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The importance of fostering *conceptual reframing* in chemistry education

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Persistent difficulties in students' ability to apply chemical knowledge across contexts suggest limits not to memory but of *cognitive flexibility*. This paper argues that such flexibility depends on *conceptual reframing*, understood as the capacity to reinterpret a phenomenon through alternative disciplinary lenses, which in this study take the form of distinct conceptual lenses within chemistry. Drawing on insights from cognitive flexibility theory, epistemic cognition, and philosophy of science, I propose that chemistry's inherently pluralistic structure requires learners to navigate among multiple legitimate modes of reasoning. I describe conceptual reframing as the cognitive process that enables this navigation and link it to mechanisms of context-sensitive activation and conceptual coordination. Building on existing ideas in science and chemistry education, I present curricular and pedagogical suggestions that emphasize recursive, phenomenon-based learning and metacognitive engagement with framing choices. Illustrative examples, such as the teaching of acid–base chemistry, demonstrate how instruction can foster conceptual reframing and knowledge transfer across contexts. Cultivating such pluralistic reasoning, I argue, is key to preparing learners to think adaptively, critically, and reflectively in a complex, interconnected world.

Introduction

Conversations among chemistry educators, across educational levels and disciplinary subfields, often return to a familiar concern: students' persistent difficulty in recalling or applying concepts learned in earlier courses. These challenges are frequently attributed to inadequate prior instruction, students' inattention, or simple failure to retain knowledge. However, research on learning and transfer indicates that such explanations overlook deeper causes. Difficulties in applying knowledge across contexts stem not only from forgetting, but from a complex interplay of cognitive, metacognitive, affective, curricular, and pedagogical factors (National Research Council, 2000; Mestre, 2005; Lobato, 2006).

In this essay, I argue that an important contributor to this problem is the limited cognitive flexibility that traditional chemistry instruction fosters in students. *Cognitive flexibility* refers to the capacity to reorganize and adapt one's conceptual and representational understanding across different contexts (Spiro *et al.*, 2017; Braem and Egner, 2018). I propose that *conceptual reframing*—defined as the ability to reinterpret a phenomenon or problem through alternative disciplinary lenses, which in this study correspond to distinct conceptual lenses within chemistry—is essential for enabling meaningful knowledge transfer in chemistry (Hammer *et al.*, 2005; Slominski *et al.*, 2020). Conceptual reframing represents the cognitive process that allows experts to move fluidly among different ways of thinking, both across and within disciplines, a capacity grounded in what philosophers of science describe as conceptual pluralism (Bensaude-Vincent and Simon, 2008; Chang, 2014; Schummer, 2015; Bélanger *et al.*, 2023a, 2023b): the recognition that disciplinary knowledge is structured through multiple, sometimes compatible and sometimes incompatible conceptual frameworks, each capturing different aspects, levels, or goals of understanding.

Chemistry as a discipline is inherently pluralistic (Ruthenberg and Mets, 2020). The same phenomenon can be represented through distinct theoretical frameworks (quantum *versus* classical descriptions of particle motion), conceptual models (valence bond *versus* molecular orbital theories), mechanistic accounts (structural *versus* kinetic explanations), or analytical perspectives (for example, the effect of proton transfer on solution pH *versus* chemical reactivity). Expert chemists routinely navigate and integrate these perspectives depending on their explanatory or predictive goals. In contrast, students typically encounter them as disconnected bodies of knowledge, each confined to a course, topic, or textbook chapter. As a result, they are seldom taught how to reframe a concept productively when the context, scale, or explanatory goal changes.

Addressing this challenge requires both curricular and pedagogical innovation. Instruction should create systematic opportunities for students to recognize diverse conceptual and analytical emphases, to articulate how different models and explanations serve distinct purposes, and to practice transferring ideas across

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representational and contextual boundaries (Nehring and Schanze, 2025). Fostering conceptual reframing is therefore not simply a matter of improving knowledge retention, but of cultivating the cognitive flexibility that underlies expert chemical thinking.

Pluralism in chemical thinking

Chemical phenomena can be understood in multiple legitimate ways, and this diversity is one of chemistry's defining strengths. The discipline operates at the intersection of theoretical principles, representational models, causal mechanisms, and practical goals. Each provides a distinct perspective through which chemists construct meaning, generate explanations, and make predictions (Chang, 2014; Ruthenberg and Mets, 2020). The coexistence of these perspectives exemplifies the pluralistic nature of chemical knowledge, which I claim manifests in at least four interrelated forms: theoretical, model, mechanistic, and analytical pluralism.

Theoretical pluralism

Theoretical pluralism arises from the coexistence of alternative or complementary foundational frameworks that offer different ontological and mathematical accounts of chemical behavior (Bélanger *et al.*, 2023a, 2023b). For instance, quantum mechanics and classical mechanics provide legitimate, though distinct, descriptions of molecular motion and energy (Bokulich, 2008). Quantum theory describes particles as probabilistic wavefunctions that exist in discrete (quantized) energy states, whereas classical mechanics treats particles as deterministic objects with continuous energy values, governed by Newton's laws. Chemists navigate among these frameworks according to the scale, purpose, and computational demands of the problem. Theoretical pluralism, therefore, reflects the existence of multiple legitimate "worldviews" within the discipline, each grounded in a different set of assumptions about the nature of matter and energy.

Model pluralism

Within a given theoretical framework, chemists rely on multiple conceptual models that embody distinct idealizations or abstractions of reality (Ruthenberg and Mets, 2020; Talanquer, 2025). Model pluralism refers to this coexistence of alternative models that emphasize different explanatory features. The contrast between valence bond and molecular orbital theories of chemical bonding is a canonical example (Galbraith *et al.*, 2021; Sánchez Gómez and Suárez, 2025). Both originate in quantum mechanics, yet one emphasizes localized electron pairing while the other emphasizes delocalized orbital structures. These models are not simply stages of historical replacement but remain actively used because each provides unique insights and predictive advantages.

Mechanistic pluralism

Chemistry also exhibits mechanistic pluralism, the existence of multiple causal narratives that explain a phenomenon at different levels of organization or temporal and energetic scales (Talanquer, 2021). A single reaction can be modeled through electronic, structural, or kinetic mechanisms. For example, a molecular transformation may be described as electron density redistribution (electronic), as the rearrangement of atoms through a transition state (structural), or as a process governed by rate-determining steps (kinetic). These explanations are not mutually exclusive; rather, they are nested and complementary. Mechanistic pluralism reflects the multilevel nature of chemical causation and highlights the integrative reasoning chemists employ when linking microscopic interactions to macroscopic observables.

Analytical pluralism

Finally, analytical pluralism concerns the different interpretive lenses chemists adopt depending on the explanatory goal or practical question at hand (Taber, 2008). For example, the same proton transfer event can be analyzed in terms of its effect on solution pH, molecular reactivity, or chemical speciation. Each perspective foregrounds a different set of variables, methods, and purposes. Analytical pluralism thus concerns not alternative theories, models, or mechanisms, but rather a different conceptual focus and investigative intent.

These four forms of pluralism shape the epistemic landscape of chemical thinking. They illustrate that chemistry is not a single, unified way of reasoning but a network of interrelated frameworks that operate across scales and purposes (Chang, 2014; Schummer, 2015). Chemists navigate among these frameworks according to the scale, purpose, and computational demands of the problem. However, this navigation is often influenced by disciplinary norms, prior knowledge, experience, and individual preferences rather than by intentional and exhaustive use of all available lenses. For experts, this pluralism is productive: it supports flexible shifting among perspectives, selective integration of insights, and creative application of knowledge. For students, however, it can be a source of fragmentation if they are not explicitly taught how these perspectives relate and when each is appropriate.

The four forms of pluralism described above can be contrasted along their epistemic focus, degree of compatibility, and implications for learning as summarized in Table 1. Together, they illustrate the multiple conceptual terrains that chemists navigate when reasoning about chemical phenomena.

An illustrative example: proton transfer

The phenomenon of proton transfer offers a useful example of how different forms of pluralism operate in chemistry. Across theoretical, model, mechanistic, and analytical perspectives, this process can be conceptualized and studied in distinct yet complementary ways. Each lens highlights distinct entities and goals of explanation, showing how chemical knowledge depends on context-specific frameworks.

Theoretical pluralism

At the theoretical level, proton transfer can be described through alternative foundational frameworks that differ in their representations of matter and energy (Demchenko, 2023).

Table 1 Different forms of conceptual pluralism in chemistry

Form of pluralism	Nature of the perspective	Level of reasoning	Typical examples	Relationship among frameworks	Implications for learning
Theoretical pluralism	Coexistence of alternative or complementary foundational frameworks that provide different ontological descriptions of chemical behavior.	Fundamental physical principles that govern matter and energy at different scales.	Classical *vs.* quantum mechanics	May be partially incompatible but valid in distinct domains of applicability.	Students must recognize boundaries of validity and conditions under which each theory applies.
Model pluralism	Use of multiple conceptual models or idealizations within a shared theoretical framework.	Representational structures used to explain or predict properties and behavior.	Valence bond *vs.* molecular orbital theory; Arrhenius, Brønsted–Lowry, and Lewis acid–base models.	Models overlap and can be integrated or selected depending on the task.	Instruction should emphasize the model's purpose, scope, and limitations.
Mechanistic pluralism	Existence of multiple causal narratives or levels of description for the same process.	Causal chains at different granularity levels linking structure, energy, and dynamics.	Electronic, structural, and kinetic accounts of chemical reactions.	Frameworks are complementary and can be integrated into multilevel explanations.	Learners benefit from connecting mechanisms across scales and identifying how causal levels interact.
Analytical pluralism	Adoption of different interpretive lenses according to the explanatory or practical goal.	Contextual framing of inquiry and choice of relevant variables and measures.	Interpreting proton transfer through effects on solution pH, reactivity, or speciation	Perspectives are context-dependent and chosen based on purpose.	Practice is needed in selecting and justifying appropriate lenses for different questions or applications.

In quantum mechanics, the process is understood in terms of changes in potential energy surfaces, electron density redistribution, and tunneling probabilities that influence the rate of proton motion. In classical mechanics, proton transfer is modeled as the motion of a particle overcoming an energy barrier along a reaction coordinate, often captured by potential energy diagrams or molecular dynamics simulations. These theories differ in their assumptions and formalisms but together provide a coherent picture of how protons move and interact within chemical systems.

Model pluralism

Within these theoretical foundations, chemists employ multiple conceptual models to represent and reason about proton transfer (Ruthenberg and Mets, 2020; Nehring and Schanze, 2025). The Arrhenius model defines acids and bases through the production of hydronium and hydroxide ions in aqueous solution. The Brønsted–Lowry model generalizes this view by focusing on proton donors and acceptors independent of the solvent environment, while the Lewis model further extends the concept to electron-pair interactions. Each model highlights different structural and energetic features of acid–base behavior and is suited to different problem contexts. These models are not mutually exclusive; they coexist as alternative idealizations that emphasize specific aspects of chemical reactivity.

Mechanistic pluralism

Mechanistic explanations of proton transfer focus on the causal processes linking molecular structure to observable behavior (Demchenko, 2023). In physical chemistry, attention may center on the transition state and the energetic pathway of proton movement, including tunneling effects and solvent reorganization. In organic chemistry, the emphasis often shifts to how protonation or deprotonation alters molecular stability, thereby influencing reactivity and reaction kinetics. In biochemistry, proton transfer is analyzed as a mechanism for structural and functional regulation, such as in enzyme catalysis, where protonation changes the conformation or electrostatic environment of an active site. These mechanistic accounts operate at different spatial and temporal scales but can be integrated into a multilevel understanding of proton transfer as both a chemical and biological process.

Analytical pluralism

Analytical pluralism concerns the choice of perspective based on explanatory or practical goals. In general chemistry, acids are typically defined as proton donors, and bases as proton acceptors, with emphasis on how these processes affect the concentrations of hydronium and hydroxide ions in aqueous solution. Instruction often centers on calculating pH values, analyzing equilibrium shifts, and predicting the effects of perturbations such as dilution or addition of acid or base. This framing is largely quantitative and emphasizes the measurable consequences of proton transfer on solution properties. In organic chemistry, the analytical focus shifts toward how proton transfer alters molecular reactivity and electronic structure, helping students rationalize mechanisms and predict reaction outcomes. In biochemistry, the same phenomenon is analyzed for its functional implications, such as how protonation events in proteins lead to conformational changes that regulate catalytic activity or molecular recognition. Each context frames proton transfer differently depending on the goals of explanation and prediction.

This example illustrates how a single chemical process can be understood through multiple theoretical, representational, mechanistic, and analytical frameworks. Recognizing proton transfer as a pluralistic construct underscores the need to help students learn how to reframe their understanding—to move flexibly among theories, models, mechanisms, and analytical lenses—depending on the problem at hand. Developing this ability requires that students not only learn individual theories, models, or mechanisms, but also recognize how each frames a phenomenon differently and reason across their boundaries.

Conceptual reframing in expert chemical thinking

In this essay, conceptual reframing is conceptualized as the capacity to reinterpret knowledge across frameworks. This competence enables experts to navigate the pluralistic structure of their discipline. Rather than applying a single stable conception across all situations, experts reorganize their knowledge dynamically, selecting and coordinating alternative frameworks as the goals or contexts of reasoning change.

Cognitive mechanism

From a cognitive perspective, reframing involves the flexible coordination of knowledge structures distributed across representational and contextual domains. Research in cognitive flexibility (Spiro *et al.*, 2017; Braem and Egner, 2018), epistemic cognition (Greene *et al.*, 2016; Markauskaite and Goodyear, 2017), and framing (Hammer *et al.*, 2005; Gordon and Tannen, 2023) suggests that expert reasoning depends on the ability to activate and coordinate different cognitive resources in response to changing problem conditions. In chemistry, this means that experts possess a richly connected network of conceptual, mathematical, and representational schemas that can be triggered and coordinated when a new explanatory focus becomes relevant.

Two related mechanisms appear central to this capacity. The first is *context-sensitive activation*, the ability to identify cues that signal which conceptual framework or model is most productive for interpreting a problem, and activate associated resources (Hammer *et al.*, 2005; Wagner, 2006). The second key mechanism is *conceptual coordination*, the capacity to translate, align, reconcile, or integrate ideas across alternative conceptual frameworks and their associated representational systems (Markauskaite and Goodyear, 2017; Legare and Shtulman, 2018). This process involves aligning meanings that are expressed differently within distinct theoretical, model-based, mechanistic, or analytical lenses. For example, connecting a thermodynamic energy profile with a molecular orbital description of bond reorganization. In this sense, conceptual coordination entails representational coordination as a supporting process.

Both mechanisms rely on metacognitive monitoring and epistemic awareness: experts are conscious of the assumptions, scope, and purposes that define each framework and can shift deliberately when those boundaries are reached (Elby and Hammer, 2010; Hofer, 2018). These processes parallel the mechanisms of adaptive expertise when viewed as a distributed phenomenon (Martin and Dixon, 2024). In this perspective, adaptive expertise involves (1) the recruitment and coordination of resources (cognitive, representational, and social) needed to address a task; (2) the reframing of problems and goals, through which individuals redefine what counts as relevant knowledge or an appropriate explanation; and (3) navigational foresight, the anticipatory capacity to recognize when to shift frameworks or representations as conditions change. Conceptual reframing, therefore, constitutes the cognitive core of distributed adaptive expertise: it enables chemists to reorganize conceptual and representational resources dynamically, aligning them with evolving goals and contexts of reasoning.

An example in practice

The transfer of electrons between chemical species provides a concrete illustration of how conceptual reframing operates in chemistry. Interpreting an electron-transfer event requires a chemist to determine which conceptual lens is most relevant to the explanatory goal or experimental context. Different framings, such as thermodynamic favorability, molecular orbital interactions, mechanistic electron flow, or electron bookkeeping, emphasize different entities, representations, and causal relationships. Moving among these framings engages the two core cognitive mechanisms of reframing: context-sensitive activation and conceptual coordination.

For example, when the goal is to assess whether an electron-transfer process will occur spontaneously, a chemist activates a thermodynamic redox frame. In this frame, electron transfer is interpreted in terms of reduction potentials and Gibbs free energy change. Relevant representations include half-reactions, electrochemical series, and quantitative relationships between ΔG and cell potential. The focus is on energetic driving forces and macroscopic observables such as cell voltage.

If the problem shifts to understanding how electron transfer occurs at the molecular level, a different conceptual frame becomes salient. The chemist may activate a molecular orbital frame, conceptualizing electron transfer as the movement of an electron from a donor orbital to an acceptor orbital. Representations shift from electrochemical equations to energy-level diagrams and orbital overlap. The same electron-transfer event is now interpreted in terms of electronic structure and orbital symmetry rather than thermodynamic favorability alone.

Alternatively, the chemist may adopt a mechanistic electron-flow framework to analyze how electrons move through a reaction pathway. In this framing, electron transfer is represented using curved-arrow notation to track the redistribution of electron density across bonds and atoms during a reaction. This frame foregrounds causal reasoning about bond formation and bond breaking, intermediates, and transition states. It requires coordination between symbolic representations and structural features to explain how local electron movements give rise to observable chemical transformations.

In other contexts, however, a redox-accounting frame may be sufficient, in which oxidation states are used to identify which species is oxidized or reduced without invoking a mechanistic picture of electron motion. Or electron transfer may be inferred indirectly through compositional changes, such as shifts in hydrogen or oxygen content, which serve as empirical proxies for changes in electron density in many chemical and biochemical systems.

Across these shifts, context-sensitive activation enables the chemist to recognize which conceptual frame is appropriate given the problem's focus: reaction feasibility, electronic structure, mechanistic pathway, or electron accounting. Conceptual coordination allows the chemist to translate information across frames, for instance, by connecting a favorable reduction potential to a plausible orbital interaction, or by relating a change in oxidation state or composition to an underlying mechanistic process. Expert reasoning depends on maintaining coherence across these frameworks while flexibly reorganizing the conceptual relations each frame emphasizes.

This example illustrates that conceptual reframing involves more than recalling alternative concepts; it requires the controlled reorganization of conceptual and representational systems to serve different explanatory aims. The same chemical phenomenon is understood through distinct, internally coherent frameworks that must be selected and coordinated dynamically. The capacity to shift among these lenses underlies expert chemical reasoning and exemplifies the mechanisms that support adaptive transfer across contexts.

Relation to conceptual change and transfer

The cognitive mechanisms illustrated in this example parallel those described in contemporary accounts of conceptual change (Amin *et al.*, 2014; Amin and Levrini, 2017). Modern perspectives reject the view of conceptual change as a wholesale replacement of misconceptions with correct scientific ideas. Instead, they emphasize the learner's ability to activate, inhibit, and coordinate multiple conceptual resources or frames depending on context (Hammer *et al.*, 2005; Shtulman and Lombrozo, 2016; diSessa, 2018; Vosniadou, 2019). From this perspective, both novices and experts engage in similar control processes, though at different levels of sophistication. While students must learn to manage the activation of intuitive and scientific frames, experts manage the activation of multiple legitimate disciplinary frameworks. Conceptual reframing can therefore be viewed as an expert-level manifestation of conceptual change: it involves similar meta-conceptual control mechanisms but applied to the navigation of a pluralistic disciplinary knowledge system rather than to the transition from everyday to scientific understanding. Table 2 contrasts conceptual change and conceptual reframing in terms of their focus, interest, mechanisms, and cognitive goals.

Conceptual reframing also provides a cognitive account of how transfer occurs in a pluralistic discipline. Traditional views of transfer often assume that knowledge acquired in one context is reapplied unchanged in another (Kaminske *et al.*, 2020). In chemistry, however, such direct transfer is rarely possible because the same phenomenon may be described through different frameworks depending on the purpose of analysis (Mestre, 2005). Reframing allows experts to achieve adaptive transfer, understood as the reinterpretation and reconstruction of prior knowledge to fit new contexts or explanatory goals.

In this view, successful transfer is not a matter of retrieving the correct concept but of recontextualizing it within new conceptual and epistemic frames (Hammer *et al.*, 2005). For example, an expert who understands proton transfer as atomic displacement in general chemistry can reframe the same process as an electronic reorganization in organic chemistry or as a regulatory mechanism in biochemistry. The underlying knowledge is related, but its conceptual organization and explanatory role change with the context. Conceptual reframing thus bridges local understanding and broader knowledge transfer by enabling learners to reinterpret rather than merely recall information.

Understanding reframing as the mechanism of adaptive transfer clarifies why students often struggle to apply prior knowledge: they may have learned individual frameworks but not how to navigate among them. Supporting this capacity requires instruction that makes the pluralistic nature of chemistry explicit and provides opportunities to practice reframing across contexts.

Table 2 Contrast between conceptual change and conceptual reframing

	Conceptual change	Conceptual reframing
Focus	How learners move from intuitive to scientific understanding.	How learners move among multiple legitimate scientific frameworks.
Interest	Restructuring conceptual systems.	Developing the ability to flexibly activate and coordinate conceptual systems.
Mechanism	Inhibition of prior frame and activation of new one, guided by epistemic control.	Metacognitive selection, contextual activation, and alignment across frameworks.
Cognitive Goal	Coherence within a single framework.	Coherence across multiple frameworks.

Fostering conceptual reframing in chemistry education

Developing students' capacity for conceptual reframing requires rethinking curricular design, instructional models, and pedagogical practice. Traditional chemistry instruction, especially at introductory levels, has often been organized around the efficient transmission of large bodies of information and algorithmic procedures (the content coverage model). While such curricula ensure exposure to canonical knowledge, they rarely cultivate the flexible reasoning needed to navigate chemistry's pluralistic structure. Enabling learners to move among alternative frameworks, and to understand when and why each is useful, demands a shift from a coverage model to a conceptual practice model—one in which learning is organized around the reinterpretation of relevant phenomena through multiple disciplinary lenses (Nehring and Schanze, 2025).

Curricula that prioritize breadth over depth often separate conceptual frameworks by topic, unit, or course, for example, treating quantum mechanics, equilibrium, and molecular structure as largely independent domains. Although students may encounter the same chemical phenomenon across courses, the associated conceptual lenses are typically introduced in isolation and without explicit comparison or coordination. As a result, students are rarely asked to examine how different frameworks offer complementary, and sometimes competing, accounts of the same process.

To foster conceptual reframing, curricular design must instead emphasize explicit, within-course recurrence and comparison of frameworks around shared phenomena, rather than relegating different lenses to different disciplinary contexts. Core chemical processes such as molecular bonding, proton transfer, and energy transformation should reappear within instructional sequences in the same course, with students intentionally prompted to reinterpret the same phenomenon through multiple conceptual lenses and to reflect on the affordances and limits of each (Adipat, 2024; Scharlott *et al.*, 2024). This recursive, phenomenon-centered structure creates systematic opportunities for students to recognize how alternative models foreground different levels of description, representational systems, and explanatory goals.

A pluralistic curriculum, in this sense, organizes learning around problems that invite reframing rather than around topics to be covered. The key distinction from traditional approaches is not merely that students encounter multiple perspectives over time, but that they are asked to coordinate and contrast these perspectives in relation to the same chemical situation, developing epistemic control over when and why each framing is productive.

The teaching of acid–base concepts provides a concrete illustration of this distinction. Traditional instruction often emphasizes a single dominant frame within a given course. For example, quantitative pH calculations in general chemistry or mechanistic proton transfer in organic chemistry. While each approach is appropriate in context, treating them separately can obscure the broader role of proton transfer as a unifying chemical mechanism. A reframing-oriented curriculum instead invites students within a single course to analyze the same acid–base phenomenon from analytical, structural, and functional perspectives, making explicit how each lens supports different explanatory aims.

For example, in a general chemistry course, students might examine ocean acidification through an analytical lens, connecting atmospheric CO_2 levels to changes in pH; analyze protonation effects on drug solubility and reactivity from an organic chemistry perspective; and consider how proton transfer modulates enzyme function in biochemical systems. Crucially, these analyses are not presented as independent applications, but as coordinated interpretations of a shared underlying process (*e.g.*, proton transfer, electron transfer).

By making these framings explicit and connecting them through shared core concepts, such as energy change, electron redistribution, and molecular stability, students can come to see chemistry as an integrated yet context-sensitive discipline. This approach models expert practice not as the exhaustive use of all possible lenses, but as the selective and reflective deployment of conceptual frameworks aligned with specific explanatory goals.

Such integration can be reinforced through intentional, collaborative curriculum design within and across course boundaries, ensuring that core concepts are revisited and applied with different explanatory purposes. This reconceptualization is urgently needed to prepare students to address complex, real-world challenges, ranging from climate change to sustainable resource management, that demand analysis from multiple scientific perspectives.

Conceptual reframing should also be supported through instructional models that treat learning from a pluralistic perspective. For example, Potvin (2023) proposes that if scientific learning is viewed not as the replacement of intuitive ideas but as the dynamic competition and coordination among coexisting conceptions, instruction should be designed around iterative cycles of assimilation, discrimination, and automatization. Students must therefore encounter multiple conceptions, including those deemed "non-normative," be guided to analyze their contextual usefulness, and be given multiple opportunities to apply targeted conceptions to strengthen automatization. Rather than eradicating intuitive ideas, instruction should help learners discriminate among them, recognize where each applies, and progressively increase the prevalence of scientifically productive frames. The same model can be extended to foster conceptual reframing, affirming conceptual plurality as a natural and essential feature of scientific reasoning.

Students' ability to reframe concepts can be further developed through engagement in the discourse practices of each subdiscipline. Constructing explanations and building arguments about relevant phenomena from multiple frames (Berland and Reiser, 2009; Berland *et al.*, 2020) helps students apply prior knowledge across diverse contexts, reinforcing conceptual integration. This approach is most effective when instruction throughout the chemistry curriculum is grounded in model-based reasoning that emphasizes particle- and molecular-level explanations (Teichert *et al.*, 2017; Saba *et al.*, 2023) and draws on general mechanisms shared across chemical domains (Talanquer, 2018), such as energy transfer, charge redistribution, and electron stabilization.

Finally, pedagogical practice must engage students in activities that promote metacognitive control over their own framing processes. Teaching for conceptual reframing means helping learners not only acquire chemical knowledge but also learn how to choose and coordinate conceptual lenses appropriate to a given problem. Several evidence-based strategies can support this goal:

- ***Explicit framing prompts***. Teachers can help students recognize framing as an intentional act by asking questions such as, "Which conceptual lens applies here and why?" or "Would a kinetic or thermodynamic perspective better explain this phenomenon?" Such prompts externalize the process of context-sensitive activation and make epistemic choices visible.
- ***Comparative analysis tasks***. Teachers can ask students to analyze the same phenomenon through multiple sub-frameworks. For example, considering a chemical reaction in energetic, structural, and mechanistic terms fosters discrimination among conceptual models and clarifies their complementary roles.
- ***Metaconceptual reflection***. Students should be encouraged to articulate the boundary conditions and limitations of each framework ("When does this model stop working?"). This practice strengthens epistemic awareness and the capacity for deliberate reframing.
- ***Representation switching***. Students should be given multiple opportunities to translate among symbolic, graphical, and verbal representations to reveal structural relations among models and develop the ability to preserve coherence across representational systems.

These strategies cultivate what Perkins (1998) called flexible performance: the ability to redeploy conceptual tools as the situation demands. They also parallel the "discrimination" and "inhibitive stop sign" phases in Potvin's (2023) conceptual prevalence model, where learners learn to recognize when one conception ceases to be useful and when another should be activated. Rather than framing learning as a confrontation between right and wrong ideas, such instruction presents it as a cognitive and epistemic choice among contextually valid alternatives (Louca *et al.*, 2004; Hammer *et al.*, 2005).

Conclusions: towards a pluralistic pedagogical stance

Fostering conceptual reframing is ultimately less about implementing specific instructional techniques than about cultivating a pluralistic pedagogical stance (Nehring and Schanze, 2025). This stance views scientific understanding as inherently layered, context-dependent, and mediated by diverse representational and conceptual systems. It values tolerance toward non-normative ideas, the explicit comparison of competing explanations, and the recognition that conceptual diversity is not an obstacle to understanding but the raw material of expert reasoning.

Such a perspective reframes chemistry learning itself not as the accumulation of stable truths, but as participation in the cognitive practices of the discipline. These practices require moving flexibly among frameworks, aligning representations, and evaluating their contextual utility. When curricula and pedagogy make this pluralism explicit, chemistry education can move beyond rote application toward cultivating learners who think and reason as adaptive, reflective participants in a pluralistic scientific community.

Supporting students in developing this capacity demands attention to the full range of factors that shape learning: cognitive and affective processes, curricular and pedagogical design, and the cultural and contextual conditions that influence students' epistemic beliefs, values, and engagement with disciplinary practices (Talanquer *et al.*, 2024; Talanquer and Kelly, 2024). As chemistry educators, we can begin by reflecting on how we ourselves frame core concepts across subdisciplines, and by making those framings visible to our students. Helping learners recognize, compare, and navigate among these perspectives will not only foster conceptual reframing but also prepare them to engage with science as a dynamic, pluralistic enterprise.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analyzed as part of this perspective paper.

References

Adipat S., (2024), Transcending traditional paradigms: the multifaceted realm of phenomenon-based learning, *Front. Educ.*, **9**, 1346403.

Amin T. G. and Levrini O., (2017), *Converging perspectives on conceptual change: Mapping an emerging paradigm in the learning sciences*, London: Routledge.

Amin T. G., Smith C. L. and Wiser M., (2014), Students conceptions and conceptual change: three overlapping phases of research, in Lederman N. G. and Abell S. K. (ed.), *Handbook of science education research*, New York: Routledge, pp. 57–81.

Bélanger M., Potvin P., Horst S., Mortimer E. F. and Shtulman A., (2023a), Introduction to representational pluralism, in Bélanger M., Potvin P., Horst S., Shtulman A. and Mortimer E. F. (ed.), *Multidisciplinary perspectives on representational pluralism in human cognition: Tracing points of convergence in psychology, science education, and philosophy of science*, New York: Routledge.

Bélanger M., Potvin P., Horst S., Shtulman A. and Mortimer E. F., (2023b), *Multidisciplinary perspectives on representational pluralism in human cognition: tracing points of convergence in psychology, science education, and philosophy of science*, New York: Routledge.

Bensaude-Vincent B. and Simon J., (2008), *Chemistry—the impure science*, London: Imperial College Press.

Berland L. K. and Reiser B. J., (2009), Making sense of argumentation and explanation, *Sci. Educ.*, **93**, 26–55.

Berland L. K., Russ R. S. and West C. P., (2020), Supporting the scientific practices through epistemologically responsive science teaching, *J. Sci. Teach. Educ.*, **31**, 264–290.

Bokulich A., (2008), *Reexamining the quantum-classical relation: Beyond reductionism and pluralism*, Cambridge: Cambridge University Press.

Braem S. and Egner T., (2018), Getting a grip on cognitive flexibility, *Curr. Dir. Psychol. Sci.*, **27**, 470–476.

Chang H., (2014), *Is water H_2O? Evidence, realism and pluralism*, Dordrecht: Springer Dordrecht.

Demchenko A. P., (2023), Proton transfer reactions: from photochemistry to biochemistry and bioenergetics, *BBA Adv.*, **3**, 100085.

diSessa A. A., (2018), A friendly introduction to "knowledge in pieces": modeling types of knowledge and their roles in learning, in Kaiser G., Forgasz H., Graven M., Kuzniak A., Simmt E. and Xu B. (ed.), *Invited lectures from the 13th international congress on mathematical education*, Cham: Springer, pp. 65–84.

Elby A. and Hammer D., (2010), Epistemological resources and framing: a cognitive framework for helping teachers interpret and respond to their students' epistemologies, in Feucht F. C. and Bendixen L. D. (ed.), *Personal epistemology in the classroom: Theory, research, and implications for practice*, Cambridge: Cambridge University Press, pp. 409–434.

Galbraith J. M., Shaik S., Danovich D., Braïda B., Wu W., Hiberty P., Cooper D. L., Karadakov P. B. and Dunning Jr. T. H., (2021), Valence bond and molecular orbital: two powerful theories that nicely complement one another, *J. Chem. Educ.*, **98**, 3617–3620.

Gordon C. and Tannen D., (2023), Framing and related concepts in interactional sociolinguistics, *Discourse Stud.*, **25**, 237–246.

Greene J. A., Sandoval W. A. and Bråten I., (2016), *Handbook of epistemic cognition*, New York: Routledge.

Hammer D., Elby A., Scherr R. E. and Redish E. F., (2005), Resources, framing, and transfer, in Mestre J. (ed.), *Transfer of learning from a modern multidisciplinary perspective*, Greenwich, CT: Information Age Publishing.

Hofer B. K., (2018), Identifying the role of epistemic cognition and metacognition in conceptual change, in Amin T. G. and Levrini O. (ed.), *Converging perspectives on conceptual change: Mapping an emerging paradigm in the learning sciences*, New York: Routledge, pp. 229–236.

Kaminske A. N., Kuepper-Tetzel C. E., Nebel C. L., Sumeracki M. A. and Ryan S. P., (2020), Transfer: a review for biology and the life sciences, *CBE Life Sci. Educ.*, **19**, es9.

Legare C. H. and Shtulman A., (2018), Explanatory pluralism across cultures and development, in Proust J. and Fortier M. (ed.), *Metacognitive diversity: An interdisciplinary approach*, Oxford, UK: Oxford University Press.

Lobato J., (2006), Alternative perspectives on the transfer of learning: history, issues, and challenges for future research, *J. Learn. Sci.*, **15**, 431–449.

Louca L., Elby A., Hammer D. and Kagey T., (2004), Epistemological resources: applying a new epistemological framework to science instruction, *Educ. Psychol.*, **39**, 57–68.

Markauskaite L. and Goodyear P., (2017), *Epistemic fluency and professional education*, Dordrecht: Springer Dordrecht.

Martin L. and Dixon C., (2024), Reenvisioning adaptive expertise as a distributed phenomenon, *Mind, Culture, Activity*, **31**, 42–61.

Mestre J., (2005), *Transfer of learning from a modern multidisciplinary perspective*, Greenwich, CT: Information Age Publishing.

National Research Council, (2000), *How people learn: Brain, mind, experience, and school: Expanded edition*, Washington, DC: The National Academies Press.

Nehring A. and Schanze S., (2025), Turning the plurality of chemistry into a resource for learning: a core competency of chemistry teachers, *Sci. Educ.*, **34**, 2051–2078.

Perkins D., (1998), What is understanding? in Stone-Wiske M. (ed.), *Teaching for understanding*, San Francisco, CA: Jossey-Bass Inc., ch. 2, pp. 39–57.

Potvin P., (2023), From conceptual change to conceptual prevalence: What the acknowledgment of representational plurality could mean for science teaching, in Bélanger M., Potvin P., Horst S., Shtulman A. and Mortimer E. F. (ed.), *Multidisciplinary perspectives on representational pluralism in human cognition: Tracing points of convergence in psychology, science education, and philosophy of science*, New York: Routledge, pp. 143–162.

Ruthenberg K. and Mets A., (2020), Chemistry is pluralistic, *Found. Chem.*, **22**, 403–419.

Saba J., Hel-Or H. and Levy S. T., (2023), Promoting learning transfer in science through a complexity approach and computational modeling, *Instruc. Sci.*, **51**, 475–507.

Sánchez Gómez P. J. and Suárez M., (2025), Plurality and identity: on the educational relations between chemistry and physics, *Chem. Educ. Res. Pract.*, **26**, 53–64.

Scharlott L. J., Rippey D. W., Rosa V. and Becker N. M., (2024), Progression toward causal mechanistic reasoning through phenomenon-based learning in introductory chemistry, *J. Chem. Educ.*, **101**, 777–788.

Schummer J., (2015), The methodological pluralism of chemistry and its philosophical implications, in Scerri E. and McIntyre L. (ed.), *Philosophy of chemistry—growth of a new discipline*, Dordrecht: Springer.

Shtulman A. and Lombrozo T., (2016), Bundles of contradiction: a coexistence view of conceptual change, in Barner D. and Baron A. S. (ed.), *Core knowledge and conceptual change*, New York: Oxford University Press, pp. 53–71.

Slominski T., Fugleberg A., Christensen W. M., Buncher J. B. and Momsen J. L., (2020), Using framing as a lens to understand context effects on expert reasoning, *CBE Life Sci. Educ.*, **19**, ar48.

Spiro R. J., Klautke H. A., Cheng C. and Gaunt A., (2017), Cognitive flexibility theory and the assessment of 21st-century skills., in Secolsky C. and Denison D. B. (ed.), *Handbook on measurement, assessment, and evaluation in higher education*, New York: Routledge, pp. 631–637.

Taber K. S., (2008), Of models, mermaids and methods: the role of analytical pluralism in understanding student learning in science, in Eriksson I. V. (ed.), *Science education in the 21st century*, Hauppauge, NY: Nova Science Publishers, pp. 69–106.

Talanquer V., (2018), Importance of understanding fundamental chemical mechanisms, *J. Chem. Educ.*, **95**, 1905–1911.

Talanquer V., (2021), Multifaceted chemical thinking: a core competence, *J. Chem. Educ.*, **98**, 3450–3456.

Talanquer V., (2025), Exploring the plurality of chemical modeling: implications for chemistry teaching, *J. Chem. Educ.*, **102**, 3090–3095.

Talanquer V., Cole R. and Rushton G. T., (2024), Thinking and learning in nested systems: the classroom level, *J. Chem. Educ.*, **101**, 295–306.

Talanquer V. and Kelly R., (2024), Thinking and learning in nested systems: the individual level, *J. Chem. Educ.*, **101**, 283–294.

Teichert M. A., Tien L. T., Dysleski L. and Rickey D., (2017), Thinking processes associated with undergraduate chemistry students' success at applying a molecular-level model in a new context, *J. Chem. Educ.*, **94**, 1195–1208.

Vosniadou S., (2019), The development of students' understanding of science, *Front. Educ.*, **4**, 32.

Wagner J. F., (2006), Transfer in pieces, *Cogn. Instr.*, **24**, 1–71.

