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Coordinating Mechanistic Reasoning and Systems Thinking in Chemistry Education

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Mechanistic reasoning and systems thinking are widely recognized as central forms of scientific and engineering reasoning in chemistry and across STEM disciplines. However, research on their development in science courses has largely proceeded along parallel tracks, with limited attention to how their coordination can support the integration of scientific explanation, prediction, and design-oriented problem solving in classroom practice. This paper examines the epistemic relationship between mechanistic reasoning and systems thinking, arguing that these forms of reasoning are complementary but have different epistemic aims. Mechanistic reasoning supports explanations of how interactions among entities and processes produce observable effects. In contrast, systems thinking draws attention to how constraints, boundaries, feedback relationships, and system conditions shape those mechanisms. Building on existing frameworks in both traditions, I propose an instructional model that coordinates these perspectives through iterative movement between mechanistic exploration, systemic framing, and coordinated design and revision. Through this process, learners revisit shared representational elements with different epistemic purposes, progressively refining explanations, predictions, and design-oriented solutions. The model is illustrated through chemistry classroom examples that show how students can move between explaining how processes unfold and reasoning about how system conditions regulate, stabilize, or modify outcomes. The paper concludes by discussing the pedagogical implications, scope conditions, and instructional challenges involved in fostering coordinated mechanistic reasoning and systems thinking in chemistry and STEM education.

Introduction

Over the past five decades, the goals of chemistry and science education have evolved from emphasizing the acquisition of isolated factual knowledge toward fostering integrated understandings that enable students to explain natural phenomena and to design or evaluate solutions to real-world problems (deBoer, 2023; Osborne, 2023). Contemporary reform efforts highlight the need for learners to develop science and engineering practices and transferable ways of thinking that are productive across diverse domains (National Research Council, 2012; National Research Council, 2013; OECD, 2025). Among the latter, mechanistic reasoning has been emphasized in disciplines such as biology, chemistry, and physics (Bachtiar, *et al.*, 2022; Graulich, *et al.*, 2026). In contrast, systems thinking has become more central to engineering, environmental science, and geoscience (York, *et al.*, 2019; Bielik, *et al.*, 2023) and is gaining growing attention within chemistry education in the context of complex and sustainability-related phenomena (Mahaffy, *et al.*, 2018; Mahaffy, *et al.*, 2019; Orgill, *et al.*, 2019; Middlecamp, *et al.*, 2025). Both forms of reasoning are fundamental to scientific inquiry and engineering practice because they support complementary epistemic goals: explaining how phenomena occur and reasoning about how

systems can be controlled, optimized, or redesigned to achieve desired outcomes.

Research on mechanistic reasoning and systems thinking in educational contexts, however, has largely proceeded along parallel but somewhat disconnected paths, including within chemistry education. Studies of mechanistic reasoning typically focus on canonical school-science phenomena that can be analyzed through localized causal processes (Krist, *et al.*, 2019; Dood and Watts, 2022). In contrast, investigations of systems thinking tend to examine complex, multicomponent phenomena that unfold across multiple scales and involve dynamic feedback (Wilensky and Resnick, 1999; Ben-Zvi-Assaraf and Orion, 2010; Hmelo-Silver, *et al.*, 2017; Jacobson, *et al.*, 2019). This separation limits students' opportunities to productively coordinate these two forms of reasoning.

While both modes of reasoning rely on similar representational resources, such as components, interactions, processes, and organizational relationships, they differ in the epistemic purposes these resources serve. Mechanistic reasoning primarily supports causal explanation by accounting for how entities and processes produce observable effects. Systems thinking, in contrast, supports reasoning about regulation, stability, optimization, and intervention by examining how constraints (factors that regulate or limit system behavior), feedbacks (processes in which system outputs influence subsequent system behavior), and system boundaries

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(the limits that define which components and interactions are included in the system under consideration) shape behavior. Such a constraint-based analysis is important because it enables learners to reason about how system conditions and interactions shape the behavior, stability, and adaptability of phenomena across contexts.

For example, mechanistic reasoning may explain how molecular interactions produce changes in ocean pH, whereas systems thinking may help determine which environmental factors influence those changes, how they regulate system behavior, and what broader consequences may emerge under different conditions. Coordinating these perspectives becomes especially important in learning contexts where students are expected not only to explain or predict phenomena but also to engage in engineering-oriented design thinking (Kelley and Knowles, 2016). In these situations, design thinking refers to the iterative process of analyzing problems, developing and evaluating possible solutions, and optimizing interventions under relevant constraints and conditions (Li, *et al.*, 2019).

This paper examines the relationship between mechanistic reasoning and systems thinking in chemistry education and proposes a way to coordinate them within phenomenon- and problem-anchored learning through iterative zooming across levels of organization. Anchored learning is understood as organizing instruction around meaningful phenomena to be explained or problems to be addressed through engineering-oriented design (Hmelo-Silver, 2004; Adipat, 2024; Scharlott, *et al.*, 2024). Within this context, coordinating mechanistic and systems perspectives can help students move between explaining how phenomena occur and reasoning about how systems can be modified, controlled, or optimized under specific constraints.

This perspective contributes to the literature in two main ways. First, it offers a theoretically grounded synthesis that clarifies the epistemic distinctions and complementarities between mechanistic reasoning and systems thinking. Second, it proposes an instructional model that operationalizes their coordination through iterative zooming. This model specifies how shared elements (e.g., components, interactions) can be revisited with different epistemic purposes to support both explanation and design practices. In this sense, the contribution extends existing frameworks by making explicit how these traditions can be brought into productive dialogue in classroom practice.

Although the examples presented in this paper are grounded in chemistry and physical science contexts, the proposed framework is designed to support the coordinated development of scientific explanation and engineering-oriented design across STEM education. It illustrates how mechanistic reasoning and systems thinking can be iteratively coordinated to deepen understanding and guide action. In this way, chemistry education serves as a productive context for advancing forms of reasoning central to STEM literacy more broadly (English, 2023; Saritaş, *et al.*, 2025; Liu, *et al.*, 2026).

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Conceptual Background

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Mechanistic Reasoning in Science Education

Mechanistic reasoning has long been recognized as a central way of constructing scientific explanations (Machamer, *et al.*, 2000). From this perspective, explaining a phenomenon involves developing causal accounts based on an analysis of the activities and organization of the entities presumed to produce it. This view has influenced research in science education, where mechanistic reasoning is regarded as a core scientific practice through which learners make sense of phenomena across biology, chemistry, and physics (Bachtiar, *et al.*, 2022; Graulich, *et al.*, 2026).

At its core, mechanistic reasoning relies on entities and their properties, interactions, activities, and organization as epistemic resources for constructing causal accounts of how a phenomenon is produced (Russ, *et al.*, 2008; Krist, *et al.*, 2019). Students who reason mechanistically construct causal accounts that connect lower-level interactions to higher-level behaviors. Through this process, learners develop explanations that integrate structure and properties at one scale with behavior and function at another, building bridges across levels of organization (Deng and Flynn, 2021). This cross-level coordination can be particularly demanding because students must relate macroscopic observations (e.g., energy absorption) to interactions among abstract entities at different organizational levels (e.g., atomic rearrangements, electronic transitions), across physical dimensions (e.g., force, energy), and types of representations (e.g., chemical symbols, energy diagrams) (van Mil, *et al.*, 2013; Talanquer, 2018; 2026).

To operationalize mechanistic reasoning in educational contexts, Russ and colleagues (2008) proposed a framework for identifying this form of reasoning in students' explanations, including seven interrelated components (Table 1). More recently, Krist, Schwartz, and Reiser (2019) characterized mechanistic reasoning across scientific domains in terms of three epistemic heuristics: (a) considering what occurs at the organizational level below the observed phenomenon, (b) identifying and characterizing relevant elements at that level, and (c) coordinating those elements across space and time to determine how they give rise to the observed phenomenon.

Educationally, mechanistic reasoning is highly valued because it enables students to move beyond description toward inference, explanation, prediction, and control (Haskel-Ittah, *et al.*, 2026). It supports reasoning across levels of organization, helping learners connect microscopic and macroscopic processes and reason both qualitatively and quantitatively about change. In doing so, students acquire tools to predict and explain novel phenomena (Windschitl, *et al.*, 2008), construct evidence-based arguments grounded in scientific reasoning (Russ, *et al.*, 2008), and evaluate or critique competing explanations (Lieber and Graulich, 2020; Shtechman, *et al.*, 2025; Martin, *et al.*, 2026).

However, fostering mechanistic reasoning in classrooms presents important challenges. Although learners can engage in mechanistic reasoning from early ages, they may represent mechanisms as sequences of isolated rather than dynamically connected events, resulting in fragmented explanations (Bolger, *et al.*, 2012). Many also default to linear or single-causal reasoning, assuming one-directional relationships rather than recognizing multiple, reciprocal influences (Grotzer, 2012; Moreira, *et al.*, 2019). As a result,

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Table 1. Mechanistic reasoning components (Russ, *et al.*, 2008) illustrated with the vinegar-baking soda reaction.

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Component	Description (Mechanistic Framing)	Example (Vinegar + Baking Soda Effervescence)
1. Describing the target phenomenon	State the specific observable event whose causal production needs to be explained.	When vinegar is mixed with baking soda, the mixture rapidly effervesces, producing bubbles and foam.
2. Identifying setup conditions	Specify the initial physical conditions under which the causal process unfolds.	Solid baking soda is added to liquid vinegar at room temperature in an open container.
3. Identifying entities	Identify the material components that participate directly in producing the effect.	Acetic acid molecules in vinegar, sodium bicarbonate ions in baking soda, water molecules, and the carbon dioxide molecules produced during the reaction.
4. Identifying activities	Describe what the entities do and how they exert causal influence on one another.	Acetic acid reacts with bicarbonate ions, transferring protons and producing carbonic acid that decomposes into carbon dioxide and water.
5. Identifying properties of entities	Specify intrinsic properties that determine how entities participate in causal interactions.	Acetic acid molecules can donate protons, and bicarbonate ions can accept them to form unstable carbonic acid molecules that decompose into carbon dioxide and water molecules.
6. Identifying organization of entities	Describe how entities and their activities are arranged in space and time to enable causal interaction.	The reaction begins where dissolved acid molecules contact bicarbonate ions and continues as reactants diffuse and products disperse throughout the solution.
7. Chaining: backward and forward	Construct a causal sequence showing how entities, properties, and activities jointly produce the phenomenon.	Because acetic acid molecules react with bicarbonate ions to produce carbon dioxide molecules in the gas phase, bubbles form and rise through the liquid, generating the observed effervescence.

they often struggle to account for the diverse contextual factors that shape component behavior. These challenges suggest that while mechanistic reasoning offers a powerful foundation for causal explanation, it requires careful scaffolding to support coordination across levels of organization (Caspari and Graulich, 2019; Krist, *et al.*, 2019; Bachtiar, *et al.*, 2022; Bachtiar, *et al.*, 2024; Kranz, *et al.*, 2026). It also requires attention to how instructional simplifications may unintentionally obscure or fragment causal reasoning, leading to incomplete understandings of complex phenomena (Haskel-Ittah, 2023; Talanquer, 2024; Livni Alcasid and Haskel-Ittah, 2026).

Systems Thinking in Science Education

While mechanistic reasoning emphasizes the causal architecture that explains how a particular phenomenon unfolds, systems thinking highlights the relational organization and constraints that regulate, stabilize, or transform that same phenomenon (Richmond, 1993; Assaraf and Orion, 2005). This way of thinking emerged in the mid-twentieth century from efforts to understand complexity in natural and artificial systems. Its intellectual roots lie in general systems theory, cybernetics, and subsequent developments in ecology, engineering, and complexity science (Hammond, 2002). These traditions challenged the reductionist assumption that systems can be fully understood by analyzing their parts in isolation, emphasizing instead that phenomena arise from patterns of interaction, regulation, and feedback among components situated within broader networks and environments. Within chemistry and STEM education, this perspective has gained prominence as a means of helping learners conceptualize complex phenomena, such as ecosystems or climate processes, that cannot be adequately explained through localized cause-and-effect reasoning alone (Ben-Zvi-Assaraf and Orion, 2010; Hmelo-Silver, *et al.*, 2017; Mahaffy, *et al.*, 2018; Momsen, *et al.*, 2022; Middlecamp, *et al.*, 2025).

At its core, systems thinking involves using boundaries, constraints, feedback relationships, and flows of matter and energy as epistemic resources for explaining and predicting system behavior over time (Assaraf and Orion, 2005; Orgill, *et al.*, 2019; York and Orgill, 2020). Feedback loops explain how processes stabilize or amplify change, while concepts such as

emergence and equilibrium describe how coherent patterns or steady states arise from distributed interactions (Arnold and Wade, 2015). Through this lens, explanation shifts from asking “*What sequence of events caused this outcome?*” to “*What relationships sustain or transform this behavior?*” Students engaged in systems thinking learn to view phenomena as emerging from networks of interacting elements, whose behaviors are shaped by structural and functional constraints, and to recognize that interventions at one point in a system may reverberate elsewhere through proximal and distal relationships (Jacobson and Wilensky, 2006).

To operationalize systems thinking in educational contexts, several frameworks have been proposed. For example, the Systems Thinking Hierarchical (STH) Model presented by Orion and Libarkin (2023) identifies nine key thinking skills (Table 2), organized into three stages: analysis of system components (Stage A), synthesis of system components (Stage B), and problem solving (Stage C). Similarly, Mehren *et al.* (2018) proposed a model emphasizing three core skills: identifying system organization, analyzing system behavior, and system modeling. Unlike the STH model, these skills are not arranged hierarchically but positioned side by side, each encompassing levels of sophistication that reflect increasingly complex forms of systems reasoning (Mambrey, *et al.*, 2020), from reasoning about direct relationships in simple systems to understanding nonlinear interactions in highly interconnected systems.

Systems thinking often foregrounds how structures enable and constrain behaviors in ways that support or undermine system functions. This aligns with structure–behavior–function (SBF) approaches used in STEM education to explain how functional outcomes emerge from organized relationships among components in complex systems (Hmelo, *et al.*, 2000; Hmelo-Silver and Pfeffer, 2004). In these frameworks, the organization of components refers not only to how parts are arranged to produce an effect, but also to how relational structures constrain, regulate, and sometimes optimize system behavior across conditions.

Educationally, systems thinking is valued for cultivating the ability to reason about complexity, interdependence, and nonlinearity, competencies that are increasingly essential for addressing contemporary global challenges such as climate



Table 2. Systems thinking skills (Orion and Libarkin, 2023) illustrated designing an optimized vinegar–baking soda eruption. Skills are grouped into three stages: A. Analysis of System Components; B. Synthesis of System Components; and C. Problem Solving.

Stages	Skill	Description (Systems Framing)	Example (Optimizing a Vinegar–Baking Soda Eruption)
A	1. Identification of the components of a specific system	Identify the elements that jointly constitute the system as a functional whole, including those that shape its boundaries.	The system includes vinegar, baking soda, the reaction container, surrounding air, produced gases and foam, and the size and shape of the container opening defining system boundaries.
	2. Identification of the processes that take place in a specific system	Recognize the processes that regulate system behavior and maintain or disrupt stability.	Acid–base reactions, gas production, heat transfer, fluid flow, and pressure buildup jointly shape the eruption behavior.
B	3. Identification of simple interactions between or among the components of the system	Describe how components are mutually constrained through reciprocal relationships.	Temperature, reactant concentration, particle size, and container geometry interact to influence reaction rate, gas accumulation, and foam expansion.
	4. Perception of the system as a dynamic entity (dynamic thinking)	Understand the system as evolving toward, maintaining, or departing certain states.	The eruption changes over time as reactants are consumed, gas accumulates, foam expands, and pressure conditions evolve.
	5. Organization of components within a framework of relationships	Interpret behavior as emerging from the organization of relationships rather than from isolated causal chains.	The vigor of the eruption emerges from the combined effects of reaction speed, gas release, foam formation, reactant dispersion, and container design rather than from any single variable alone.
C	6. Identification of cycles of matter and energy within systems (cyclic thinking)	Recognize continuous flows and redistributions that sustain system behavior over time.	Matter and energy are continuously redistributed as reactants dissolve and disperse, gases escape, heat transfers to the surroundings, and foam circulates through the system.
	7. Identification of patterns (generalization)	Identify system-level regularities that hold across cases and conditions.	Increasing temperature or reactant surface area generally increases reaction rate and foam production across similar reaction systems.
	8. Recognizing hidden components of systems	Identify influences that shape system behavior but are not directly observable.	Pressure gradients, local concentration changes, gas solubility, and turbulence inside the foam influence eruption behavior even though they are not directly visible.
	9. Temporal thinking forwards and backwards	Reason about how system behavior depends on prior states and how changing conditions reshape behavior.	Altering variables such as reactant ratio, temperature, or container opening changes how the eruption develops over time and affects the final height and duration of the gas release.

change, resource management, and public health (Brundiers, *et al.*, 2021). By mapping relationships across levels of organization, students learn to connect micro-level processes with macro-level patterns, interpret feedback-driven stability and instability, and appreciate how system boundaries and constraints influence observed behavior. These practices support adaptive problem solving and prepare learners to design and evaluate solutions in contexts where multiple variables interact dynamically.

Yet research also highlights persistent challenges in developing robust systems thinking. Learners may struggle to identify system components and processes, recognize their relationships, reason about variation over time and space, and attend to hidden variables (Assaraf and Orion, 2005; Talanquer, 2019). They may also struggle to map interactions across scales (Sabel, *et al.*, 2023; Szozda, *et al.*, 2023), reason about feedback mechanisms (Eidin, *et al.*, 2024), or identify distal relationships (Grotzer and Shane Tutwiler, 2014), making it difficult to connect local processes with global outcomes and to recognize or predict emergent behaviors. These challenges suggest that cultivating systems thinking requires explicit attention to practices such as model building (constructing representations of system components and interactions), boundary definition (determining what elements and processes are included in the system under study), constraint identification (recognizing factors that regulate or limit system behavior), and feedback analysis (tracing reciprocal influences that shape system dynamics over time). It also requires opportunities for learners to iteratively test, refine, and

reconcile their understandings of how complex systems behave (Pazicni and Flynn, 2019; Gilissen, *et al.*, 2020).

Contrasting the Two Reasoning Approaches

It is important to recognize that the distinction between mechanistic reasoning and systems thinking is not always clear-cut, particularly in chemistry education. Many chemical systems and phenomena involve collective, probabilistic, and emergent properties and behaviors (Luisi, 2002; Tümay, 2023). Explaining properties such as bonding capacity at the atomic level, molecular geometry and polarity at the molecular level, or gas diffusion, chemical equilibrium, and colligative properties at the multiparticle level often requires attention to multilevel interactions, statistical behavior, dynamic stabilization, and emergent patterns (Samon and Levy, 2020), even when learners are primarily engaged in constructing mechanistic explanations. In these contexts, mechanistic reasoning may incorporate ideas commonly associated with systems-oriented analyses while still focusing on how interactions among entities produce observable effects.

The presence of emergent properties (e.g., molecular polarity) and behaviors (e.g., chemical equilibrium), feedback processes (e.g., equilibrium shifts), or multilevel organization (e.g., micelle formation) does not necessarily require using systems thinking in the sense used in this paper. What differentiates systems thinking is not the mere use of these constructs, but also the epistemic orientation of the analysis. Systems thinking becomes more central when attention shifts toward how mechanisms are constrained, regulated, stabilized,

or modified within broader system contexts, particularly in situations involving intervention, optimization, or reasoning across interconnected systems. Mechanistic reasoning, in contrast, may employ many of the same conceptual resources while remaining primarily oriented toward explaining how interactions and processes generate certain behaviors.

From this perspective, mechanistic reasoning and systems thinking are best understood as *partially overlapping epistemic orientations* rather than fully distinct categories of reasoning. Both draw on representational resources such as components, interactions, and organization, but they employ these resources in service of different epistemic aims and become especially complementary in contexts requiring both explanation and intervention.

When mechanistic reasoning is used in isolation, learners may focus primarily on direct causal pathways while underestimating how environmental conditions, distal influences, and system constraints shape the operation and consequences of those mechanisms across situations (Grotzer, 2012). Conversely, systems-oriented explanations may remain largely descriptive or teleological when detached from mechanistic accounts of how system behaviors are causally produced (Churchman, 1979; Szozda, *et al.*, 2023). Coordinating these perspectives can thus support students in developing more flexible forms of reasoning capable of addressing phenomena and problems in which mechanistic processes and system-level conditions continuously interact to shape behavior over time.

Consider the example of the mixture of vinegar and baking soda presented in Tables 1 and 2. Mechanistic reasoning helps explain how acetic acid reacts with bicarbonate ions to produce carbon dioxide gas, generating bubbles and foam. However, such an account alone does not fully explain why the vigor, duration, or height of the eruption changes under different conditions. Addressing these questions requires attention to system-level factors such as temperature, reactant concentration, particle size, container geometry, gas escape pathways, and pressure buildup. These variables do not simply add additional causes; they shape how the underlying mechanism operates within the broader system. A systems perspective becomes important for explaining why the same mechanism produces different outcomes across contexts and for reasoning about how the behavior of the system can be modified, controlled, or optimized.

The discussion above highlights that mechanistic reasoning and systems thinking often overlap in the representational resources they employ and may both contribute to explaining the same phenomenon. However, their coordination becomes more intelligible when examining the distinct epistemic purposes they prioritize and the different forms of explanation they privilege. The following sections analyze these differences more explicitly.

Contrasting Epistemic Aims and Explanatory Logic

Although mechanistic reasoning and systems thinking may address the same phenomena, they often differ in their epistemic aims; that is, in what they seek to explain and what counts as a satisfactory account. Mechanistic reasoning primarily seeks to explain how entities and processes generate observable effects through causal interactions, whereas systems thinking focuses on how interactions, constraints, and feedback relationships regulate, stabilize, or transform system

behavior across contexts (Russ, *et al.*, 2008; Arnold and Wade, 2015; Haskel-Ittah, *et al.*, 2026). These differences become particularly visible when learners are asked not only to explain a phenomenon but also to determine how to respond to it.

Consider a situation in which a person is hyperventilating and experiencing dizziness. Students might be asked to explain what is happening in the body and to propose how to help restore normal functioning. Addressing this problem requires understanding both how the condition arises and how it can be regulated.

A mechanistic approach focuses on tracing the *causal production* of the phenomenon. That is, it seeks to explain how the activities and interactions of relevant entities generate the observed outcome. In the problem above, a mechanistic account would examine how rapid breathing reduces carbon dioxide levels in the blood, shifting chemical equilibria and decreasing hydrogen ion concentration, which leads to an increase in blood pH. This explanation provides a causal account of how hyperventilation produces alkalosis and may also support predictions about how changes in carbon dioxide concentration influence blood chemistry. However, on its own, it offers limited insight into how the body typically maintains pH within viable bounds, how multiple physiological systems interact to regulate those conditions over time, or how different interventions may affect system stability under changing circumstances.

In contrast, a systems-oriented approach focuses on the *causal regulation* of system behavior. Rather than asking how a phenomenon is produced, it seeks to explain how interactions among system components, constraints, and feedback relationships influence whether that phenomenon is maintained or altered over time. In the same scenario, a systems-oriented account would emphasize the feedback relationships between respiratory control centers, blood chemistry, buffering systems, and metabolic demands that normally regulate pH levels. It would highlight how disruptions to these feedback loops lead to instability and how restoring balance depends on the coordinated interaction of multiple subsystems operating under physiological constraints. Such a perspective supports reasoning about regulation, adaptation, and intervention within a dynamic system. Yet, when detached from a mechanistic account, systems-oriented explanations may remain largely descriptive or teleological, as if the body “aims” to maintain balance, without specifying the concrete processes through which regulation occurs (Trommler and Hammann, 2020).

Coordinating mechanistic reasoning and systems thinking enables a deeper form of understanding in which phenomena are interpreted as the result of mechanisms operating within systems governed by constraints and feedback relationships. In the hyperventilation scenario, such coordination supports not only explaining why blood pH increases but also reasoning about how specific interventions, such as altering breathing patterns, may restore equilibrium. Students are thus able to move beyond explaining how the phenomenon is produced toward reasoning about how system behavior can be regulated, stabilized, or modified across contexts.

Differences in Analytical Orientation

The two reasoning modes also differ in how they frame phenomena for analysis and in the methodological approaches they employ to understand and influence system behavior.

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Mechanistic reasoning typically operates within relatively well-defined boundaries, assuming that phenomena can be explained by analyzing the entities and processes internal to a system. Its methodological stance often involves isolating components, examining their properties and interactions, and tracing causal sequences.

Systems thinking, in contrast, treats boundaries not as given but as conceptual constructs that must be deliberately defined based on the goals of the analysis or design task. It assumes that entities and their behaviors are shaped by the constraints, feedback, and interactions of the systems in which they are embedded. Methodologically, this entails a synthetic approach focused on identifying relationships, analyzing feedback processes, and exploring system dynamics over time, often through modeling and simulation.

In short, mechanistic reasoning examines what happens within established boundaries, while systems thinking asks how those boundaries shape system behavior.

Differences in Direction of Reasoning

Mechanistic reasoning and systems thinking also differ in the typical direction in which reasoning unfolds.

Mechanistic reasoning often proceeds in a bottom-up direction that mirrors the epistemic heuristics articulated by Krist et al. (2019). Learners begin by *zooming in* to consider what occurs at a scalar level below the observed phenomenon, then identify and characterize the relevant elements and interactions at that level, and finally *zoom out* by coordinating those elements across space and time to determine how they give rise to the macroscopic outcome.

Systems thinking, by contrast, often adopts a “*zoom-out, zoom-in, then zoom-out*” orientation that reflects how systems are conceptualized in the literature (Talanquer and Szozda, 2024). It begins with the analysis of system boundaries, constraints, and overall dynamic patterns (Assaraf and Orion, 2005), then zooms in to examine how these systemic features shape the activities of components at lower levels, and finally zooms out again to interpret how system behavior or function changes when constraints or relationships are altered (Orion and Libarkin, 2023). This form of reasoning is multi-scalar, weaving back and forth between different levels of organization to capture reciprocal influences between parts and wholes.

These differences become particularly salient in contexts where students must both explain and respond to complex phenomena. Consider the problem of understanding and mitigating ocean acidification. Students may be asked to explain why increasing atmospheric CO₂ leads to changes in ocean pH and to propose strategies for reducing these effects.

A mechanistic analysis focuses on the underlying chemical processes. Learners examine how dissolved CO₂ reacts with water to form carbonic acid, how this acid dissociates into bicarbonate and hydrogen ions, and how these equilibria shift as CO₂ concentrations increase. This *bottom-up causal account* explains how changes in atmospheric CO₂ produce changes in ocean pH. However, on its own, it provides limited insight into how these processes are influenced by broader environmental conditions or how the system might respond to intervention.

A systems-oriented perspective, in contrast, considers the larger system in which these processes are embedded. It examines how atmospheric CO₂ levels, ocean temperature, circulation patterns, and biological activity interact to shape the behavior of the ocean–atmosphere system over time. In this

top-down causal account, ocean acidification is understood as an emergent outcome of interacting subsystems governed by multiple constraints and feedback processes. This view helps explain why similar increases in CO₂ may produce different effects under different environmental conditions and highlights potential leverage points for intervention. Yet, without mechanistic detail, such explanations may remain too general to specify how particular changes influence chemical processes at the molecular level. Coordinating both perspectives allows students to understand not only how ocean acidification occurs but also why its effects vary across contexts and how targeted interventions might alter system behavior.

Complementarity and Tensions

Despite their differences, mechanistic reasoning and systems thinking are not opposing frameworks but complementary perspectives that illuminate different dimensions of the same phenomenon. Their coordination, however, gives rise to important cognitive, epistemic, and instructional tensions. Learners often struggle to reconcile localized, sequential causal reasoning with multilevel, feedback-driven system dynamics, while differing criteria for explanation and the tendency to teach these approaches in isolation further complicate their integration (Assaraf and Orion, 2005; Grotzer, 2012).

These tensions reflect not only the complexity of coordinating multiple levels and forms of explanation, but also differences in how the two approaches organize inquiry and understanding. Mechanistic reasoning often seeks explanatory clarity through decomposition and localization of component processes (Bechtel and Richardson, 2010), whereas systems thinking emphasizes integration across levels, relationships, and constraints. Coordinating these perspectives therefore requires learners to move iteratively between tracing localized mechanisms and analyzing how system organization and conditions shape overall behavior.

The challenges of coordination become especially visible when learners must reconcile mechanistic explanations with system-level constraints, as in contexts where both explanation and intervention are required. Consider a scenario in which a toxic or flammable gas is released in an enclosed space, such as a laboratory or industrial facility. Students may be asked to explain how the gas spreads and to propose strategies to minimize exposure or risk.

A mechanistic analysis focuses on the processes driving gas movement. Learners examine how gas molecules diffuse due to random motion, how concentration gradients drive net movement, and how properties such as density and temperature influence dispersion. This perspective provides a causal account of how the gas spreads through the environment, but on its own offers limited insight into how that distribution is shaped by the broader system or how it might be effectively controlled.

A systems-oriented perspective shifts attention to the larger configuration in which these processes occur. It considers how boundaries (walls, doors), flows (air currents), and constraints (temperature gradients) interact to shape the distribution of the gas over time. From this viewpoint, gas dispersion is understood as an emergent pattern resulting from interacting components and constraints. This perspective enables reasoning about where gas concentrations may accumulate and how interventions, such as adjusting ventilation or altering airflow, can modify system behavior. Yet, without mechanistic

detail, such reasoning may lack precision in predicting how specific changes influence gas movement at the molecular level.

This example illustrates that coordination is not merely additive but transformative. It enables learners to move from explaining processes to reasoning about control, regulation, and design within dynamic environments, thereby integrating scientific explanation with engineering-oriented intervention. In doing so, students develop more flexible and generative forms of reasoning for addressing complex problems.

In the following section, I outline an instructional framework that brings these reasoning modes into productive dialogue within anchored learning in chemistry and across STEM subjects, demonstrating how iterative movement between mechanistic and systems perspectives can deepen understanding and support more integrated scientific reasoning and engineering design.

Coordinating Mechanistic Reasoning and Systems Thinking

Mechanistic reasoning and systems thinking can be productively coordinated within a single act of inquiry or design. Rather than functioning as isolated modes of analysis, they operate as complementary perspectives through which learners examine, interpret, and act upon the same phenomenon. Coordination does not involve repeating identical analytic steps within each mode. Instead, learners revisit shared elements (e.g., components, interactions, and organization) for different epistemic purposes. Mechanistic reasoning helps explain how entities and processes produce observable effects, whereas systems thinking examines how broader conditions, constraints, and relationships shape system behavior. Within this framework, explanation and design become iterative processes in which causal accounts and systems analyses continually inform one another.

The proposed framework emphasizes coordination rather than full integration. The goal is not to collapse mechanistic reasoning and systems thinking into a single unified mode of reasoning, but to support learners in moving strategically between distinct epistemic orientations depending on the goals of the task. Such movement becomes particularly important when students must not only explain phenomena but also reason about how system behavior can be modified, controlled, optimized, or redesigned under relevant constraints and conditions.

The phases described below differ not only in the reasoning resources they foreground but also in their primary epistemic aims. Mechanistic exploration and systemic framing are primarily analytical phases focused on developing increasingly sophisticated accounts of (1) how a phenomenon is produced and (2) how its behavior is shaped by broader system conditions. Coordinated design and revision shifts attention toward action by bringing these analytical perspectives together to propose, evaluate, test, and refine interventions. Although opportunities for design-oriented reasoning may arise during the first two phases, intervention becomes the explicit focus of this phase.

Figure 1 represents the framework as interacting cycles connected through iterative processes of interpretation, intervention, testing, and revision. Mechanistic reasoning and systems thinking continuously inform one another as learners move among explaining how phenomena arise, analyzing how system conditions influence their behavior, and evaluating how interventions alter outcomes.

Given a phenomenon to analyze, explain, and control, this coordinated reasoning can unfold through the following phases:

- Mechanistic Exploration.** Students construct a causal account of how the phenomenon arises. This phase draws primarily on mechanistic reasoning and builds on epistemic heuristics described by Krist et al. (2019). Learners:

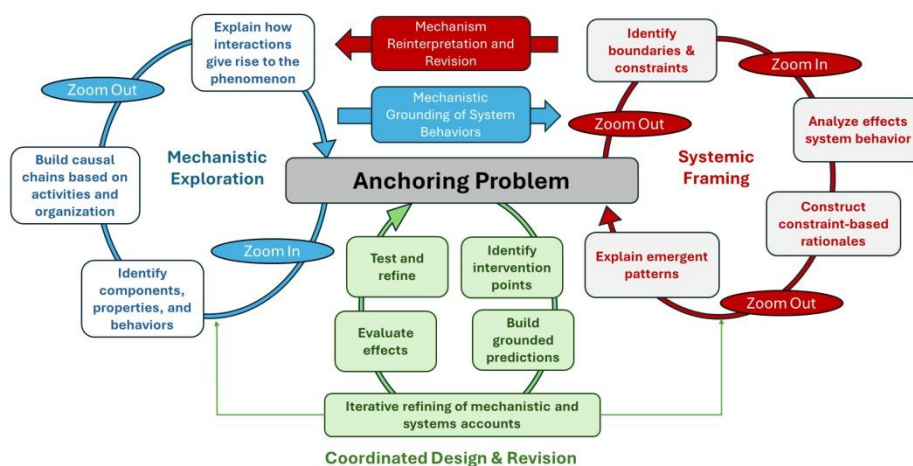


Figure 1. Proposed instructional model for coordinating mechanistic reasoning and systems thinking. Mechanistic exploration (blue) focuses on explaining how interactions among components and processes produce observable phenomena. Systemic framing (red) focuses on analyzing how boundaries, constraints, feedback relationships, and system organization shape, regulate, or modify those mechanisms and their outcomes. Coordinated design and revision (green) represents the iterative testing, evaluation, and refinement of explanations and interventions. The model emphasizes iterative movement between zooming in to analyze localized causal processes and zooming out to examine system-level dynamics, enabling learners to develop increasingly coherent, context-sensitive, and design-oriented understandings of phenomena and problems.

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- a) zoom in to identify relevant components, properties, and interactions;
- b) build causal chains based on component activities and organization, before
- c) zoom out to explain how these interactions generate the observed phenomenon.

For example, in the vinegar and baking soda case, students explain how acetic acid molecules react with bicarbonate ions to produce carbon dioxide molecules in the gas phase, leading to effervescence.

2. **Systemic Framing.** Students reinterpret the mechanistic account within the context of the broader system in which the phenomenon occurs. This phase foregrounds systems thinking by directing attention toward system boundaries, constraints, feedback relationships, and interactions across levels. Learners:
 - a) zoom out to identify boundaries, constraints, and feedback relationships not previously considered;
 - b) zoom in to examine how these system-level conditions shape the operation, relevance, or effectiveness of previously identified mechanisms; and
 - c) zoom out again to explain how interactions among mechanisms, constraints, and environmental conditions produce broader system-level patterns.

In the vinegar and baking soda example, students analyze how factors such as temperature, reactant concentration, particle size, container geometry, and gas escape pathways influence the vigor, duration, and height of the eruption.

3. **Coordinated Design and Revision.** Having developed mechanistic and systems-based accounts of the phenomenon, students coordinate these perspectives to propose, test, evaluate, and refine interventions. In this phase, learners use mechanistic reasoning to predict how specific changes may alter localized processes, while systems thinking helps evaluate how those changes interact with broader system conditions and constraints. Learners:
 - a) identify potential intervention points by determining which components, interactions, or system conditions can be modified to influence system behavior;

- b) construct mechanistic and systems-based predictions about how proposed changes may affect both localized processes and broader system dynamics;
- c) evaluate how constraints, boundary conditions, and feedback relationships may enhance, limit, or alter the effects of proposed interventions, including possible unintended consequences; and
- d) test, compare, and iteratively refine interventions using evidence gathered through observation, experimentation, or simulation.

In the vinegar and baking soda example, students design the most effervescent “volcano” possible by manipulating variables such as temperature, concentration, container shape, or reactant proportions. In doing so, they continually coordinate mechanistic explanations of gas production with systems analyses of how environmental conditions and constraints shape eruption behavior.

The distinctions among these phases can be summarized in terms of their epistemic focus, guiding questions, and role in refining explanations and interventions (Table 3). In classroom practice, this process can be visualized as interacting layers of explanation, systems analysis, and design, in which mechanistic insights are continually contextualized within broader system dynamics, and systems interpretations are repeatedly refined through causal analysis and intervention. Such coordination fosters cognitive flexibility (Ionescu, 2012), enabling learners to move fluidly across levels of organization and appreciate the reciprocal relationships between mechanisms, systems, and designed interventions.

Illustrating Coordinated Reasoning in Chemistry

To illustrate how mechanistic reasoning and systems thinking can be coordinated in chemistry learning, consider a design challenge adapted from prior work on chemical control and optimization (Caushi, *et al.*, 2021). The epistemic purpose of this activity is to engage students in coordinating mechanistic reasoning and systems thinking. In doing so, learners pursue three complementary epistemic aims: explaining how the phenomenon is produced, understanding how system conditions regulate its behavior, and designing, evaluating, and refining interventions intended to achieve a desired outcome.

Table 3. Coordinating Mechanistic Reasoning and Systems Thinking through Iterative Zooming

Phase	Epistemic Focus	Guiding Questions	Role in Explanation and Design	Example
Mechanistic Exploration	Causal production and mechanistic explanation	How is the phenomenon produced? Which entities, properties, and interactions generate the phenomenon?	Construction of an initial causal account of the phenomenon	Gas particles diffuse due to random motion
Systemic Framing	System constraints, regulation, and contextual variation	What boundaries, constraints, feedbacks, and environmental conditions shape system behavior? How do these conditions influence the mechanisms?	Reinterpretation of mechanistic explanations within broader system contexts	Ventilation, concentration and temperature gradients, and physical space shape gas distribution
Coordinated Design and Revision	Intervention, prediction, and iterative refinement	Which components, interactions, or conditions can be modified to influence outcomes? What unintended consequences may emerge?	Coordination of mechanistic and systems perspectives to evaluate, test, and optimize interventions or solutions	Adjusting airflow, containment, or ventilation modifies gas dispersion and exposure risk

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In particular, students are asked to determine how to generate the most vigorous methane combustion possible within a container of fixed volume. Addressing this problem requires not only explaining how methane combustion occurs, but also reasoning about how system conditions, constraints, and interventions influence the magnitude and stability of the resulting explosion. The task creates opportunities for learners to coordinate mechanistic reasoning with systems thinking to explain, predict, and design.

Phase 1: Mechanistic Exploration (Zooming In and Out)

Students begin by constructing a mechanistic account of methane combustion in the container. They identify the relevant components, including methane, oxygen in the air, the ignition source, combustion products, and the container, along with relevant properties such as flammability, reactant amounts, gas composition, and fixed volume. Through observation, experimentation, or simulation, students trace the causal chain: methane and oxygen mix in the container; the ignition source provides sufficient energy to initiate combustion; methane reacts with oxygen to form carbon dioxide and water vapor in an exothermic process; the rapid formation and heating of gaseous products increase pressure inside the container; and the resulting pressure difference ejects the lid, producing the “boom.”

Teachers can scaffold this phase by prompting students to map the sequence of events and then zoom in to analyze the process at the molecular level. Students might represent methane and oxygen particles before ignition, the rearrangement of atoms during combustion, and the formation of gaseous products after reaction. Classroom discussion can guide them to connect molecular-level events, such as bond breaking, bond forming, and molecular redistributions, with macroscopic outcomes such as energy release, pressure buildup, lid displacement, and sound.

Formative assessment during this phase can focus on the causal coherence of students' explanations, their ability to identify relevant entities and interactions, and their use of chemical models to connect molecular-level processes with observable effects. Evidence of productive mechanistic reasoning includes students explaining why both methane and oxygen are needed, how ignition initiates the reaction, how energy is generated, how combustion products and heating contribute to pressure changes, and why those pressure changes produce the observed explosion.

Phase 2: Systemic Framing (Zooming Out, In, and Out Again)

In this second stage, students adopt a systems-thinking stance to reinterpret the combustion mechanism within the broader system in which it occurs. At this point, students should have a coherent causal explanation for how methane combustion produces pressure buildup and explosion. However, that explanation alone does not fully account for why the intensity of the explosion varies under different conditions, why combustion may fail to occur in some cases, or how the system might be modified to maximize or regulate the outcome.

During the mechanistic phase, students may already have recognized relevant setup conditions such as methane concentration, oxygen availability, container volume, ignition location, or temperature as factors affecting combustion. In this phase, however, these elements are reconsidered not simply as initial conditions influencing a reaction, but as interacting system constraints and boundary conditions that shape overall system behavior, regulate energy transfer, and define opportunities and limits for intervention and optimization.

Students begin by zooming out to identify the broader system within which combustion unfolds, mapping its boundaries, constraints, flows, and interactions. The system now includes the combustion chamber, surrounding atmosphere, air composition, energy inputs and outputs, heat transfer processes, and the structural properties of the container. These factors define the conditions within which the previously identified combustion mechanisms operate.

Students then zoom in again to examine how these constraints dynamically interact with the combustion process. For example:

- The methane-to-oxygen ratio constrains whether combustion is incomplete, sustained, or explosive, regulating both energy release and pressure buildup.
- Container volume and geometry shape how rapidly pressure accumulates and how combustion products expand through the system.
- Heat transfer through the container walls influences reaction temperature, affecting combustion rate and the propagation of the flame front.
- Pressure-release pathways regulate gas flow and energy dissipation, limiting or amplifying explosive behavior.

As students elaborate these relationships, their reasoning can be scaffolded by asking them to build systems maps, feedback diagrams, or causal loop models showing how interacting constraints regulate combustion behavior. (Aubrecht, *et al.*, 2019; MacDonald, *et al.*, 2025). For example, increasing combustion intensity may generate higher temperatures that accelerate reaction rates, reinforcing pressure buildup, while pressure-release mechanisms or heat loss may counteract this process and stabilize the system. These constraints do not simply add contextual detail to the original mechanistic account; they reorganize it by determining which mechanisms dominate, which are limited, and under what conditions combustion becomes more vigorous or self-limiting.

Formative assessment during this phase can focus on students' ability to identify and justify system boundaries, analyze relationships among constraints and mechanisms, and reason about how system conditions shape, regulate, or modulate combustion behavior across different contexts.

Phase 3: Coordinated Design and Revision

In the final stage, students coordinate mechanistic and systems perspectives to propose, test, evaluate, and refine interventions designed to maximize the vigor of methane combustion under specified conditions. At this point, learners move beyond explaining how combustion occurs or how system constraints shape behavior. They now use these complementary

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perspectives to reason about how modifications to the system may alter localized chemical processes and system dynamics.

Students begin by identifying potential intervention points within the system. They determine which components, interactions, or system conditions can be modified to influence combustion behavior, such as methane concentration, oxygen availability, ignition position, container geometry, vent size, or heat retention. In doing so, they revisit previously identified mechanisms and constraints while considering how changes at one level may propagate through the broader system.

Students then construct mechanistic and systems-based predictions about how proposed modifications may alter both the combustion process and overall system behavior. For example, they may predict that increasing methane concentration within certain limits will increase energy release and pressure buildup, while also recognizing that excessive fuel concentration may reduce oxygen availability and suppress efficient combustion. Similarly, reducing vent size may increase internal pressure but also elevate the risk of structural failure or incomplete combustion due to altered airflow.

As learners evaluate these possibilities, they analyze how constraints, boundary conditions, and feedback relationships may amplify, limit, or redirect the effects of their interventions. They may consider how heat accumulation accelerates combustion rates, how gas expansion influences pressure dynamics, or how container geometry affects flame propagation and energy dissipation. Students are also encouraged to anticipate unintended consequences and tradeoffs, recognizing that modifications intended to optimize one aspect of system behavior may destabilize others.

Students then test, compare, and iteratively refine their proposed interventions using experimentation, simulations, or evidence-based argumentation. They may compare alternative system configurations, revise predictions in light of observed outcomes, and refine both their mechanistic explanations and systems analyses accordingly. In this process, mechanistic reasoning helps explain why particular interventions alter combustion behavior, while systems thinking helps evaluate how those changes interact with broader constraints and system conditions.

This phase highlights the design dimension of coordinated reasoning in chemistry education. Students come to understand systems not as static collections of components, but as dynamic arrangements of interacting relationships that can be intentionally modified to achieve desired outcomes under specific constraints. The coordination of mechanistic reasoning and systems thinking thus supports more flexible forms of explanation, prediction, intervention, and optimization that mirror authentic scientific and engineering practice.

Formative assessment during this phase can focus on students' ability to coordinate causal and systems-based reasoning when justifying predictions, evaluating tradeoffs, and refining interventions. Evidence of productive coordination emerges when students can explain not only how combustion occurs, but also how modifying system conditions alters the operation, effectiveness, and consequences of the underlying mechanisms across contexts.

Instructional Implications and Scope Conditions

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The methane-combustion case illustrates how coordinating mechanistic reasoning and systems thinking can support both scientific explanation and engineering-oriented design, providing a foundation for pedagogical approaches that foster flexible, multilevel reasoning in chemistry and across STEM domains. Within the proposed framework, students move iteratively between explaining how phenomena are produced, analyzing how system conditions shape their behavior, and evaluating how interventions may modify outcomes. In doing so, mechanistic reasoning and systems thinking are treated as complementary epistemic perspectives that focus on different dimensions of the same phenomenon.

The instructional sequence proposed in this paper is particularly suited for anchored phenomena and problems that require not only explanation but also prediction, intervention, optimization, or design. In such contexts, beginning with mechanistic exploration provides an important pedagogical foundation because it grounds subsequent systems-oriented reasoning in explicit causal processes. This progression helps prevent systems-oriented analyses from becoming purely descriptive or teleological while also helping students recognize that mechanistic processes do not operate independently of system conditions and boundaries.

The framework is therefore most valuable for phenomena and problems in which the operation and consequences of mechanisms depend on system conditions, constraints, and interactions across levels of organization. These contexts may involve complex and dynamically evolving systems, such as combustion processes, chemical equilibria, metabolic regulation, or climate-related chemistry, but they may also include more bounded design-oriented problems commonly encountered in chemistry classrooms. For example, students may investigate how to optimize the voltage produced by a potato battery, maximize the adsorption of food coloring on eggshells, or design water-repellent surfaces under different conditions. In such cases, understanding depends not only on identifying the mechanisms responsible for observed effects, but also on reasoning about how variations in system conditions, material properties, boundaries, or environmental factors regulate, stabilize, amplify, or constrain those mechanisms. These types of problems often require learners to evaluate tradeoffs, identify leverage points for intervention, and iteratively optimize outcomes, making coordinated mechanistic and systems reasoning particularly productive.

The examples presented above highlight a central tenet advanced in this perspective. In the proposed framework, the distinction between mechanistic reasoning and systems thinking is not understood as depending primarily on the intrinsic complexity of a phenomenon or on the mere presence of emergent, probabilistic, dynamic, or multilevel behavior. What differentiates these forms of reasoning is not the type of system being studied, but the epistemic aims toward which reasoning is directed. The same phenomenon may thus be approached from different epistemic orientations depending on the inquiry goals. For example, eutrophication may be



examined mechanistically when the goal is to explain how excess nutrients alter oxygen availability through biological and chemical processes, or systemically when the goal is to analyze how agricultural practices, water flow, ecosystem interactions, and human interventions shape the behavior of the broader aquatic system over time. Similarly, the chemical degradation of plastics may involve mechanistic explanations of polymer breakdown or be approached using systems thinking, considering material design, environmental accumulation, waste management, and long-term ecological consequences.

Lists of systems-thinking characteristics often emphasize representational or analytical features of reasoning, such as attending to interactions, emergence, feedback, or temporal change (York and Orgill, 2020; Rocabado and Orgill, 2025). However, many of these features may also appear in sophisticated forms of mechanistic reasoning, particularly in chemistry, where explanations frequently involve collective, probabilistic, and multilevel phenomena. From the perspective advanced in this paper, the distinction between mechanistic reasoning and systems thinking lies less in the specific constructs employed than in the epistemic purposes those constructs serve.

Although the framework advanced in this paper is broadly applicable across a range of chemistry and STEM contexts, its productive use depends on the nature of the learning goals, the characteristics of the phenomenon or problem, and students' developing representational and reasoning capacities. However, it is not intended as a universal model for all chemistry learning. For simpler or single-causal phenomena, mechanistic reasoning alone may be sufficient, and coordinating systems thinking may add unnecessary complexity. Similarly, in early learning contexts where students have limited representational competence or little experience with mechanistic modelling, instruction may initially need to emphasize foundational causal reasoning before introducing more sophisticated systems-oriented analyses.

The proposed approach does not necessarily resolve all known challenges in mechanistic reasoning or systems thinking, but it directly addresses several persistent and well-documented difficulties in STEM learning. Students often construct linear and isolated causal chains that overlook how environmental conditions, hidden variables, or distal factors shape outcomes (Grotzer, 2012; Bachtiar, *et al.*, 2022). Conversely, systems-oriented reasoning may remain descriptive but causally underdeveloped when students identify relationships or patterns without understanding the mechanisms through which they arise. Coordinating these forms of reasoning brings such limitations into productive tension by making both causal production and causal regulation visible and discussable within the same modelling process.

Because coordinating mechanistic reasoning and systems thinking places substantial cognitive demands on learners, meaningful implementation requires deliberate instructional scaffolding. Students are rarely asked to move iteratively between localized causal reasoning, systems-level analysis, and design-oriented intervention while coordinating ideas across levels of organization and timescales. Effective supports may

thus include structured prompting, visual representations such as particle models and systems maps, iterative prediction and revision cycles, collaborative discussion, and explicit comparison of mechanistic and systems-oriented explanations. Such scaffolds can help learners recognize when they are reasoning mechanistically, when they are reasoning systemically, and how these perspectives can be coordinated to refine explanations and interventions over time.

At the same time, learners bring valuable cognitive resources that instruction can build upon, including intuitive causal schemas grounded in everyday experience, emerging notions of balance and regulation, and increasing facility with multiple representations (Penner, 2000; Jacobson and Wilensky, 2006; Jacobson, *et al.*, 2019). Making these resources explicit through modelling, discussion, and iterative revision can support the development of more flexible and sophisticated forms of scientific reasoning.

Meaningful adoption of this framework also depends on teacher preparation and curricular support. Teachers require tools to recognize partial yet productive reasoning, design scaffolded modelling sequences, and guide students in shifting between mechanistic and systems-oriented perspectives. Curriculum materials must support sustained engagement with anchoring phenomena and problems that demand increasing levels of coordination, while assessment practices must prioritize coherence, adaptability, and explanatory adequacy over surface completeness or procedural correctness.

Consequently, implementing coordinated mechanistic reasoning and systems thinking is not simply a matter of modifying classroom tasks. It requires the deliberate design of learning environments, instructional practices, assessment approaches, and curricular structures that authentically engage students in explanation, prediction, and design. Within such environments, students' reasoning becomes visible, open to critique, and iteratively refined (Windschitl, *et al.*, 2018), supporting increasingly sophisticated coordination between causal and systems-oriented perspectives over time.

It is important to note that the framework proposed here is intended as a conceptual and instructional heuristic rather than an empirically validated model of learning. Its purpose is to make explicit how mechanistic reasoning and systems thinking could be coordinated in chemistry and STEM classrooms, thereby generating hypotheses about how students' reasoning may develop under such conditions. Evidence of productive coordination would not be limited to the accumulation of additional knowledge but would instead be reflected in qualitative shifts in students' reasoning. For example, learners may not only construct causal explanations but also revise them considering system-level constraints, explain how mechanisms operate differently under varying conditions, and use this coordinated understanding to justify predictions, evaluate tradeoffs, or optimize interventions. Such performances provide a basis for future empirical work aimed at examining how coordinated reasoning emerges, how it can be scaffolded instructionally, and what forms of understanding and design capacity it enables across contexts.

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Conclusion

Coordinating mechanistic reasoning and systems thinking within anchored learning reframes chemistry and STEM education as the cultivation of adaptive ways of explaining, predicting, and designing (National Research Council, 2012; National Research Council, 2013; OECD, 2025). When students learn to move between analyzing how mechanisms produce effects and explaining why those effects persist, change, or stabilize under specific constraints, they develop a form of epistemic flexibility that is essential for reasoning across scales, contexts, and domains. Cultivating this flexibility is crucial for fostering understanding of the kinds of authentic problems and issues that chemistry (Mahaffy, *et al.*, 2018; Mahaffy, *et al.*, 2019; Talanquer, *et al.*, 2020; Talanquer, 2026) and STEM educators (Sadler, *et al.*, 2025; Tytler, *et al.*, 2025; Liu, *et al.*, 2026) argue should lie at the heart of contemporary curricula.

This paper has argued that coordinating mechanistic reasoning and systems thinking can support forms of understanding that neither approach fully affords in isolation. Mechanistic reasoning alone may produce explanations that are causally precise but insufficiently attentive to contextual constraints and system dynamics, whereas systems thinking alone may yield accounts that emphasize patterns and relationships without adequately explaining how those patterns are produced. Coordinating these perspectives helps bring causal production and causal regulation into alignment while supporting students in moving between explanation, prediction, intervention, and optimization.

The instructional framework proposed here illustrates one possible way to support such coordination through iterative movement between mechanistic exploration, systemic framing, and coordinated design and revision. Rather than treating mechanistic reasoning and systems thinking as separate or competing traditions, the framework positions them as complementary epistemic orientations that become especially productive in contexts requiring learners to explain phenomena while also reasoning about how outcomes can be modified under specific constraints and conditions.

Fostering coordination between mechanistic reasoning and systems thinking can therefore support a more integrated vision of chemistry and STEM education. Chemistry is particularly well positioned to support this coordination because it provides opportunities to investigate systems of increasing complexity while relying on a relatively coherent set of explanatory principles. This progression enables learners to develop mechanistic reasoning and encounter systems-oriented concepts such as emergence, feedback, constraints, and adaptation within contexts that remain intellectually accessible. At the same time, chemistry's dual orientation toward understanding and transforming the material world creates authentic opportunities to coordinate explanation and design in the pursuit of desired outcomes. In this sense, coordinated reasoning becomes not simply an instructional strategy, but a way of preparing students to engage more thoughtfully and effectively with the complex scientific and technological challenges that increasingly shape contemporary life.

Chemistry Education Research and Practice

Conflicts of interest

There are no conflicts to declare.

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Data Availability Statement

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

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