Construction of a Project-Based Learning Model under the Generative Artificial Intelligence Multi-Agent Collaborative Framework

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Abstract: *The breakthrough development of generative artificial intelligence provides technical possibilities for its integration into project-based learning. However, how to organically integrate the content generation capability of generative artificial intelligence with the distributed collaboration capability of multi-agent systems to construct an adaptive project-based learning support framework remains a core issue in the current field of educational technology research. This study focuses on the construction of a project-based learning model under the generative artificial intelligence multi-agent collaborative framework, and it elaborates on the topic from three dimensions: theoretical foundation, architectural design, and process regulation. At the level of theoretical foundation, this study explains the educational application logic of generative artificial intelligence and the architectural principles of the multi-agent collaborative mechanism. At the level of architectural design, this study constructs a learning support framework that encompasses intelligent task decomposition, multi-agent role configuration, and generative resource organization. At the level of process regulation, this study explores the intelligent perception of the learning process, the emergent characteristics of group knowledge construction, and the closed-loop feedback mechanism for outcomes. This research aims to provide a theoretical reference for the deep integration of generative artificial intelligence in the educational field and to offer framework support for the intelligent transformation of project-based learning.*

Keywords: *generative artificial intelligence; multi-agent systems; project-based learning; learning architecture; process regulation mechanism*

Introduction

With the breakthrough development of generative artificial intelligence technology, intelligent systems represented by large language models have demonstrated unprecedented capabilities in semantic understanding, content generation, and multi-round interaction, and they have opened up new possibilities for model innovation in the educational field. Project-based learning, as a teaching paradigm centered on problem-driven and task-oriented approaches, emphasizes learners' active inquiry and collaborative construction in authentic contexts. However, traditional project-based learning still faces many challenges in task adaptation, resource provision, process support, and outcome evaluation. The intervention of generative artificial intelligence is expected to overcome these limitations, but the application of a single model can hardly cover the complex needs of the entire project-based learning process. The introduction of multi-agent systems provides a technical pathway for the distributed deployment and collaborative support of functions. Integrating generative artificial intelligence with multi-agent systems to construct a support framework tailored to the characteristics of project-based learning has significant theoretical value and practical implications. This study aims to systematically construct a project-based learning model under the generative artificial intelligence multi-agent collaborative framework, and it elaborates on the topic from three levels: theoretical foundation, architectural design, and process regulation, so as to provide a systematic reference for the theoretical development and technological application of project-based learning in the intelligent era.

1. Theoretical Foundation and Constituent Elements of the Generative Artificial Intelligence Multi-Agent Collaborative Framework

1.1 Educational Application Logic and Technical Characteristics of Generative Artificial Intelligence

Generative artificial intelligence, with large language models at its core, exhibits technical characteristics of content generation, semantic understanding, and multi-round dialogue, and its educational application logic is embodied in a deep restructuring of knowledge representation methods and learning interaction forms. Different from traditional information retrieval systems, generative artificial intelligence can generate diverse texts, codes, diagrams, and even simulated scenarios based on input prompts, and this characteristic enables it to assume the functions of a resource generator, an idea stimulator, and a thinking expander in project-based learning. From a technical perspective, generative artificial intelligence possesses context maintenance capabilities, cross-modal information processing capabilities, and emergent reasoning capabilities, and it can provide adaptive support in complex problem situations, thus forming a deep coupling with learners' cognitive activities[1].

The technical characteristics of generative artificial intelligence determine its functional boundaries and modes of operation in project-based learning. Large-scale pre-training endows the model with a rich knowledge base, while instruction fine-tuning and reinforcement learning from human feedback enable it to meet the specific needs of educational contexts. In project-based learning, generative artificial intelligence can generate learning materials in real time, simulate dialogue roles, or provide problem-solving ideas according to task requirements, thereby changing learners' pathways for acquiring information and constructing knowledge. The uniqueness of this technical logic lies in its elevation of artificial intelligence from a tool attribute to a participatory component of the learning environment, which provides a technical prerequisite for the establishment of a multi-agent collaborative framework.

1.2 Architectural Principles and Operating Rules of the Multi-Agent Collaborative Mechanism

A multi-agent system consists of multiple intelligent entities that possess autonomy, social ability, and reactivity, and its architectural principles are built upon the functional differentiation of agents and the protocols of interaction. In educational contexts, agents can be assigned specialized functions such as resource recommendation, process monitoring, collaboration facilitation, and outcome evaluation, and they form a support network for the entire project-based learning process through information exchange and behavioral coordination among agents. The operating rules of the multi-agent collaborative mechanism rely on communication languages, shared ontologies, and negotiation strategies, and agents interact according to preset rules or learned strategies in order to achieve the optimization and dynamic balance of the overall goal.

The introduction of generative artificial intelligence endows the multi-agent system with a higher level of adaptability and generative capability. Traditional multi-agent systems mostly rely on rule-driven behavioral patterns, but after integrating generative artificial intelligence, agents can autonomously adjust their collaboration modes according to changes in the learning context and generate adaptive support strategies. The collaboration among agents is no longer limited to the execution of preset tasks; instead, it extends to the understanding of learners' intentions, the prediction of project progress, and the anticipation of resource needs. The core value of this mechanism lies in integrating the content generation capability of generative artificial intelligence with the distributed collaboration capability of multi-agent systems to build an intelligent educational support system with adaptive characteristics[2].

1.3 Element Reorganization and Intelligent Transformation of the Project-Based Learning Space

The constituent elements of project-based learning include learning tasks, learning resources, learning activities, and learning outcomes. With the intervention of the generative artificial intelligence multi-agent collaborative framework, these elements present characteristics of reorganization and evolution. Learning tasks shift from static presets to dynamic generation, and agents adjust the complexity and openness of the tasks in real time according to learner characteristics and project progress, thereby keeping the tasks always within the learners' zone of proximal development. The organization of learning resources shifts from a preset resource repository to an on-demand generation model, and generative artificial intelligence instantly produces context-appropriate learning materials based on project needs, thus improving the degree of matching between resources and tasks.

The intelligent transformation of the project-based learning space is reflected in the evolution of interaction relationships and outcome forms. The interaction in learning activities expands from a binary human-to-human interaction to a diverse interaction network of human-machine-multi-agent, and agents serve as mediators and regulators between learners and tasks, thus promoting the deep development of group knowledge construction. The representational form of learning outcomes breaks through the traditional text or product form, and it evolves into a multimodal outcome set that includes process data, generative content, and reflective records. This outcome set not only reflects the learning results but also carries the trajectory of the learning process. This transformation is not a simple superposition of technical elements; rather, through the restructuring of relationships among learning elements, it forms a new type of learning ecosystem characterized by adaptability, generativity, and collaboration.

2. Design of the Project-Based Learning Architecture Based on Multi-Agent Collaboration

2.1 Intelligent Decomposition and Dynamic Adaptation Mechanism of Learning Tasks

The intelligent decomposition of learning tasks is built upon the semantic understanding and structural analysis of project goals by generative artificial intelligence. The multi-agent system progressively breaks down the overall project goals into hierarchical sub-task units based on the project theme, the cognitive level of the learners, and the intrinsic logical relationships among the tasks. The process of task decomposition is not a simple linear segmentation; instead, through comprehensive consideration of the dependencies among tasks, resource requirements, and difficulty gradients, the system forms an interconnected task network. Generative artificial intelligence undertakes the functions of task representation generation and decomposition path optimization in this process, and it adjusts the granularity and complexity of the tasks according to the dynamic changes in the project context[3].

The core of the dynamic adaptation mechanism lies in the real-time regulation of the matching relationship between learners and tasks. The multi-agent system continuously collects learners' interaction data, progress information, and cognitive performance to construct a learner characteristic model, and it makes adaptive adjustments to task difficulty, task type, and task presentation mode based on this model. When a learner shows cognitive difficulty in a certain sub-task, the adaptation mechanism can trigger a secondary decomposition of the task or provide supportive scaffolds. When the learner demonstrates ability beyond expectations, the system can dynamically increase the challenge level of the task. This mechanism ensures that the learning task always remains within the learner's zone of proximal development, and it maintains a dynamic balance between cognitive engagement and task completion.

2.2 Multi-Agent Role Configuration and Collaborative Interaction Mode

The role configuration of multi-agents adopts a differentiated design based on the stage-specific needs and functional positioning of project-based learning. From the dimension of function division, agents can be configured as task-guiding agents, resource-supplying agents, process-monitoring agents, and reflection-promoting agents. The task-guiding agent is responsible for planning the project process and prompting task milestones. The resource-supplying agent generates or recommends learning materials according to demand. The process-monitoring agent tracks learning behaviors and provides warning information. The reflection-promoting agent guides learners in metacognitive thinking through questioning and dialogue. Different types of agents complement each other in function and interconnect in information, thereby forming a support network for the entire process of project-based learning.

The construction of the collaborative interaction mode is based on the communication protocols and negotiation mechanisms among agents. At the project initiation stage, agents form a unified representation of the project goals and learner characteristics through information sharing. At the project advancement stage, agents provide parallel support for the learning process according to their respective functional positions, and they exchange information and coordinate behaviors at key nodes. When task conflicts or resource competition arise, agents reach a consensus on behavioral strategies through negotiation mechanisms. The introduction of generative artificial intelligence enables the interaction among agents to go beyond the constraints of preset rules, and it allows agents to generate appropriate interaction content and collaboration methods according to contextual changes, thus forming a collaborative mode characterized by contextual awareness.

2.3 Generative Organization and Adaptive Flow Path of Learning Resources

The generative organization of learning resources is embodied in the dynamic construction of resource content, resource form, and resource sequence. Generative artificial intelligence generates resource content that meets current learning needs in real time based on the stage-specific requirements of project tasks, the cognitive characteristics of learners, and the problem situations emerging during interaction. The resource form exhibits multimodal characteristics, covering types such as textual materials, diagrammatic illustrations, code examples, simulated scenarios, and dialogue scripts. The organization of the resource sequence follows the cognitive law of progression from concrete to abstract and from simple to complex, and it makes personalized adjustments according to learners' cognitive styles and learning preferences, thereby forming an adaptive resource supply path.

The establishment of the adaptive flow path relies on the real-time perception of resource demands and resource distribution by the multi-agent system. The direction of resource flow is jointly determined by the degree of task demand, the cognitive state of the learner, and the degree of resource matching. When a learner encounters a cognitive obstacle at a certain task node, the system triggers the resource-supplying agent to push supportive materials to the learner. When a knowledge gap emerges in group collaboration, resources flow and are shared among different learners. The flow path is not a fixed preset; instead, it is dynamically reconstructed as the project progresses, as learners interact, and as task demands change. Generative artificial intelligence ensures that, during the flow process, resources can update their content and adjust their form based on feedback information, thus forming a deep coupling relationship between resources and learning activities[4].

3. Process Regulation Mechanism of Learning under the Generative Multi-Agent Collaborative Framework

3.1 Intelligent Perception of the Learning Process and Collaborative Intervention Strategies

The intelligent perception of the learning process is established on the basis of real-time collection and in-depth analysis of multimodal learning data. The multi-agent system continuously acquires learners' interaction trajectories, dialogue content, task completion status, and cognitive representation products through perception nodes embedded in the project-based learning environment, and it forms a multidimensional representation of the learning process. Generative artificial intelligence undertakes the functions of semantic understanding and pattern recognition in this process, and it can extract key information from unstructured learning dialogues, identify learners' cognitive states, emotional characteristics, and collaboration levels, and transform this information into a contextual model that can be shared among agents. The perception mechanism not only focuses on the behavioral performance of individual learners but also tracks interaction patterns and task progress at the group level, thereby forming a multi-level process representation from the micro to the macro scale[5].

The construction of the collaborative intervention strategy is based on the situational model generated by intelligent perception and the preset regulation rules. When the system detects that the learning process deviates from the expected trajectory or encounters a cognitive bottleneck, the relevant functional agents trigger intervention behaviors according to the negotiation mechanism. The intervention strategy exhibits layered characteristics: at the individual level, it manifests as hint generation, problem guidance, or resource pushing; at the group level, it manifests as collaboration restructuring, task adjustment, or discussion guidance. Generative artificial intelligence enables the intervention content to be contextually adaptive, allowing it to generate personalized feedback information based on the learner's expression style and cognitive habits. The intervention behaviors among different agents form an overall effect through the coordination mechanism, avoiding duplication or conflict of interventions, and ensuring the coherence and effectiveness of the regulatory actions.

3.2 Emergent Characteristics and Evolutionary Laws of Group Knowledge Construction

Group knowledge construction presents dynamically emergent characteristics under the generative multi-agent collaborative framework. The multi-agent system, as a mediating entity, not only records the viewpoints, arguments, and productive outcomes generated during group interactions but also integrates and reorganizes scattered knowledge elements through generative artificial intelligence, thereby facilitating the externalization of tacit knowledge and the systematization of fragmented perspectives. During the collaborative sessions of project-based learning, the dialogues, resource sharing, and idea exchanges among learners form the foundational material for knowledge construction. Through semantic analysis, association recognition, and structured organization of these materials, the multi-agent system enables the emergence of a knowledge network at the group level. The emergence process is not a simple aggregation of knowledge; instead, through the reorganization and generation of knowledge elements by the agents, it forms novel knowledge structures that transcend the sum of individual cognitions.

The revelation of evolutionary laws requires examining the dynamic change trajectory of the group knowledge network from a temporal dimension. At the project initiation stage, group knowledge construction manifests as the divergence of viewpoints and the convergence of resources, and the multi-agent system facilitates the preliminary integration of knowledge elements through topic clustering and association recommendation. At the project advancement stage, the knowledge network exhibits structured characteristics, with core concepts and key issues gradually emerging, and the agents promote the in-depth development of knowledge construction by guiding discussions and providing argumentation support. At the project conclusion stage, group knowledge condenses into transferable outcome forms, and the agents facilitate learners' metacognitive understanding of the construction process by tracing the knowledge evolution path and providing reflective prompts. Throughout this process, generative artificial intelligence continuously generates connective relationships among knowledge nodes, thereby enabling the group knowledge network to maintain dynamic balance and the capacity for continuous generation during its evolution[6].

3.3 Diversified Representation of Learning Outcomes and Feedback Loop Mechanism

The diversified representation of learning outcomes breaks through the limitation of traditional single outcome forms and presents an organic integration of process-based and result-based products. Under the generative multi-agent collaborative framework, learning outcomes include not only the final works or reports produced by the project but also various intermediate products generated during the project process, such as problem definition documents, solution sketches, discussion minutes, reflection logs, and learning trajectory data recorded by the multi-agent system. Generative artificial intelligence integrates and reconstructs these process-based materials to generate an outcome representation that fully presents the learning journey. The representation methods of the outcomes exhibit multimodal characteristics, which can be textual narration, graphical presentation, dialogue playback, or dynamic demonstration, and they adaptively select the methods based on the usage scenarios of the outcomes and the needs of the audience.

The establishment of the feedback loop mechanism is based on the cyclic association between learning outcomes and the learning process. The multi-agent system analyzes and evaluates the learning outcomes, thereby generating multi-level feedback information targeting learners, teacher groups, and the agents themselves. The feedback targeting learners focuses on outcome quality, ability development, and directions for improvement, and it is presented in forms such as generative comments, comparative analyses, and suggestion prompts. The feedback targeting teacher groups provides evaluation information regarding project design and support strategies. The feedback targeting the agents themselves is used to optimize the perception models, intervention strategies, and resource organization methods. The feedback information flows back to each node of the learning process through the multi-agent system, thereby exerting a regulatory effect on subsequent task decomposition, resource provision, and collaborative intervention, thus forming a closed-loop optimization mechanism between the learning process and outcome production. The continuous operation of this mechanism enables the project-based learning model to evolve iteratively, achieving dual improvements in learning effectiveness and system performance.

Conclusion

This study focuses on the construction of a project-based learning model under the generative artificial intelligence multi-agent collaborative framework, and it systematically discusses the model from three dimensions: theoretical foundations, architectural design, and process regulation. At the level of theoretical foundations, the study clarifies the educational application logic and technical characteristics of generative artificial intelligence, reveals the architectural principles and operational rules of the multi-agent collaborative mechanism, and analyzes the element restructuring and intelligent transformation characteristics of the project-based learning space under technological intervention. At the level of architectural design, the study constructs a project-based learning support framework that encompasses task decomposition, role configuration, and resource organization, thereby forming a system design scheme characterized by dynamic adaptability and collaborative interaction. At the level of process regulation, the study explores the intelligent perception and collaborative intervention strategies of the learning process, the emergent characteristics and evolutionary laws of group knowledge construction, and the diversified representation of learning outcomes and the feedback loop mechanism, thereby revealing the regulatory paths and optimization logic of the learning process under intelligent support. The theoretical framework constructed in this study provides a systematic reference for the deep integration of generative artificial intelligence in the field of education. Subsequent research can further explore the adaptive adjustment mechanisms in different educational scenarios based on this framework, deepen the understanding of the emergence laws in the multi-agent collaborative process, and promote the theoretical integration and technological evolution of generative artificial intelligence and project-based learning.

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