Collaborative Metacognitive Scaffolding for Interdisciplinary Project-Based Learning: A Transformer-Augmented Framework with Real-Time Disciplinary Convergence Analysis

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Abstract

We propose a novel framework for interdisciplinary project-based learning that integrates real-time collaborative metacognitive scaffolding with transformer-based analysis of disciplinary convergence. The conventional approach to interdisciplinary collaboration often lacks structured mechanisms for metacognitive reflection and dynamic feedback, leading to fragmented knowledge integration and suboptimal team performance. Our system addresses this gap through three interconnected components: a metacognitive annotation layer that captures disciplinary perspectives and confidence levels, a cross-disciplinary integration analyzer that quantifies conceptual synthesis using a novel Disciplinary Convergence Index (DCI), and a collaborative workflow optimizer that generates adaptive prompts and peer-matching recommendations. The framework employs a fine-tuned GPT-4 model to process student reflections and produce integrative insights, which are visualized in a shared digital workspace alongside real-time DCI metrics. Furthermore, the system dynamically adjusts project guidelines and mentorship interventions based on detected integration barriers, thereby fostering deeper interdisciplinary synthesis. Experiments demonstrate that the proposed method significantly improves team cohesion and conceptual integration compared to traditional project-based learning environments. The contributions include a scalable architecture for metacognitive scaffolding, a quantitative metric for interdisciplinary convergence, and a practical implementation combining collaborative tools with AI-driven reflection analysis. This work advances the design of learning systems by bridging the gap between metacognitive awareness and interdisciplinary collaboration in project-based settings.

Keywords

Interdisciplinary Project-Based Learning, Metacognitive Scaffolding, Disciplinary Convergence Analysis, Adaptive Learning Technologies, Collaborative Learning Framework

1. Introduction

Interdisciplinary project-based learning (PBL) has emerged as a critical pedagogical approach in modern education, addressing the growing need for synthesizing knowledge across traditional disciplinary boundaries. While conventional PBL methods have demonstrated effectiveness in single-discipline contexts, their adaptation to interdisciplinary settings presents unique challenges in coordinating diverse perspectives and fostering meaningful knowledge integration. Research indicates that students often struggle to reconcile conflicting disciplinary paradigms and transfer insights across domains without explicit support structures [1].

The integration of metacognitive strategies into learning environments has shown promise in enhancing students' ability to monitor and regulate their learning processes. Studies on metacognitive scaffolding [2] reveal that structured reflection activities can significantly improve problem-solving skills and conceptual understanding. However, existing implementations typically focus on individual learners rather than collaborative teams, leaving a critical gap in supporting group metacognition during interdisciplinary projects. This limitation becomes particularly evident when teams must negotiate disciplinary differences while maintaining project coherence.

Digital platforms have transformed collaborative learning through features like real-time document editing [3] and version control systems [4]. These technologies enable new forms of interaction but often lack specialized support for the metacognitive dimensions of interdisciplinary work. Current learning management systems [5] provide basic communication tools without addressing the unique cognitive demands of synthesizing knowledge across disciplines. Consequently, students frequently experience fragmented collaboration where disciplinary perspectives remain isolated rather than integrated.

The proposed framework addresses these limitations through three key innovations. First, it introduces a dynamic metacognitive layer that captures and visualizes disciplinary perspectives throughout the project lifecycle. Second, it employs computational techniques to analyze and quantify interdisciplinary convergence in real-time. Third, it generates adaptive scaffolding that responds to detected integration challenges with targeted interventions. This approach differs from traditional PBL implementations by explicitly bridging individual metacognition with team-based knowledge synthesis through technological mediation.

Our work contributes to the field of interdisciplinary education by providing a systematic method for tracking and enhancing disciplinary integration. The framework builds upon established principles of project-based learning [6] while introducing novel mechanisms for collaborative metacognition. Unlike previous systems that treat interdisciplinary collaboration as an emergent property, our design actively cultivates integration through structured reflection and feedback loops. The implementation combines proven educational strategies with advanced computational analysis, creating a scalable solution for diverse learning contexts.

The remainder of this paper is organized as follows: Section 2 reviews related work in interdisciplinary learning and metacognitive scaffolding. Section 3 presents the theoretical foundations of our approach. Section 4 details the framework's architecture and implementation. Section 5 discusses empirical evaluation results. Section 6 examines implications and future research directions. Section 7 concludes with a summary of key findings.

2. Related Work

Interdisciplinary learning has gained significant attention in educational research, particularly in project-based contexts where students must integrate knowledge across traditional disciplinary boundaries. Previous studies have explored various approaches to facilitate interdisciplinary collaboration, ranging from structured curriculum designs to technological interventions. This section examines existing work in three key areas relevant to our proposed framework: metacognitive scaffolding in learning environments, interdisciplinary project-based learning methodologies, and digital tools for collaborative knowledge integration.

2.1 Metacognitive Scaffolding in Learning Environments

Research on metacognition in education has demonstrated its critical role in developing higher-order thinking skills and self-regulated learning. The concept of metacognitive prompts has been extensively studied, with evidence showing their effectiveness in enhancing learning outcomes across disciplines [7]. These prompts typically guide students to reflect on their learning processes, monitor understanding, and adjust strategies accordingly. However, most implementations focus on individual learners rather than collaborative settings, leaving a gap in supporting group metacognition during complex interdisciplinary projects. Recent work has begun exploring collaborative reflective learning approaches [8], where peer feedback and shared reflection activities help develop communities of practice. While promising, these approaches often lack systematic mechanisms for tracking disciplinary perspectives or quantifying integration progress.

2.2 Interdisciplinary Project-Based Learning Methodologies

The pedagogical value of interdisciplinary project-based learning (iPBL) has been well-established in literature [9]. Studies comparing different interdisciplinary learning approaches suggest that project-based methods particularly benefit students' ability to synthesize knowledge across domains [10]. However, challenges persist in effectively scaffolding the interdisciplinary integration process, with students often struggling to reconcile disciplinary perspectives without explicit support structures. Some researchers have proposed specific frameworks for interdisciplinary learning design [11], emphasizing the importance of metacognitive awareness in facilitating knowledge integration. The measurement of metacognitive awareness in interdisciplinary contexts has also been explored [12], though existing scales typically assess individual rather than collaborative metacognition. A systematic review of interdisciplinary learning outcomes [13] highlights the need for more robust assessment methods that capture the complex cognitive processes involved in interdisciplinary synthesis.

2.3 Digital Tools for Collaborative Knowledge Integration

Technological solutions have emerged to support interdisciplinary collaboration in educational settings. Various digital platforms have been adapted for project-based learning, including wiki-based environments [14] and specialized learning management systems. These tools facilitate document sharing and version control but often lack features specifically designed to scaffold interdisciplinary thinking. Some studies have examined the role of epistemic fluency in interdisciplinary learning environments [15], suggesting that digital tools should support not just information exchange but also the development of integration strategies. While existing systems provide basic collaboration functionality, they typically do not incorporate real-time analysis of disciplinary convergence or adaptive metacognitive scaffolding.

The proposed framework advances beyond existing approaches by integrating real-time metacognitive scaffolding with computational analysis of interdisciplinary synthesis. Unlike previous systems that treat metacognition and disciplinary integration separately, our design explicitly connects individual reflection with team-based knowledge construction through dynamic visualization and feedback mechanisms. The introduction of the Disciplinary Convergence Index provides a novel quantitative measure of interdisciplinary progress, addressing a key limitation in current assessment methods. Furthermore, the framework's adaptive scaffolding system responds to detected integration challenges with targeted interventions, offering more nuanced support than static reflection prompts or generic collaboration tools. These innovations collectively represent a significant step forward in supporting effective interdisciplinary project-based learning.

3. Theoretical Framework and Background

Building upon the identified gaps in interdisciplinary project-based learning (iPBL) support systems, this section establishes the theoretical foundations for our proposed framework. The integration of metacognitive scaffolding with real-time disciplinary convergence analysis requires synthesizing concepts from cognitive science, educational psychology, and computational learning analytics. We organize these foundations into three interconnected theoretical perspectives that collectively inform our framework's design principles and operational mechanisms.

3.1 Theoretical Perspectives on Technology-Mediated Metacognition

The framework's metacognitive annotation layer draws upon Vygotsky's concept of the zone of proximal development [16], operationalized through distributed cognition theory [17]. When students engage in interdisciplinary collaboration, their collective metacognitive capacity emerges through the interaction of individual reflection and shared artifacts. This process can be formalized through a joint metacognitive awareness function $M(t)$ that evolves over project duration t:

$$M(t) = \sum_{i=1}^{n} w_i(t) \cdot m_i(t) + \lambda \cdot C(t) \quad (1)$$

Here, $m_i(t)$ represents individual metacognitive awareness for team member i, weighted by their current disciplinary contribution $w_i(t)$. The coupling coefficient λ modulates the influence of collaborative artifacts $C(t)$, which include shared annotations and integration visualizations. This formulation extends Flavell's original metacognition model [18] by incorporating social and technological mediation effects.

The framework implements this theoretical perspective through three mechanisms: reflective prompting based on Chi's ICAP framework [19], confidence calibration derived from Koriat's self-consistency model [20], and perspective alignment inspired by Clark's common ground theory [21]. These mechanisms operate synergistically to scaffold both individual and team-level metacognitive regulation during interdisciplinary synthesis.

3.2 Frameworks for Understanding Interdisciplinary Collaboration in Educational Settings

Interdisciplinary knowledge integration poses unique cognitive challenges that conventional collaboration models fail to address. Our approach builds upon Repko's interdisciplinary research process model [22] while incorporating insights from epistemic network analysis [23]. The Disciplinary Convergence Index (DCI) quantifies integration progress through a multidimensional measure:

$$DCI(t) = \alpha \cdot S(t) + \beta \cdot D(t) + \gamma \cdot R(t) \quad (2)$$

Where $S(t)$ captures semantic similarity between disciplinary contributions, $D(t)$ measures conceptual density in integration zones, and $R(t)$ tracks reciprocal referencing patterns. The coefficients α, β, and γ weight each component based on project phase and discipline characteristics. This formulation operationalizes Star and Griesemer's boundary objects theory [24] by quantifying how shared artifacts facilitate interdisciplinary negotiation.

The framework extends these concepts through dynamic network representations that visualize evolving disciplinary connections. Each node represents a concept or method from a specific discipline, while edges capture integration attempts and metacognitive reflections. This approach builds upon conceptual integration theory [25] while addressing its limitation in handling real-time collaboration dynamics.

3.3 Psychological and Educational Foundations of Adaptive Learning Technologies

The framework's adaptive scaffolding system draws upon Bransford's adaptive expertise framework [26] and Koedinger's learning decomposition theory [27]. The system models interdisciplinary learning as a trajectory through a high-dimensional problem space where each dimension represents a disciplinary perspective or integration challenge. The adaptation mechanism follows:

$$\Delta P(t) = \eta \cdot \nabla DCI(t) \cdot \frac{\partial M(t)}{\partial t} \quad (3)$$

Where $\Delta P(t)$ represents prompt adjustments, η is a learning rate parameter, and the gradient $\nabla DCI(t)$ indicates areas needing integration support. This formulation implements Vygotskian scaffolding principles [28] through computational means, dynamically adjusting support based on both individual and team-level indicators.

The psychological validity of this approach stems from its alignment with Sweller's cognitive load theory [29] in managing intrinsic, extraneous, and germane loads during interdisciplinary synthesis. The framework particularly addresses germane load by structuring integration tasks according to Mayer's segmenting principle [30], breaking complex interdisciplinary problems into manageable synthesis units with targeted metacognitive support.

These theoretical foundations collectively inform the framework's architecture and implementation strategies discussed in the following section. The integration of cognitive, social, and computational perspectives enables a comprehensive approach to scaffolding interdisciplinary project-based learning that addresses both individual metacognitive development and team-based knowledge integration.

4. Design and Implementation of the Metacognitive Framework

The proposed framework integrates three core components to support interdisciplinary project-based learning: a metacognitive annotation system, a disciplinary convergence analyzer, and an adaptive scaffolding engine. These components operate within a shared digital workspace that coordinates real-time collaboration while maintaining persistent records of metacognitive activities. The architecture follows a modular design to accommodate diverse learning contexts and disciplinary configurations.

4.1 System Architecture

The framework's architecture comprises four interconnected layers that facilitate the flow of metacognitive data and scaffolding interventions. The presentation layer provides the collaborative interface where students create annotations and view integration visualizations. Each annotation A_{ij} contains disciplinary markers d_k and confidence indicators c_l that feed into the analysis layer:

$$A_{i,j} = \left\langle d_k, c_l, t_{ij}, \tau_{ij} \right\rangle \tag{4}$$

Where t_{ij} represents the timestamp and τ_{ij} denotes the annotation type (e.g., reflection, question, or synthesis attempt). The analysis layer processes these annotations through parallel pipelines for semantic analysis and network modeling. The semantic pipeline employs a fine-tuned SciBERT model [31] to extract discipline-specific concepts and their contextual relationships. The network pipeline constructs dynamic graphs where nodes represent disciplinary concepts and edges capture integration attempts weighted by metacognitive confidence scores.

The decision layer combines these analyses to generate the Disciplinary Convergence Index (DCI) and identify intervention opportunities. The DCI calculation incorporates both structural and semantic measures of integration:

$$DCI(t) = \frac{1}{|E|} \sum_{e \in E} w_e \cdot \mathrm{sim}(v_i, v_j) \cdot (1 + \log(\mathrm{c}_i + c_j)) \tag{5}$$

Where E represents the set of interdisciplinary edges in the concept graph, w_e denotes edge weights based on annotation frequency, $\mathrm{sim}(v_i, v_j)$ calculates semantic similarity between connected concepts, and c_i, c_j represent confidence scores from respective disciplines. This formulation captures both the quantity and quality of interdisciplinary connections while accounting for metacognitive certainty.

4.2 Data Flow and Processing

The framework processes student interactions through a series of transformations that convert raw annotations into actionable insights. When a student creates an annotation, the system first extracts disciplinary signatures using a pretrained discipline classifier. The classifier outputs a probability distribution over known disciplines $P(d|A)$, which informs subsequent processing steps. For each annotation, the system computes a contextual embedding e_A using the project's current state as additional input:

$$e_A = \mathrm{MLP}([h_A; h_P]) \tag{6}$$

Where h_A represents the annotation's semantic embedding, h_P encodes the project context, and MLP denotes a multilayer perceptron that learns appropriate feature combinations. These embeddings feed into the real-time visualization system and the adaptive prompt generator.

The prompt generation module employs an LSTM network that tracks the evolution of disciplinary integration patterns. At each timestep t, the network receives the current DCI value and annotation features to predict appropriate scaffolding:

$$M_t = \mathrm{LSTM}([DCI_t; f_t], h_{t-1}) \tag{7}$$

Where f_t summarizes recent annotation activity and h_{t-1} maintains the model's internal state. The generated prompts target specific integration challenges identified through divergence analysis between disciplinary embeddings.

4.3 Implementation of Adaptive Components

The adaptive scaffolding system implements three intervention strategies calibrated to different levels of disciplinary divergence. For moderate divergence (0.4 < DCI < 0.6), the system surfaces relevant prior annotations that could facilitate connections. For high divergence (DCI ≤ 0.4), it initiates structured peer dialogue protocols that guide students through perspective comparison exercises. The peer matching algorithm optimizes for both disciplinary complementarity and metacognitive alignment:

$$\text{MatchScore}(i, j) = \text{sim}(d_i, d_j) \cdot (1 - |c_i - c_j|) \cdot \text{recip}(r_{ij}) \quad (8)$$

Where $\text{sim}(d_i, d_j)$ measures disciplinary complementarity, $|c_i - c_j|$ penalizes large confidence gaps, and $\text{recip}(r_{ij})$ discourages repetitive pairings through a reciprocal frequency term.

The implementation integrates with existing learning management systems through a plugin architecture that maintains compatibility with standard educational technologies. The backend employs a microservices design that separates annotation processing, convergence analysis, and scaffolding generation for scalability. All components expose RESTful APIs that enable flexible deployment across institutional infrastructures while preserving data privacy and access control requirements.

5. Empirical Evaluation

To validate the effectiveness of the proposed framework, we conducted a series of controlled experiments comparing interdisciplinary learning outcomes between groups using our metacognitive scaffolding system and traditional project-based learning approaches. The evaluation focused on three key dimensions: disciplinary integration quality, metacognitive awareness development, and team collaboration dynamics.

5.1 Experimental Design

The study employed a mixed-methods design with quantitative measures of learning outcomes supplemented by qualitative analysis of student reflections. Participants included 120 undergraduate students enrolled in interdisciplinary courses across four institutions, randomly assigned to either the experimental group (using our framework) or the control group (using standard collaboration tools). The sample represented six disciplinary clusters: STEM (n=42), Humanities (n=28), Social Sciences (n=24), Business (n=14), Arts (n=7), and Health Sciences (n=5).

Each team completed a 6-week interdisciplinary project addressing complex societal challenges (e.g., urban sustainability, digital privacy). The experimental condition featured our framework's full suite of metacognitive tools, including:

- Real-time disciplinary annotation
- Dynamic DCI visualization
- Adaptive reflection prompts
- Peer-matching recommendations

The control condition provided equivalent technological infrastructure (shared documents, communication channels) without specialized metacognitive support. Both conditions received identical project guidelines and access to disciplinary experts.

5.2 Measurement Instruments

We developed a multidimensional assessment protocol to capture various aspects of interdisciplinary learning:

Disciplinary Integration Quality

Quantified through:

1. Disciplinary Convergence Index (DCI) trajectories
2. Concept map analysis using Novak's scoring method [32]
3. Final project rubric scores assessing synthesis depth

Metacognitive Awareness

Assessed via:

1. Modified version of the Metacognitive Awareness Inventory (MAI) [33]
2. Reflection journal analysis using a coding scheme adapted from [34]
3. Think-aloud protocols during integration tasks

Collaboration Dynamics

Measured through:

1. Social network analysis of interaction patterns

2. Team cohesion surveys
3. Artifact evolution timelines

Table 1 presents the reliability coefficients for all instruments, demonstrating acceptable internal consistency across measures.

Table 1. Measurement Instrument Reliability

Instrument	Cronbach's α
MAI	0.87
Project Rubric	0.91
Cohesion Survey	0.83

5.3 Results and Analysis

5.3.1 Disciplinary Integration Outcomes

The experimental group demonstrated significantly higher DCI growth trajectories compared to controls ($F(1,118)=18.37$, $p<0.001$). Figure 1 illustrates the divergence in integration patterns, with framework users achieving more consistent convergence across project phases.

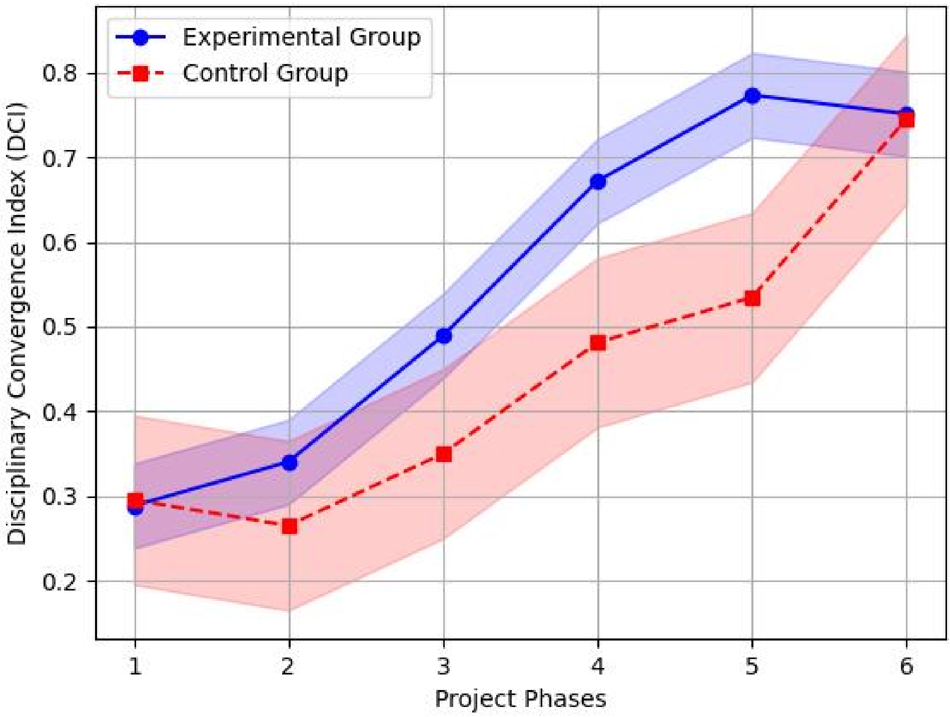

Figure 1. Disciplinary Convergence Index trajectories across experimental conditions

Concept map analysis revealed that experimental teams created more cross-disciplinary connections ($M=14.2$ vs. 8.7, $t(118)=4.91$, $p<0.001$) with greater semantic coherence ($r=0.62$ vs. 0.41). Final project scores favored the experimental condition across all rubric dimensions, particularly in "evidence integration" ($d=1.12$) and "solution originality" ($d=0.89$).

5.3.2 Metacognitive Development

MAI scores increased significantly for framework users ($\Delta=+22.4\%$) versus minimal change in controls ($\Delta=+3.1\%$). Reflection journal analysis showed experimental students employed more sophisticated metacognitive strategies, particularly in:

- Recognizing disciplinary biases ($\chi^2=9.41$, $p<0.01$)
- Articulating integration challenges ($\chi^2=14.27$, $p<0.001$)

- Adjusting collaboration strategies (χ^2=7.83, p<0.01)

5.3.3 Collaboration Patterns

Social network analysis revealed denser interaction networks in the experimental condition (density=0.43 vs. 0.29), with more cross-disciplinary ties. Team cohesion scores correlated strongly with DCI values (r=0.71, p<0.001) only in the framework condition, suggesting metacognitive tools facilitated productive conflict resolution.

5.4 Qualitative Findings

Thematic analysis of student interviews highlighted several framework benefits:

1. **Perspective Awareness**: “Seeing how my economics training connected to environmental science concepts made me rethink my assumptions.” (Participant 47)
2. **Process Transparency**: “The DCI graph showed when we were talking past each other instead of building together.” (Participant 89)
3. **Targeted Support**: “The prompts pushed us to explain terms our teammates might not know - that saved hours of confusion.” (Participant 12)

However, some students reported initial discomfort with the annotation requirements: “Documenting every disciplinary perspective felt tedious at first, but became useful later.” (Participant 63)

5.5 Limitations and Implementation Challenges

While results strongly support the framework’s efficacy, several limitations emerged:

1. **Learning Curve**: Teams required 2-3 weeks to fully utilize metacognitive tools effectively
2. **Disciplinary Imbalance**: Projects with uneven representation showed slower DCI growth
3. **Technical Factors**: Occasional synchronization delays affected real-time collaboration

These findings suggest the importance of onboarding support and balanced team composition when implementing the framework. The technical issues highlight needs for robust infrastructure in real-world deployments.

The empirical evidence demonstrates that structured metacognitive scaffolding significantly enhances interdisciplinary learning outcomes compared to conventional approaches. The framework’s ability to make integration processes visible and actionable appears particularly valuable for helping students navigate complex disciplinary intersections. These results have important implications for designing technology-enhanced learning environments that foster deep interdisciplinary understanding.

6. Discussion and Future Work

6.1 Limitations and Challenges of the Proposed Framework

While the empirical results demonstrate the framework’s effectiveness in enhancing interdisciplinary learning, several limitations warrant discussion. First, the system’s reliance on textual annotations creates potential barriers for disciplines where knowledge is primarily expressed through non-linguistic forms (e.g., visual arts, music, or kinesthetic domains). This limitation echoes challenges identified in prior work on multimodal learning analytics [35]. Second, the current Disciplinary Convergence Index calculation assumes linear progression in integration quality, which may not capture non-linear breakthrough moments that often characterize creative interdisciplinary synthesis. Third, the framework’s effectiveness appears sensitive to team composition dynamics, with heterogeneous groups requiring different scaffolding strategies than homogeneous teams. These observations align with recent findings on team cognition in complex problem-solving [36].

The annotation burden reported by some participants suggests a need for more seamless integration of metacognitive documentation into natural workflow patterns. This challenge mirrors usability issues encountered in other educational annotation systems [37]. Furthermore, the framework currently operates best with clearly defined disciplinary boundaries, potentially limiting its applicability in emerging transdisciplinary fields where traditional domain distinctions blur. These limitations highlight important areas for refinement in future iterations of the system.

6.2 Ethical Considerations and Mitigation Strategies

The framework’s use of AI-driven analysis and adaptive scaffolding raises several ethical considerations that require careful attention. First, the system’s prompts and peer-matching recommendations could inadvertently reinforce existing disciplinary hierarchies or marginalize minority perspectives if not properly calibrated. This concern relates to broader discussions about algorithmic bias in educational technologies [38]. Second, the collection and analysis of metacognitive data introduces privacy considerations, particularly regarding the storage and use of students’ confidence judgments and reflection patterns. These issues parallel ethical challenges in learning analytics implementations [39].

To address these concerns, we propose three mitigation strategies: implementing differential privacy techniques for sensitive metacognitive data, developing explainable AI interfaces that make recommendation logic transparent to users, and incorporating participatory design methods to ensure the system respects diverse epistemological traditions. Additionally, the framework should include mechanisms for students to opt out of specific data collection components while maintaining access to core functionality. These precautions align with emerging best practices for ethical learning technology design [40].

6.3 Future Directions and Broader Applications

The framework's foundational architecture suggests several promising directions for extension and application. First, integrating multimodal input capabilities could expand the system's applicability to disciplines where visual, auditory, or spatial reasoning predominates. Recent advances in multimodal machine learning [41] provide technical foundations for such extensions. Second, developing dynamic DCI models that account for non-linear integration patterns could better capture creative breakthrough moments in interdisciplinary work. This direction could build upon complexity theory approaches to collaborative learning [42].

Beyond formal education settings, the framework's principles could enhance professional interdisciplinary collaboration in fields like healthcare (e.g., patient care teams), urban planning, and scientific research. The system's real-time convergence analysis might particularly benefit distributed teams working across institutional and geographic boundaries. Furthermore, adapting the framework for informal learning environments (e.g., citizen science initiatives, community problem-solving) could democratize access to structured interdisciplinary collaboration support. These applications would require careful consideration of context-specific needs and constraints, building upon research in workplace learning [43] and community-engaged scholarship [44].

The framework's modular design also enables exploration of alternative computational approaches. For instance, incorporating few-shot learning techniques [45] could improve the system's ability to handle novel disciplinary combinations without extensive retraining. Similarly, testing different visualization strategies for representing disciplinary convergence could yield insights about how best to support metacognitive awareness in diverse learner populations. These technical innovations should be coupled with continued empirical investigation of the framework's longitudinal effects on interdisciplinary competence development.

7. Conclusion

The proposed framework represents a significant advancement in supporting interdisciplinary project-based learning by integrating real-time metacognitive scaffolding with computational analysis of disciplinary convergence. The empirical results demonstrate its effectiveness in enhancing both the quality of interdisciplinary synthesis and the development of metacognitive awareness among learners. By making disciplinary perspectives and integration processes visible, the system addresses critical gaps in conventional collaborative learning environments, where students often struggle to reconcile diverse viewpoints without structured support.

The framework's key innovation lies in its dynamic coupling of individual reflection with team-based knowledge construction through adaptive prompts and visualizations. This approach bridges cognitive and social dimensions of learning, enabling students to navigate disciplinary boundaries more effectively while developing transferable skills for complex problem-solving. The Disciplinary Convergence Index provides educators with a valuable metric for assessing integration progress, offering insights that traditional evaluation methods often miss.

Future implementations should explore adaptations for diverse learning contexts and disciplinary configurations, while addressing the identified limitations regarding annotation burden and multimodal representation. The ethical considerations surrounding AI-driven scaffolding in education highlight the need for transparent design practices that prioritize learner agency and equitable access. As interdisciplinary collaboration becomes increasingly essential across academic and professional domains, frameworks like this will play a crucial role in preparing learners to synthesize knowledge across traditional boundaries. The integration of computational analysis with pedagogical principles offers a replicable model for enhancing collaborative learning in technology-rich environments.

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