensitive activation*: this mechanism involves recognizing cues that signal which conceptual frame is most productive for interpreting a problem (Förster and Liberman, 2007; Goodhew *et al.*, 2021). In chemical reasoning, such cues may include the presence of thermodynamic data, reaction coordinate diagrams, molecular structures, or particulate representations. Activation determines which organized configuration of resources becomes foregrounded at a given moment.

2. *Conceptual coordination*: this mechanism refers to the establishment of explicit inferential links between ideas expressed within different conceptual frames. Coordination occurs when a learner does not merely shift from one lens to another, but actively relates claims generated in one frame to claims generated in another. For example, linking structural features to thermodynamic stability. Coordination, therefore, involves cross-frame mapping and constraint alignment, rather than simple co-activation or sequential switching between frames (Linn, 2005; Markauskaite and Goodyear, 2017).

Conceptual coordination is analytically distinct from epistemic control. Epistemic control concerns monitoring one's reasoning, evaluating the adequacy of an active frame, and deciding whether to maintain, revise, or replace it (Saba *et al.*, 2023). Activation determines which frame comes online; coordination determines how ideas across frames are related; epistemic control governs when and why reframing occurs.

The reaction task used in this study was designed to elicit conceptual reframing by requiring students to interpret a simple chemical system first with minimal information, then with thermodynamic data and kinetic information. This structure allows us to examine:

- Which frames students initially activate
- How new information induces (or not) frame shifts
- Whether students coordinate multiple explanatory lenses or remain bound to a single frame

Through this lens, students' reasoning is evaluated not solely in terms of correctness, but as evidence of their capacity—or difficulty—to engage in conceptual reframing in a pluralistic disciplinary context.

Research goals and questions

The goal of this study was to investigate how undergraduate and graduate chemistry students activate and coordinate conceptual frames when predicting the outcome of a chemical reaction. We examine the ways students interpret the problem, how those interpretations shift (or fail to shift) as new information is introduced, and what these patterns reveal about their capacity for conceptual reframing.

To this end, we focus on the cognitive resources students draw upon as well as the barriers that prevent productive frame activation and coordination. The following research questions guided the study:

• What features, concepts, and representational cues do students attend to when making initial predictions about a chemical process? (*Context-sensitive activation*)

• How do students' conceptual frames shift, or remain stable, as new thermodynamic and kinetic information is provided? (*Frame revision and reframing*)

• To what extent do students coordinate structural, thermodynamic, and kinetic ideas when reasoning about the system? (*Conceptual coordination*)

Together, these questions enable us to characterize how students organize and reorganize their knowledge in response to changing task demands.

Research methods

Context and participants

This study was conducted at a public, research-intensive university in the United States and involved both chemistry graduate students (n_{GS} = 19) and undergraduate students (n_{UGS} = 6) who had completed at least one year of general chemistry coursework. This criterion ensured that all participants had been exposed to foundational concepts related to chemical reactions. A total of 25 student volunteers participated in the study. For ease of reference, they are identified as Participant 1 through Participant 25 (P1–P25) in the sections that follow.

All participants were thoroughly informed of their rights as human subjects, and informed consent was obtained in accordance with the Institutional Review Board (IRB) procedures at the university. These steps ensured that ethical standards were upheld throughout the research process.

Research instrument and data collection

All participants completed a semi-structured think-aloud interview lasting between 15 and 30 minutes, conducted *via* Zoom. Interviews were video recorded, transcribed, and anonymized for analysis. The use of Zoom was motivated by both pragmatic and methodological considerations. At the time of data collection, the interviewer had limited mobility, and many participants were in different locations and had highly variable schedules. Prior research has documented that synchronous video-based interviews can yield data comparable in quality to in-person interviews, particularly for think-aloud protocols that focus on verbalized reasoning (Lobe *et al.*, 2022; Anthony *et al.*, 2025). To minimize potential constraints associated with the online format, participants were encouraged to use Zoom's annotation tools to draw, highlight, or mark features on the slides when helpful. They were also invited to write or sketch on paper and share their work *via* screen sharing, chat upload, or email during the session. In practice, most reasoning was verbal, but participants had access to multiple modalities for externalizing their thinking (Chatha and Bretz, 2020).

The interview task was developed by the second author and was informed by prior tasks used in the Chemical Thinking curriculum at the University of Arizona (Talanquer and Pollard, 2010). The initial version was designed to elicit reasoning across structural, thermodynamic, and kinetic perspectives using a simplified reaction system. Both authors engaged in iterative discussions to refine the task's content, structure, and sequencing to ensure conceptual clarity and alignment with the study's theoretical goals. Adjustments were made to the wording of prompts, the order in which information was introduced, and the representational features included in each slide. This collaborative refinement process aimed to enhance the task's ability to elicit shifts in reasoning while maintaining coherence and accessibility for participants.

The interview protocol was designed to elicit participants' real-time reasoning, including their initial conceptual framing of the problem, their responses to new information, and any shifts in their predictions or justifications. Participants were told at the outset that they would analyze a chemical system and make predictions about its behavior. They were not informed that additional information would be introduced in stages. This decision was intentional, as the goal was to observe how students responded to the information available at each moment without anticipating future prompts.

Each interview began with a PowerPoint slide displaying the initial prompt (Fig. 1a). The slide presented a simple chemical reaction between single atoms, $A + B \rightleftharpoons AB$, shown in both symbolic form and *via* a particulate-level diagram, taking place at 300 K. Participants were given five possible answer choices: four particulate depictions of potential outcomes at equilibrium and a fifth option stating that more information would be needed to determine the result. Participants were asked to read the prompt aloud and articulate their thinking as they selected and justified an initial prediction. No time limits were imposed, and additional information was not introduced until the participant had clearly articulated and justified their reasoning.

After participants completed their analysis of Slide 1, the interviewer advanced to Slide 2, which introduced additional thermodynamic information (ΔH and ΔS values) and a qualitative energy diagram (Fig. 1b). The transition occurred only after the participant had committed to an initial prediction and explanation. At this stage, participants were asked whether they wished to revise their prediction considering the new information and to explain any changes in reasoning. Slides 3 and 4 did not introduce new types of information; rather, they modified the temperature condition (292 K and 305 K, respectively) while keeping all other data constant (Fig. 1c and d). Participants were again invited to predict system behavior and justify their responses.

The use of a simplified generic reaction was intentional. Because the task involves bond formation, one can qualitatively infer that the process is likely exothermic ($\Delta H < 0$), while the reduction in particle number suggests a decrease in entropy ($\Delta S < 0$). Thus, reaction favorability depends on temperature, and numerical prediction of the equilibrium state would require coordination of thermodynamic relationships (*e.g.*, ΔG and K). The task therefore offered opportunities for students to apply structural, thermodynamic, and kinetic reasoning, both qualitatively and quantitatively, if they recognized the relevant cues.

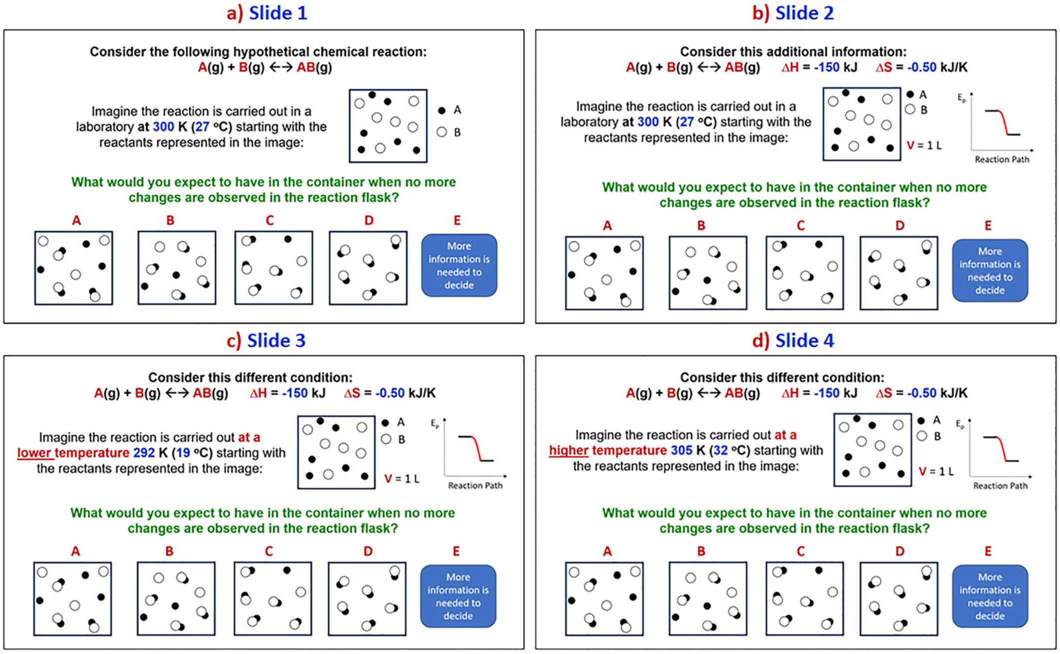

Fig. 1 Sequence of slides used to elicit and track students' reasoning during the interview. (a) Slide 1 presents the reaction in symbolic and particulate representations and asks students to predict the system's outcome at 300 K. (b) Slide 2 introduces additional thermodynamic information (ΔH and ΔS), a qualitative energy diagram, and the container volume, prompting students to reconsider their prediction. (c) Slide 3 maintains all prior information but lowers the temperature to 292 K, asking students to revise their prediction under the new condition. (d) Slide 4 similarly varies only the temperature (305 K), inviting further revision and comparison of reasoning across conditions.

Overall, the interview instrument was designed to probe students' capacity to activate and coordinate multiple conceptual frameworks under progressively changing informational conditions. By introducing thermodynamic data only after an initial prediction had been articulated, and subsequently varying temperature while holding other variables constant, the protocol allowed us to observe when students preserved, revised, or reorganized their conceptual frames in response to evolving information and constraints.

Data analysis

Interview transcripts were analyzed using a qualitative, iterative thematic approach designed to characterize (a) the conceptual resources students activated, (b) the interpretive frames that organized those resources, and (c) how students revised or coordinated ideas across stages of the task.

The analysis proceeded in three stages.

1. *Open coding (inductive phase)*. Both authors independently coded an initial subset of transcripts to identify recurring ideas, attention patterns, and justifications without imposing predetermined categories tied to canonical chemistry knowledge. Codes captured what students explicitly attended to (*e.g.*, particle ratios, reversible arrow, ΔH value, collision frequency), how they justified predictions (*e.g.*, "goes to completion," "exothermic means favored"), and how they responded to new cues. At this stage, we did not code for correctness or completeness relative to normative expectations; rather, we focused on identifying the interpretive structures students themselves constructed.

2. *Code refinement and frame construction*. Through iterative comparison and discussion, initial codes were clustered into broader set of reasoning that functioned as locally coherent interpretive frames (*e.g.*, Stoichiometric Completion, Surface Equilibrium, Temperature–Feasibility). These frames were derived from patterns in students' discourse (which ideas co-occurred and how they structured predictions) rather than from *a prior* disciplinary categories. The identification of frames preceded evaluation of how fully students integrated canonical thermodynamic concepts.

3. *Thematic synthesis and coordination analysis.* In a subsequent analytic layer, we examined the extent to which students coordinated structural, thermodynamic, and kinetic ideas within or across frames. At this stage, normative thermodynamic relationships (*e.g.*, ΔG–K connections, integration of ΔH and ΔS) served as an interpretive benchmark for assessing coordination. This benchmark was not used to define the frames themselves, but to characterize how reasoning within a frame aligned with or diverged from canonical disciplinary integration.

To ensure trustworthiness, the two coders established inter-rater agreement through repeated calibration, negotiated consensus, and documentation of decision-making throughout the coding process. The coding scheme evolved iteratively, but all changes were applied retroactively to earlier transcripts to maintain coherence.

This analytic approach allowed us to preserve the inductive identification of students' framing patterns while also examining how those patterns related to disciplinary expectations.

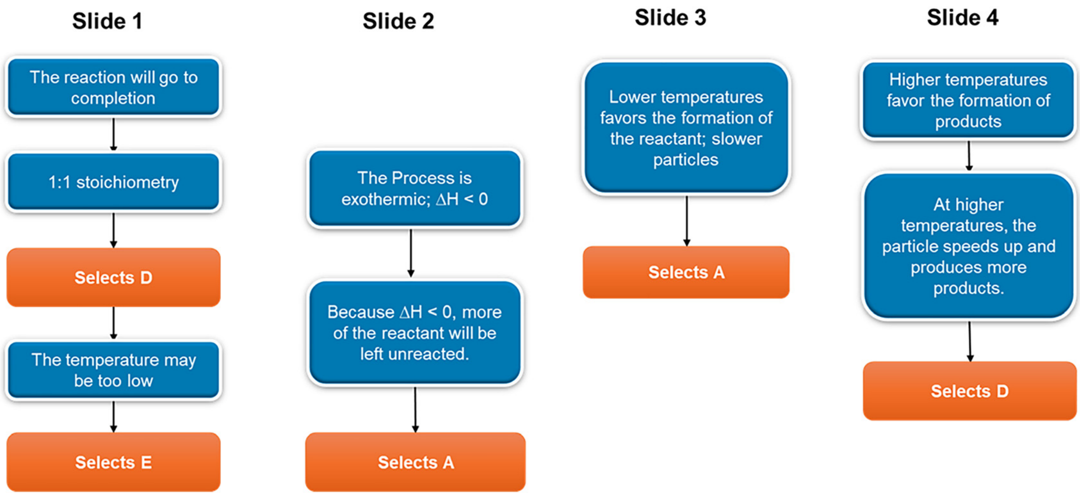

Fig. 2 Example of a reasoning diagram constructed to support inferences about conceptual reframing (Participant P5). Arrows represent the flow and evolution of ideas within slides. Conceptual frames were inferred from the ideas students articulated as they engaged with the information presented at each stage. The complete set of diagrams for all study participants is provided in the SI.

A purely deductive coding scheme centered on specific thermodynamic concepts (*e.g.*, ΔG, K, entropy) would have obscured the broader interpretive structures students constructed and would not have captured frames such as Temperature–Feasibility or Frame Collapse, which do not map neatly onto canonical categories.

Reasoning diagrams were constructed for each participant to visualize the organization and evolution of ideas across stages, supporting inferences about frame stability and reframing. Fig. 2 presents an example of these diagrams; the complete set is provided in the SI.

Main findings

Analysis of interview data revealed that students relied on a limited range of conceptual resources when making predictions about the outcome of the reaction and struggled to shift or coordinate conceptual frames, even when additional information was introduced. The findings are organized around the three research questions guiding the study.

RQ1: What features, concepts, and representational cues do students attend to when making initial predictions about a chemical process? (*Context-sensitive activation*)

Analysis of student reasoning on the initial slide revealed three distinct frames guiding their early interpretations: (1) a *Stoichiometric Completion* Frame, (2) a *Surface Equilibrium Frame*, and (3) a *Temperature–Feasibility Frame*. These frames reflect the cues students noticed and the cognitive resources they activated when making their first prediction.

1. *Stoichiometric Completion Frame* (15/25 students; 60%). Most participants initially interpreted the reaction through a stoichiometric lens, focusing primarily on relative particle counts and the 1 : 1 reactant ratio depicted in the particulate diagram. Students assumed that the reaction would proceed to completion, predicting that all six A atoms and all six B atoms would form six AB molecules. Typical justifications included statements such as:

• *"There are 6 A and 6 B... There should be 6 products."* (P20)
• *"My first thought is counting the number of atoms between the 2 molecules, and they are equal. So, if they did fully react, I would choose like D."* (P9)
• *"The reaction would probably go to completion. And the A plus B equals AB. It's a one-to-one ratio."* (P18)

This frame reflects a strong reliance on explicit representational cues (particle counts, atom pairing) and generalized reaction-completeness assumptions. Notably, this frame was used by both undergraduates and graduate students, suggesting that reliance on surface features persists even at advanced levels.

In terms of answer choices, all students in this frame selected Option D as their initial prediction, which depicts complete conversion to AB.

2. *Surface Equilibrium Frame* (6/25 students; 24%). A smaller subset of students adopted what we describe as a surface equilibrium frame, typically triggered by the presence of the double arrow in the chemical equation. These students inferred that the reaction does not go to completion, but their reasoning rarely extended beyond this minimal interpretation:

• *"With arrows like on the reaction. You know, you have these arrows going both ways. So, you know, technically, you have these molecules being formed. But then they go back to being A and B."* (P25)

Students in this frame selected Options A, B, or C (various mixtures of A, B, and AB) or Option E ("More information needed"), but generally offered little justification for the relative proportions they chose. Only three students referenced dynamic equilibrium, and just one student connected equilibrium behavior to thermodynamics or free energy.

This frame was thus characterized by:

• Recognition of reversibility based on notation,
• Minimal causal or energetic reasoning,

• A lack of connection between equilibrium and underlying thermodynamic factors.

3. *Temperature-Feasibility Frame* (4/25 students; 16%). A third group selected Option E, indicating that more information was needed, often citing temperature as a key missing factor. These students did not refer to equilibrium, nor did they meaningfully engage with thermodynamic concepts. Instead, they seemed to adopt a feasibility frame, treating the reaction as conditional, as illustrated by this excerpt:

• *"Usually gas at like room temperature, they don't react that much unless you heat them up a little bit."* (P10)

Two participants (2/25; 8%) in this group cited the need for additional thermodynamic information, such as ΔH and ΔS, to make a prediction.

This frame appears to reflect attention to conditionality cues: the notion that reactions depend on external conditions, and some level of engagement with thermodynamic reasoning.

Across all three frames, students consistently drew on:

• *Explicit representational cues* (particle counts, arrow type)

• *Generalized intuitive assumptions* (*e.g.*, "*reactions go to completion*")

• *Heuristic reasoning* (*e.g.*, "*more collisions → more product*")

In contrast, more sophisticated conceptual resources, such as ΔG–K relationships, the interplay of ΔH and ΔS, or qualitative predictions about bond formation and entropy, were rarely activated spontaneously. Only one student inferred that the reaction was likely exothermic based on bond formation.

Even students who later demonstrated knowledge of thermodynamics or kinetics did not initially activate these resources, suggesting that their challenge stemmed not from conceptual absence but from context-sensitive activation: these students did not perceive the cues that would typically signal the relevance of those frameworks.

Initial frames were not stable in all cases, and several students revised their predictions even before additional information was provided (see alluvial diagram in Fig. 3). Nine of the 25 participants (36%) changed their answer while analyzing the first slide. The shift reflected a change in conceptual frame, moving from a Stoichiometric Completion Frame to either a Surface Equilibrium Frame (6 students) or a Temperature–Feasibility Frame (2 students) after noticing overlooked cues (such as the double arrow) or when prompted to justify their reasoning. The following excerpt illustrates these types of frame switches:

• *"I didn't realize at first that it was like the two arrows on top in the equation. Note that it's an equilibrium reaction, so it probably wouldn't go to completion."* (P18)

Only one of the students who changed their answer switched from a Temperature-Feasibility frame to a Surface Equilibrium frame after considering factors that could influence chemical equilibrium.

This early-phase re-analysis highlights the fragility of students' initial interpretations and demonstrates how readily their framing can shift, or be refined, in response to newly noticed representational cues or metacognitive prompts. These shifts occurred without the introduction of new data, suggesting that students' initial frames are context-sensitive and weakly anchored.

RQ2: How do students' conceptual frames shift—or remain stable—as new thermodynamic and kinetic information is provided? (*Frame revision and reframing*)

When students were presented with additional information on Slide 2, including the reaction's enthalpy and entropy changes ($\Delta H = -150$ kJ; $\Delta S = -0.50$ kJ K^{-1}) and a qualitative energy diagram, their reasoning patterns shifted in several ways. Although these data were sufficient for a complete thermodynamic analysis ($\Delta G = 0$ at 300 K, implying $K = 1$), very few participants used or coordinated the concepts needed to make such a prediction. Instead, the new information triggered divergent reframing paths, giving rise to five patterns: (1) emergence of a new *Energetic Favorability* Frame, (2) near disappearance of

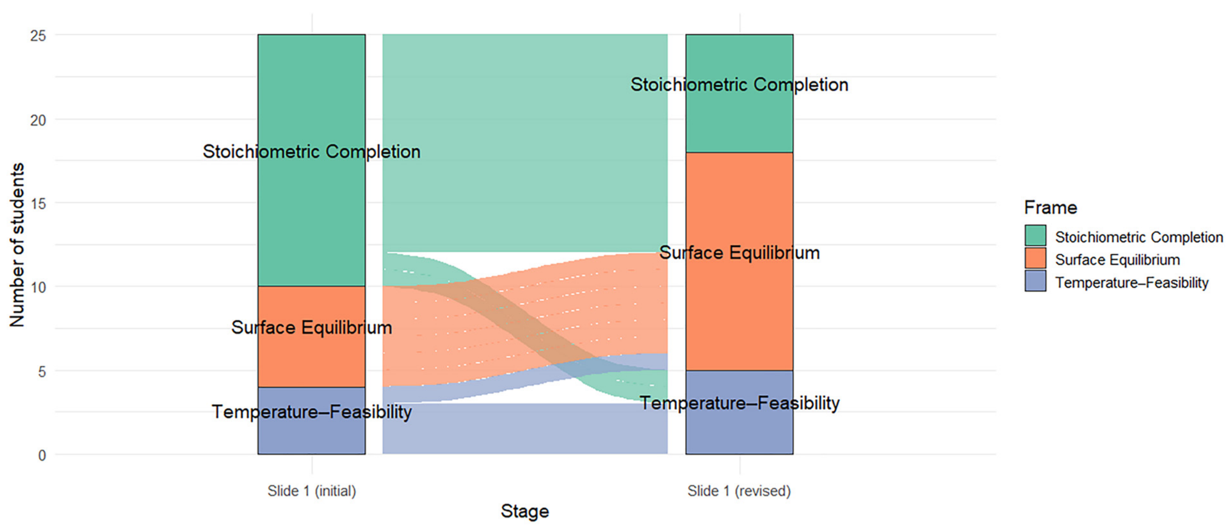

Fig. 3 Alluvial diagram showing shifts in the initial framing of the reaction on Slide 1.

the *Stoichiometric Completion* Frame, (3) modest persistence of the *Surface Equilibrium* Frame, (4) dissolution of the *Temperature–Feasibility* Frame, and (5) an *Epistemic-Uncertainty* (Frame-Collapse) response. Below, we describe the dominant patterns that emerged when students confronted the new data.

1. *Emergence of an Energetic Favorability Frame* (14/25 students; 56%). The most prominent shift following the presentation of thermodynamic data was the emergence of an Energetic Favorability Frame, adopted by fourteen students who originally held diverse frames. Students in this group focused almost exclusively on enthalpy ($\Delta H < 0$) or the potential energy diagram, often concluding that:

• *"It looks like the reactants have a higher energy than the products. So, then, once equilibrium is reached, I think I might expect to see more product."* (P12)

• *"If it's a more stable product, then it probably will want to go to completion."* (P24)

Entropy (ΔS) was less frequently referenced, and when mentioned, its influence was often not incorporated into reasoning.

This frame was characterized by:

• Heavy reliance on a single energetic cue (usually ΔH or the energy diagram),

• No integration of ΔH and ΔS,

• Minimal or no reference to ΔG or K,

• Incorrect assumptions about directionality ("exothermic always means mostly product"),

• A partial but incomplete reframing in which energetic cues override other factors.

The emergence of this frame indicates that, while thermodynamic data activated new resources, these resources were often applied in a simplified, uncoordinated manner, resulting in inaccurate predictions.

2. *Near disappearance of the Stoichiometric Completion Frame* (1/25 students; 4%). Although 15 students initially adopted a Stoichiometric Completion Frame, only seven retained this interpretation after re-examining the first slide, and just one student ultimately sustained this frame once the thermodynamic information was introduced on Slide 2. This student calculated $\Delta G = 0$ but did not understand how to interpret this result, stating uncertainty about the implications for reaction extent and eventually defaulting back to the initial "all AB" prediction. This case reflects a failed or incomplete reframing attempt, rather than true persistence of a stoichiometric lens.

Overall, the stoichiometric frame largely collapsed once thermodynamic data were presented, not because students adopted a more sophisticated alternative, but because the new cues failed to support productive reframing.

3. *Modest persistence of the Surface Equilibrium Frame* (5/25; 20%). Although thirteen students concluded Slide 1 using some form of equilibrium-oriented reasoning, only three maintained that same frame when working on Slide 2. Two additional students, who had initially relied on stoichiometric completion or temperature-feasibility frames, shifted to an equilibrium frame after the thermodynamic information was introduced.

Among those who maintained or switched to the frame, three were unable to connect the thermodynamic data to equilibrium considerations in any meaningful way. One other student used the values to calculate $\Delta G = 0$ but incorrectly interpreted this result as indicating that the reaction was spontaneous and therefore product-favored. Only three students in this group, and in the entire sample, recognized, after prompting, that the ΔH and ΔS data could be used to determine the equilibrium constant. Two of them correctly identified Option B as a plausible prediction based on their $K = 1$ value, while one student incorrectly inferred that this meant "equal amounts of reactants and products," leading to the selection of Option A.

Thus, the equilibrium frame was not strengthened by the thermodynamic information; it was merely sustained by a small subset of students. For most, equilibrium-based reasoning remained partial, qualitative, and only loosely connected to the quantitative and representational cues provided.

4. *Dissolution of the Temperature–Feasibility Frame* (0/25 students; 0%). Five students used a temperature-feasibility frame on Slide 1, but none of them maintained a related version of this frame on Slide 2. Three shifted into an Energetic Favorability Frame, one switched to a Surface Equilibrium frame, and one experienced a frame collapse. Thus, the temperature-feasibility frame transformed or collapsed, with students adopting a new reasoning strategy once concrete thermodynamic information was provided.

5. *Epistemic-Uncertainty (Frame-Collapse) response* (5/25 students, 20%). A final group of five students responded to the new data by abandoning their prior frame without adopting a new one. These students concluded that the problem could not be solved and selected "More information needed" despite having been given all relevant thermodynamic information.

Their explanations often involved requests for irrelevant or unnecessary additional data, such as whether a catalyst was present or how pressure would affect the system.

This response pattern reflects:

• Recognition that their prior frame was inadequate,

• Failure of the thermodynamic data to cue any alternative conceptual resource,

• Lack of metacognitive strategies for reframing,

• A retreat into epistemic uncertainty rather than conceptual progress.

We interpret these cases as examples of frame collapse: students recognized that their earlier reasoning did not work but lacked the resources to construct a new frame.

Overall, slide 2 triggered substantial reframing, but not toward canonical thermodynamic reasoning (see Fig. 4). Only a small minority engaged in equilibrium-based thinking; a larger group adopted a simplified energetic-favorability perspective; and many experienced frame instability, collapse, or partial activation without coordination. The thermodynamic information functioned as weak cues for most participants and did not reliably support meaningful conceptual reframing.

When the reaction conditions were modified in Slides 3 and 4, keeping all information constant except for temperature (292 K in Slide 3 and 305 K in Slide 4), students' frames shifted

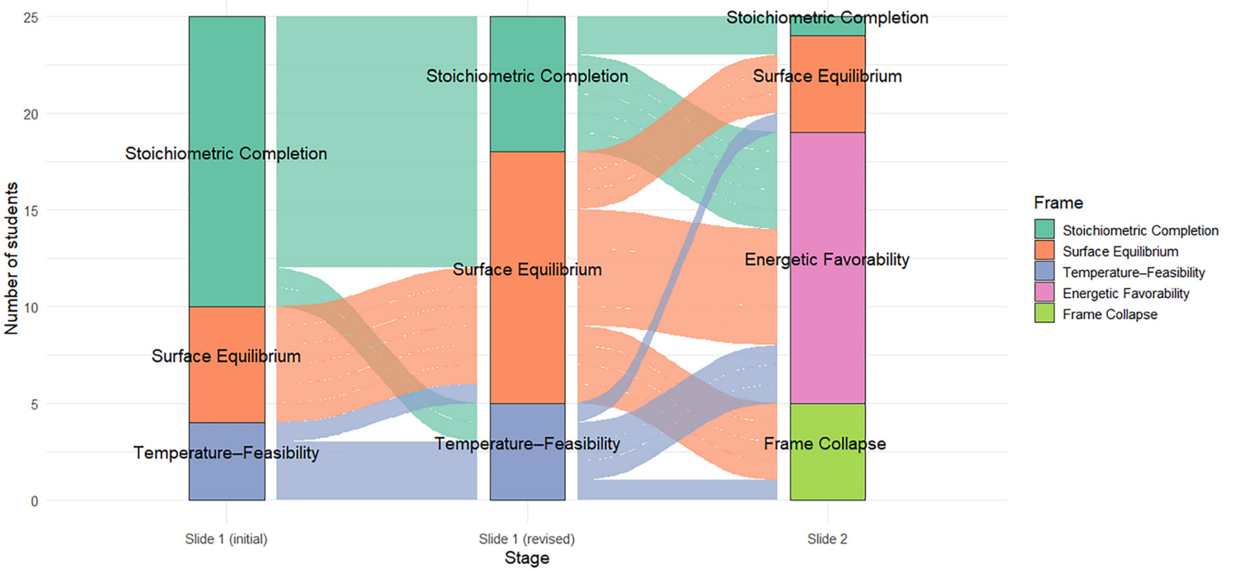

Fig. 4 Alluvial diagram showing frame shifts when thermodynamic data is presented in Slide 2.

again, revealing additional patterns in reframing and reasoning. At 292 K, the thermodynamic data imply $\Delta G < 0$ and $K > 1$, whereas at 305 K, $\Delta G > 0$ and $K < 1$. Despite these clear thermodynamic implications, the temperature change did not cause most students to engage in a fully coordinated thermodynamic analysis. Instead, the shift in temperature activated a new set of partial or alternative frames, highlighting four recurring tendencies.

First, an increasing number of students (11 total) engaged in partial quantitative reasoning by calculating ΔG using the provided ΔH and ΔS values. Most used the resulting ΔG value qualitatively, typically to state whether the amount of product will increase or decrease, but did not compute K or map the value onto a particulate representation. Only the two students who had successfully coordinated ΔG and K on Slide 2 repeated this full analytic sequence and used K to choose the quantitatively appropriate option.

Second, fourteen students activated a ΔH-based heuristic, inferring that exothermic reactions produce more product at low temperature and more reactant at high temperature. These students did not integrate entropy or ΔG, but the temperature change reinforced or induced a shift toward an energetics-based frame. Their reasoning was generally qualitative as illustrated by this participant:

• *"So, if you have it at a lower temperature, it'll proceed farther, because we can see that it'll be more favored towards the products with the reaction path that is exothermic."* (P18)

While correct for this particular system, the reasoning reflects single-cue thermodynamic activation rather than coordinated analysis.

Third, several students (eleven) adopted a kinetic–particle-motion line of reasoning, interpreting temperature changes as affecting molecular speed and collision frequency. These students predicted, for example, that fewer AB molecules would form at lower temperatures because particles "move more slowly," "collide less often," or "may not have enough energy to react." Representative comments included:

• *"The reactants. A and B won't be moving around as much and won't be colliding with other of the reactants, so they won't form as much products, because it's at a lower temperature."* (P11)

• *"Maybe the temperature has to do with whether or not there's enough energy to bond these things."* (P3)

This reflects a reframing toward kinetic thinking, but one that confuses rate with extent: students relied on collision-based reasoning to predict equilibrium composition, indicating that temperature served as a cue for a new frame, but not a productive one.

Fourth, three students predicted that lower temperatures would yield fewer AB molecules but did so without offering a mechanistic or conceptual basis. They did not reference particle motion, thermodynamics, or equilibrium; instead, they provided intuitive judgments such as:

• *"So, since this reaction is happening at low temperature, so the product will be low, less than the previous one."* (P13)

These responses appear to reflect an undifferentiated intuitive frame in which temperature is treated as a general suppressor of chemical change, rather than as a cue to engage kinetic or thermodynamic reasoning.

When students repeated the task at a higher temperature (305 K), many of the same patterns reappeared, but in reverse. Students who had argued that "low temperature slows particles and reduces product" now claimed that "higher temperature speeds things up and produces more product," again conflating rate with extent. Those who had previously used ΔH-based heuristics similarly reversed their claims. As one student explained:

• *"...with this being an exothermic reaction, increasing the temperature may push things back a little bit. So, it might regress back to reactants"* (P8).

Most students who calculated ΔG at 292 K also repeated the calculation at 305 K, again using the value only qualitatively.

Overall, the temperature manipulations in Slides 3 and 4 did more than simply reproduce earlier single-cue patterns; they broadened the range of ideas students drew upon. For many, the change in temperature served as a meaningful cognitive trigger: several students began incorporating kinetic considerations, others applied ΔH-based heuristics appropriately for this system, and an increasing number engaged in quantitative reasoning by calculating ΔG under the new conditions. These responses show that students were actively trying to make sense of how temperature affects chemical behavior and were willing to bring new forms of reasoning online as the representational context shifted.

At the same time, these newly activated ideas often remained only partially coordinated. Kinetic insights were used to reason about equilibrium composition, ΔH-based heuristics were not integrated with entropy, and ΔG calculations were typically interpreted qualitatively rather than carried through to K or particulate predictions. Thus, temperature changes tended to elicit new resources rather than promote the integration of those resources.

Seen from this perspective, the temperature manipulations revealed both the adaptability and the fragility of students' reasoning. They showed that students can and do shift their frames in response to contextual cues, drawing productively on familiar disciplinary ideas. Yet these shifts also underscored the challenge of coordinating structural, kinetic, and thermodynamic perspectives into a single explanatory framework.

RQ3: To what extent do students coordinate structural, thermodynamic, and kinetic ideas when reasoning about the system? (Conceptual coordination)

Across all phases of the task, students demonstrated only minimal coordination of structural, thermodynamic, and kinetic ideas. Although the problem was designed to elicit integration across these domains, participants generally reasoned within a single conceptual frame at a time, shifting frames when new cues were introduced rather than coordinating ideas across frameworks. Several patterns characterize the nature and limits of students' conceptual coordination.

A first and pervasive pattern was the tendency for structural reasoning to remain isolated from other conceptual domains. Structural cues, such as particle counts, stoichiometric ratios, or the depiction of bond formation, were frequently used to justify early predictions, but they were not integrated with thermodynamic or kinetic considerations even when conditions changed. Students rarely linked the particulate diagram to energetic data or used structural insights to support claims about reaction extent or equilibrium.

Thermodynamic reasoning, although cued by the introduction of ΔH, ΔS, and temperature values, was similarly fragmented. Many students focused on ΔH alone, treating exothermicity as a deterministic indicator of directionality without considering entropy or free energy. Even when students calculated ΔG, the result was typically used only qualitatively to infer whether "more product" or "more reactant" would form. Only two participants completed the full sequence of quantitative steps—calculating ΔG, deriving K, and mapping the result onto the particulate representation—yet even they did not coordinate these thermodynamic insights with structural or kinetic reasoning. Thus, quantitative reasoning was rare, and when it occurred, it tended to operate in isolation rather than as part of a coordinated explanatory chain.

Kinetic ideas were invoked by a subset of students only after the temperature changed in Slides 3 and 4, and even then, reasoning was largely restricted to intuitive claims about particle speed, collision frequency, or not enough energy to react. Only one student referred explicitly to the activation energy depicted in the energy diagram. For most participants, the energy diagram did not cue kinetic reasoning at all, and when kinetic ideas did appear, they functioned as an alternative frame rather than as a coexisting lens. Students used kinetic arguments to predict equilibrium composition, confusing rate with extent, and did not attempt to reconcile kinetic and thermodynamic considerations.

A striking pattern across participants was the sequential activation of resources. Students tended to adopt whichever frame was cued most strongly by the information currently in front of them, rather than coordinating multiple ideas simultaneously. For example, they moved from stoichiometric reasoning (Slide 1) to enthalpy-based heuristics (Slide 2) to particle-speed reasoning (Slide 3) depending on which cue was most salient, but these ideas remained compartmentalized. New resources replaced old ones rather than being integrated with them.

Overall, conceptual coordination was extremely limited. Most students worked within a single framework at any given time, shifted frames as new cues appeared, and rarely attempted to reconcile competing ideas or build integrated explanations. Only two participants demonstrated coordinated thermodynamic reasoning, and even they did not extend this coordination to structural or kinetic domains. The broader pattern reveals conceptual fragmentation: students relied on isolated ideas, activated sequentially rather than jointly, and struggled to construct a coherent, multilevel account of the system.

Discussion

This study explored how undergraduate and graduate chemistry students constructed and revised predictions about a simple reaction as new information was introduced or contextual features were changed. Rather than evaluating conceptual mastery in isolation, we analyzed how students interpreted available cues, which conceptual frames they activated, and how their reasoning evolved across changing informational conditions.

Our findings align with a broad body of research on chemistry problem-solving that has shown that students often focus on a limited subset of available variables, struggle to integrate knowledge, and rely on unproductive reasoning strategies (Kraft *et al.*, 2010; Tsaparlis, 2021). However, the present study extends this literature by examining how students' reasoning shifted when the informational landscape changed. Instead of analyzing a static problem-solving episode, we traced how interpretive frames evolved as additional cues were introduced or conditions varied. This dynamic perspective allowed us to observe not only which variables students attended to, but also what conceptual frames they deployed and how and when.

Consistent with framing perspectives in the learning sciences (Hammer *et al.*, 2005; Brown and Hammer, 2008) and with Data-Frame Theory (Klein *et al.*, 2006; Klein *et al.*, 2007), students' reasoning appeared organized around locally coherent interpretive frames. Early responses were guided by explicit structural cues and familiar heuristics. As new information was presented, many students attempted to incorporate it, sometimes elaborating their existing frame and sometimes shifting to a new one. These shifts did not necessarily follow a linear trajectory toward canonical chemical reasoning. In several cases, students preserved elements of prior interpretations while integrating new cues, a pattern that resonates with prior research on frame preservation and elaboration in data analysis contexts (Berg and Moon, 2023; Zhou and Moon, 2023).

Across the interview sequence, a central pattern emerged: students relied on locally coherent frames that allowed them to make sense of the information at hand, but rarely coordinated multiple lenses simultaneously. Early predictions drew on productive and familiar resources: stoichiometric ratios, structural features in particulate diagrams, and common assumptions about reactions proceeding to completion. These results align with findings that students' initial reasoning in chemistry is deeply grounded in intuition and explicit cues (Talanquer, 2006; 2014). Even the Temperature–Feasibility Frame, although not thermodynamically grounded, reflects students' recognition that conditions matter and that chemical processes are contingent, an epistemic strength documented in studies of students' early modeling practices (Schwarz *et al.*, 2009).

As participants justified their reasoning or encountered new information, they showed a willingness to reconsider and revise their frames. They noticed new cues (especially the reversible arrow) and attempted to reconcile them with prior interpretations. This flexibility is consistent with research showing that students shift dynamically among interpretive resources in response to contextual signals (Goodhew *et al.*, 2021), and with Data-Frame Theory accounts in which learners elaborate or revise frames when new information challenges prior interpretations (Klein *et al.*, 2007; Berg and Moon, 2023).

At the same time, reframing often occurred in partial or uncoordinated ways. When thermodynamic data were introduced, many students activated energetic analyses to generate meaningful, if simplified, judgments. These shifts align with prior work showing that energetic cues are more salient for learners, whereas entropy and free energy are more difficult to integrate (Carson and Watson, 2002). Even when students computed ΔG, the value was typically used qualitatively rather than as part of a coordinated quantitative argument involving K or equilibrium composition. This pattern aligns with literature documenting students' difficulty integrating ΔH, ΔS, ΔG, and K into a coherent thermodynamic model (Bain *et al.*, 2014).

Temperature changes elicited additional productive but uncoordinated frames. Some students turned to kinetic reasoning, drawing on intuitive but valuable ideas about molecular speed and collision frequency, although often conflating kinetic and thermodynamic consequences (Bain and Towns, 2016). Others invoked ΔH-based heuristics to reason about temperature effects on exothermic reactions. Still others experimented with quantitative reasoning, computing ΔG under new conditions even if they did not connect those values to K or particulate representations. Only a small number demonstrated coordinated thermodynamic reasoning linking ΔH, ΔS, ΔG, K, and equilibrium composition, and even these students did not consistently integrate structural or kinetic considerations. Together, these patterns suggest meaningful but compartmentalized activation of disciplinary knowledge.

These results underscore the difficulty students face in discerning which conceptual resources are appropriate to activate in each moment, particularly in a domain like chemistry, where multiple representational layers must be coordinated. Students tended to respond to whichever cue was most salient, whether a particulate ratio, a bidirectional arrow, or a temperature value. While this pattern is consistent with an activation-based interpretation, our data do not allow us to determine definitively whether alternative resources were present but not activated, or whether some relationships (*e.g.*, ΔG–K connections) were incompletely developed. What the interviews show is that such resources were not invoked or coordinated during the task. Thus, students experienced difficulty managing and integrating multiple explanatory lenses, whether due to limits in activation, coordination, or conceptual development.

In general, our findings provide a nuanced picture of both strengths and challenges. Learners responded systematically to salient cues, revised interpretations when prompted, and drew on a range of disciplinary ideas. Yet these ideas often functioned within isolated frames, with new frames replacing rather than coordinating with prior ones (Brown, 2014). Structural, energetic, and kinetic insights tended to operate independently. This pattern parallels findings from research on multivariate reasoning, in which students frequently treat relevant variables sequentially rather than constructing integrated models (Kraft *et al.*, 2010). Our contribution lies in documenting how this fragmentation unfolds dynamically as informational cues change, revealing the temporal structure of frame shifts rather than examining variable use at a single moment.

Ultimately, students' reasoning in this task was strongly shaped by the frames activated in context. Rather than revealing entrenched misconceptions, the interviews illuminate a dynamic yet fragile sense-making process in which students responded productively to individual cues but struggled to integrate multiple explanatory perspectives. Whether this fragmentation reflects primarily activation challenges, incomplete conceptual integration, or both cannot be fully resolved from the present data. What is clear is that coordinating multiple disciplinary lenses poses substantial demands that extend beyond applying individual concepts in isolation.

In this sense, the challenges observed here point not only to conceptual fragmentation but also to the importance of supporting students in developing strategies for managing and integrating multiple explanatory perspectives during problem-solving.

Implications for teaching and learning

The findings of this study offer several important insights for the design of learning environments that support richer and more flexible reasoning in chemistry. A central implication is that instruction needs to foreground not only conceptual knowledge but also the framing practices that make that knowledge useful. Because students' reasoning in this task was strongly shaped by which ideas were cued in the moment, instruction should help learners become more aware of the frames they are using, more deliberate in deciding when a frame is productive, and more capable of coordinating multiple frames when problems demand it (Potvin, 2023). Teaching students how to recognize the limits of a given lens, and how to shift or expand that lens when new information becomes relevant, may be as essential as teaching the underlying concepts themselves. Supporting conceptual reframing may help students both activate relevant knowledge and strengthen connections among ideas that are only partially integrated.

The results further suggest that thermodynamic and kinetic ideas should not be taught as separate, sequential units but as interrelated lenses on the same phenomena. Many students in the study treated ΔH, ΔS, ΔG, K, structure, and rate as independent concepts that operate in isolation. When confronted with new data, they often replaced one cue with another rather than integrating them. Instruction that revisits the same system through structural, energetic, and kinetic perspectives could help students see these ideas as complementary rather than compartmentalized. Such integration differs from traditional curricular sequencing, in which thermodynamics, kinetics, and structure may appear in different units or courses without explicit coordination; instead, it calls for deliberate comparison and integration of these lenses within the analysis of the same phenomenon. For example, opportunities to explore how bond formation, entropy changes, activation energy, and equilibrium all shape the behavior of a single reaction may help students understand how and why different concepts matter at different points in an analysis.

Another implication concerns representational fluency (Rau, 2016). Students relied heavily on surface features of particulate diagrams or symbolic notation because these cues were familiar and interpretable, whereas representations such as energy diagrams or entropy values did not readily activate the intended ideas. Instruction can play a more deliberate role in unpacking what each representation affords and how information in one representation maps onto another (Talanquer, 2022). Modeling how expert chemists move among particulate, symbolic, energetic, and mechanistic representations may help students develop a more integrated representational repertoire and reduce the likelihood of single-cue reasoning.

The study also demonstrates that difficulties with framing and coordination are not limited to novice learners. Graduate students showed many of the same tendencies as undergraduates: they defaulted to stoichiometric cues, overemphasized enthalpy, rarely used entropy, and struggled to relate ΔG and K to particulate-level outcomes. This suggests that the need for support in conceptual reframing and coordination persists well beyond introductory courses. Graduate-level instruction may need to attend more explicitly to epistemic control and representational reasoning, rather than assuming that advanced coursework alone ensures conceptual integration.

Finally, the findings have implications for assessment. Traditional assessments that ask students to apply specific formulas or recall isolated facts offer little insight into how students choose which ideas to use or how they coordinate them (Stowe *et al.*, 2021). Tasks like the one used in this study, more open-ended, representation-rich, and requiring justification, can illuminate how students frame problems, which cues they attend to, and where coordination breaks down. Such assessments can help instructors diagnose not only what students know, but how they are making sense of complex information and where additional scaffolding might support deeper integration.

Together, these implications point toward instructional approaches that cultivate flexibility, awareness, and coordination (Potvin, 2023; Nehring and Schanze, 2025). By helping students see chemistry not as a set of disconnected tools but as a system of interrelated frameworks, educators can better support learners in developing the adaptive expertise needed to navigate complex chemical phenomena.

Limitations

Several limitations of this study should be acknowledged when interpreting the findings. The first concerns the scope and composition of the sample. The 25 participants were drawn from a single institution and included a mix of undergraduate and graduate students whose prior coursework and experiences may not reflect the broader population of chemistry learners. Although the sample was appropriate for a qualitative, exploratory study, it necessarily limits the generalizability of the results.

The methodological choice to use individual think-aloud interviews also shapes the nature of the findings. Clinical interviews offer a powerful window into students' in-the-moment reasoning, yet they do not fully capture how students reason in typical classroom environments, where time pressures, peer interactions, and instructional cues may lead to different patterns of frame activation and coordination. Moreover, the interviewer's prompts, intended to encourage elaboration and ensure clarity, may have influenced how and when students shifted frames. These prompts reveal what students can do when supported, but they also complicate interpretations of what students would have done independently. Because participants were not informed in advance that additional information would be presented, some expressions of uncertainty may reflect expectations about forthcoming data rather than purely conceptual instability.

The interviews were conducted *via* Zoom for logistical and accessibility reasons. While prior research suggests that video-conferenced interviews can yield data comparable in richness and reliability to in-person formats, remote interaction may nevertheless influence how participants engage with materials or externalize their reasoning. Although students were able to annotate slides and share written work digitally, subtle differences in interactional dynamics or representational use compared to face-to-face settings cannot be ruled out.

A further limitation lies in the design of the reaction system itself. The A + B ⇌ AB reaction was purposefully abstract, allowing us to focus on reasoning processes without the confounding influence of domain-specific memorized facts. While this abstraction was a strength for isolating conceptual framing, it may also reduce ecological validity. Students may respond differently when working with reactions embedded in richer chemical contexts or tied to familiar substances.

Additionally, the study was designed to investigate how students deploy and coordinate ideas, not to measure conceptual accuracy or mastery. As such, the interpretations focus on the reasoning processes students exhibited rather than on whether they arrived at correct predictions. Consequently, the study cannot determine whether concepts that were not invoked were unavailable to students or simply not activated within this context. This distinction cannot be resolved definitively with the present data.

Finally, the study captures reasoning at a single moment in time. Framing processes are dynamic and may evolve with instruction, experience, or repeated exposure to similar tasks. Without longitudinal follow-up, we cannot determine whether the frames students activated here reflect stable tendencies or transient responses to the specific representational environment of the interview.

Despite these limitations, the study provides a rich and nuanced account of how students navigate structural, thermodynamic, and kinetic information and offers valuable insights into the challenges and potential of conceptual reframing in chemistry learning.

Author contributions

Onyinye Joy Ikenyirimba contributed to the study conceptualization and led the investigation, including data collection, formal analysis, data curation, and preparation of the original manuscript draft. Vicente Talanquer contributed to the study conceptualization, methodology, and supervision, and led the review and editing of the manuscript. All authors reviewed and approved the final manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

The interview data supporting this study are not publicly available due to ethical considerations and confidentiality requirements mandated by our Institutional Review Board (IRB). Sharing these data would compromise participant anonymity.

Supplementary information (SI) includes the reasoning diagrams for all study participants. See DOI: https://doi.org/10.1039/d5rp00440c.

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