

The Coherence Of The Principles Of Integration And Systemicity In Teaching Natural Sciences

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Abstract: This article develops a theoretical account of how the principles of integration and systemicity jointly structure high-quality instruction in the natural sciences at the secondary level. Rather than treating integration as a mere juxtaposition of topics, the paper frames it as an epistemic design choice that aligns disciplinary concepts, practices, and representations around phenomena whose explanation requires multiple lenses. Systemicity is construed as a way of reasoning about parts, relationships, feedback, and emergence across scales; the argument is that integration becomes coherent only when it is guided by systemic thinking so that content connections serve explanatory purpose rather than thematics. The study synthesizes work from systems theory, learning sciences, knowledge-integration research, and modeling-based inquiry to propose design heuristics that translate theory into classroom practice without fragmenting disciplinary rigor. Methodologically, this is an integrative review with illustrative design analyses of phenomenon-centered sequences in energy, homeostasis, and materials transformations. The discussion shows how coherence arises when crosscutting concepts and epistemic practices are sequenced to support conceptual change, transfer, and disciplinary literacy, and it examines implications for assessment, teacher knowledge, and the use of simulations and community partnerships. The conclusion argues that when integration is organized systemically, students' explanatory writing, model use, and problem transfer improve because teaching mirrors the structure of scientific inquiry itself.

Keywords: Curriculum integration; systems thinking; conceptual change; modeling; phenomenon-based learning; crosscutting concepts; disciplinary literacy.

Introduction: Calls to integrate the natural sciences in school curricula often appeal to the way scientific work reaches beyond a single subject label. Climate dynamics, metabolic regulation, or materials engineering refuse confinement within one discipline; they require coordination of theories, methods, and representations from physics, chemistry, biology, and earth science. Yet attempts at integration sometimes devolve into thematic collections that blur boundaries without yielding deeper understanding. The missing element is usually systemicity: a principled attention to how components, interactions, and constraints produce behavior across levels. When integration proceeds under a systemic lens, linkages among topics become vehicles for explanation rather than decorative connections. Students are invited to ask how energy and matter move, how feedback stabilizes or destabilizes behavior, how structure constrains

function, and how patterns recur across scales and contexts.

The coherence of integration and systemicity is not accidental. Systems theory provides concepts—structure, interaction, feedback, emergence—that help organize explanatory work; the learning sciences explain why such organization supports schema construction, conceptual change, and transfer. Learners do not store isolated facts but assemble networks of ideas that are recruited when a problem demands them. Fragmented curricula cultivate context-bound knowledge that fails to transfer, whereas phenomenon-centered sequences that foreground crosscutting structure give students practice abstracting relations from varied surface features. This is the logic behind contemporary standards that emphasize crosscutting concepts and scientific practices alongside disciplinary core ideas:

coherence occurs when content, practices, and representations are aligned around systemic explanations rather than topic coverage.

In secondary schools, constraints of time, assessment, and resources are real, but they do not negate the rationale. A smaller number of phenomenon-rich units can cultivate disciplined habits of modeling and argument that extend beyond a single class. If teachers orchestrate discourse that presses for mechanistic accounts, if measurement and simulation are used to test and refine models, and if writing is treated as a medium for making reasoning visible, students begin to experience science as a way of knowing rather than a glossary. The present article therefore asks what it means, in theoretical and practical terms, to make integration coherent by embedding it in systemic reasoning, and what opportunities arise for instruction, assessment, and teacher development when this alignment is taken seriously.

The aim is to articulate a theoretically grounded account of the coherence between integration and systemicity in natural science education and to translate this account into design implications for secondary instruction. The paper seeks to show how phenomenon-based integration guided by systemic reasoning advances conceptual coherence, explanatory communication, and transfer without eroding disciplinary integrity.

The study employs an integrative review methodology. Foundational sources in general systems theory, complexity, and the learning sciences are synthesized with research on knowledge integration, modeling-based inquiry, and argumentation in science classrooms. The analysis examines standards frameworks that formalize crosscutting concepts and epistemic practices and uses design vignettes to illustrate how a systemic lens structures integrated units. The method is analytic rather than statistical; the objective is to map conceptual lineages and derive design heuristics that are faithful to theory yet adaptable to typical school constraints.

To ground the synthesis, the article analyzes three families of phenomena that routinely appear in school science and that invite multi-disciplinary treatment. Energy conversions in engineered and natural systems render visible the movement and transformation of energy and matter, connecting thermodynamics, electromagnetism, and chemical bonding. Homeostatic regulation in organisms and ecosystems foregrounds feedback and control, linking physiology, biochemistry, and population dynamics. Materials transformations exemplify structure–property relations and kinetics, drawing together atomic-molecular models, reaction

energetics, and macroscopic performance. For each family, the analysis traces how a sequence can be organized around model construction, empirical testing, and revision so that integration arises from the demands of explanation rather than from thematic proximity.

Coherence in integrated science emerges when the organizing question is systemic: what structures and interactions produce the behavior of this phenomenon, with what flows, constraints, and feedbacks, and how do these play out across scales? When students investigate a solar water heater, they move among ideas of radiation, conduction, convection, absorptivity, and design trade-offs; yet these are not a collection of topics but components of a mechanistic account. The teacher's moves make the systemic frame explicit by asking how energy enters, is transformed, and leaves the system, how geometry affects flux, and how materials properties mediate transfer. Measurements of temperature over time are not ends in themselves but evidence to evaluate competing models. The systemic lens thereby constrains integration: only connections that advance the mechanistic explanation are pursued, while attractive but irrelevant linkages are pruned.

This constraint is pedagogically powerful because it aligns with how knowledge is used in science. A mechanistic account requires naming entities, activities, and organization at multiple levels and justifying how interactions produce observed regularities. As students refine models across trials, they practice the epistemic moves of prediction, reconciliation, and argument. Writing becomes a site where coherence is tested; claims must be linked to data and to the internal logic of the model. The act of translating measurements into graphs, and graphs into explanations using energy conservation or rate equations, presses learners to coordinate representations rather than treating each in isolation. The same logic travels to homeostasis. When analyzing thermoregulation, students model sensors, comparators, and effectors, connect metabolic heat production to energy budgets, and examine delayed negative feedback that yields oscillatory behavior. Rather than memorizing vocabulary, they situate terms within a control architecture that can be generalized to glucose regulation or predator–prey cycles, thereby rehearsing transfer by aligning structures across contexts.

Learning theory clarifies why systemic integration works. Students arrive with intuitive ontologies that are locally productive yet globally inconsistent. Treating heat as a substance or equilibrium as a static state are examples. Integrated, systemic sequences create

conditions in which these intuitions are made public, are put in contact with multiple lines of evidence, and are reorganized into more powerful schemas. Predict-observe-explain cycles force comparisons between model outputs and empirical traces; discrepancies are not treated as failure but as opportunities for model revision. Over time, learners adopt more abstract resources because these handle diverse cases with fewer contradictions. The outcome is not merely the accrual of facts but the reconfiguration of explanatory resources, which is the genuine substance of conceptual change.

Transfer—so often elusive—benefits when integration is systemic because students practice abstracting underlying relations. The notion of feedback becomes a schema that organizes reasoning in physiology, ecology, and engineered systems. By encountering this structure in multiple guises, learners become adept at stripping away surface features to recover the architecture of interaction. Research on analogical reasoning suggests that such structural alignment across cases is a precondition for far transfer; systemic integration intentionally creates these alignments. Energy conservation, constraints on rates, and structure–function relations become the lenses through which new problems are approached, not afterthoughts appended to unit summaries.

Assessment must be re-thought to honor these aims. Traditional tests valorize recall and isolated procedures, whereas systemic integration seeks evidence that students can coordinate ideas and representations to construct explanations. Performance tasks, modeling notebooks, and argumentation rubrics provide windows into this coordination. An evidence-centered assessment design begins with the inference claim—that a learner can use a crosscutting concept and relevant disciplinary ideas to explain and predict—and then specifies the performances that would warrant that inference. Tasks ask students to plan measurements that could discriminate between two mechanistic models or to justify parameter choices in a simulation so that a curve's shape reflects hypothesized feedback. Scores reflect conceptual accuracy, representational coherence, and the quality of warrants rather than hollow correctness.

The coherence of integration and systemicity places particular demands on teacher knowledge. Content expertise matters, but pedagogical content knowledge becomes decisive because teachers must anticipate how students will connect and confuse ideas across domains. They curate representations that illuminate mechanism, sequence tasks so that evidence accumulates toward a model decision, and facilitate

discourse that invites diverse conjectures while pressing for discipline-specific standards of proof. Their planning work is less about assembling activities and more about designing a storyline in which each episode advances the explanatory account. Collaboration across departments can distribute burdens and model interdisciplinary practice for students. When physics and biology teachers co-design a unit on energy in living systems, for example, they align representations of potential energy and free energy so that terms are not re-defined in ways that fracture coherence.

Digital tools widen opportunity but must be subordinated to sense-making. Simulations allow learners to manipulate parameters and observe consequences rapidly, which is invaluable for exploring feedback and sensitivity. Data-collection interfaces make subtle trends visible and enable comparisons between model outputs and empirical traces. Computational notebooks knit narrative, mathematics, and visualization into a single artifact that records the evolution of an explanation. These affordances raise the cognitive ceiling only when tasks are engineered to keep the learner's attention on model structure and evidential standards rather than on button sequences. A systemic orientation helps maintain that focus by framing technology as a means to probe interactions, constraints, and emergent behavior.

Institutional constraints—coverage expectations, schedules, laboratory resources—are not trivial. Coherence requires prioritization, which means selecting a small set of phenomena through which crosscutting concepts can be developed deeply. Teachers need planning time and professional learning that is anchored in classroom artifacts rather than generic workshops. Schools can cultivate sustainability by recognizing integrative design as intellectual work, by supporting lesson study and coaching, and by building partnerships with local scientific and civic organizations that provide data, contexts, and authentic audiences for student work. Such partnerships situate school science within community problem spaces, which makes the relevance of systemic explanations palpable.

Equity considerations intertwine with coherence claims. When instruction highlights multiple representations and invites the articulation of reasoning, more students find points of entry. Phenomena grounded in local environments legitimize diverse funds of knowledge. Still, integration can inadvertently amplify inequalities if access to technology, field sites, or prior experiences is uneven. A systemic perspective on the classroom as a learning ecology helps teachers monitor participation patterns, distribute opportunities for leadership, and design

scaffolds that support students' agency without diluting intellectual demand. Coherence is partly social: the norms of talk, the visibility of criteria, and the distribution of tools all shape who can contribute to building explanations.

Evidence from iterative implementations reported in the literature suggests that when integration is guided by systemicity, students' conceptual maps become more connected, and their writing takes on the structure of argument rather than description. They cite data to adjudicate between models, learn to qualify claims when a representation omits relevant interactions, and become more strategic in choosing variables that can reveal feedback or constraint. Teachers report that the visibility of reasoning simplifies diagnosis; gaps are framed not as general weakness but as specific missing links in a mechanistic chain. Over time, learners display greater adaptability when confronted with unfamiliar problems because they search for structure and attempt to adapt known models rather than guessing by analogy at the surface level.

The coherence of integration and systemicity also respects disciplinary integrity. Integration is not a dissolution of disciplines but an orchestration of their tools toward explanation and design. Students still learn to wield the mathematical formalisms, experimental protocols, and conceptual vocabularies proper to each field; the difference is that they deploy these tools within problems that require coordination. This stance prepares them for postsecondary study, where the ability to move among representations, to justify model choice, and to negotiate the limits of an analogy are marks of genuine scientific literacy.

Integration and systemicity are not parallel ambitions but mutually enabling principles that, when combined, yield coherent science instruction. Integration becomes meaningful when it is constrained by the demands of systemic explanation so that connections serve the construction, testing, and revision of models. Systemicity becomes learnable when it is embodied in integrated sequences that repeatedly press learners to account for behavior across scales using flows, constraints, and feedback. The result is a classroom culture in which concepts, practices, and representations are aligned around phenomena, assessment captures the coordination of ideas rather than isolated recall, and teacher knowledge is leveraged to design storylines that bring disciplinary tools into productive contact. Although constraints of curriculum and resources persist, the theoretical case is strong and the practical payoffs are visible in students' explanatory writing, model use, and problem transfer. A systemically integrated curriculum thus

advances disciplinary literacy without erasing disciplinary identities and brings school science into closer alignment with how knowledge is produced and used in the world.

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