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Redefining Educational Simulation: EduVerse as a User-Defined and Developmental Multi-Agent Simulation Space

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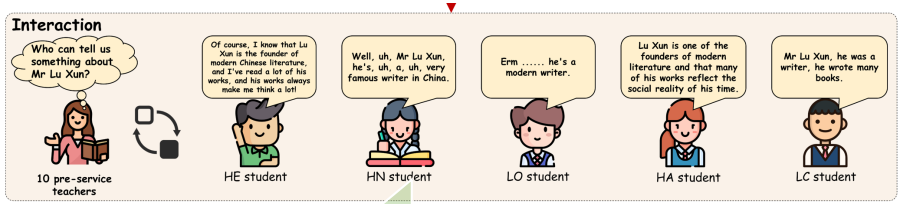
Motivation: From Individual to Group

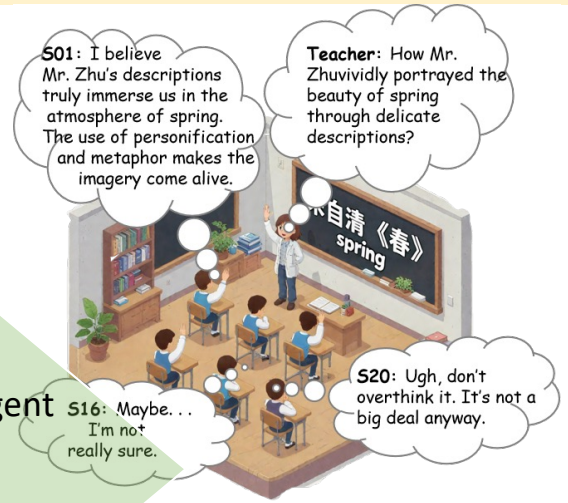
Limitations of Traditional Approaches:

- Homogeneous learners, ignoring individuality and social needs
- Static interactions, lacking adaptation and long-term dynamics
- Missing social dimensions such as peer learning and emotion



Individual Modeling: Virtual students with consistent yet adaptive personalities

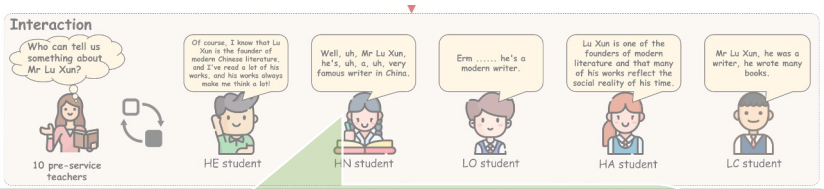
Group Simulation: Multi-agent classrooms with emergent social behaviors



How to model individual agents that are "like real students"?

How to achieve group interactions that are "like real classrooms"?

Motivation: From Individual to Group



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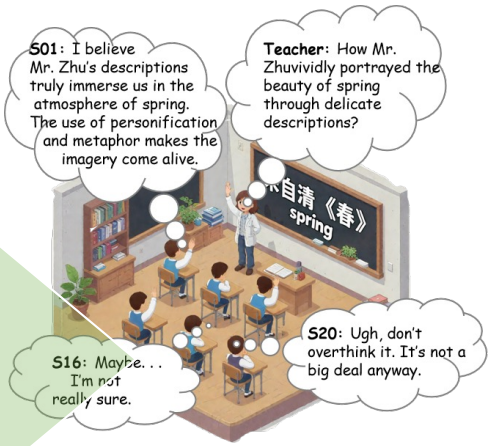
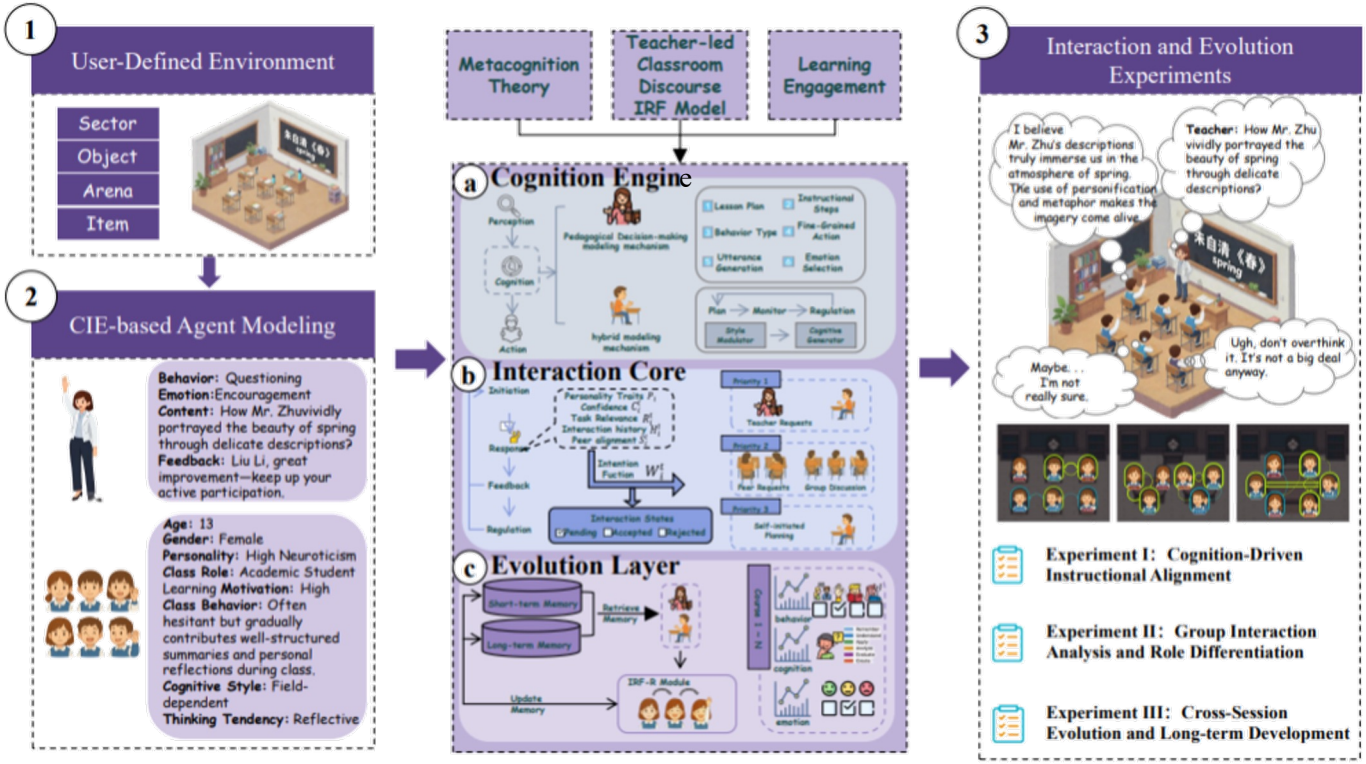


Individual Modeling (SOEI)	Group Simulation (EduVerse)
✅ "Like real students"	🎯 "Like real classrooms"
Single agent consistency	Multi-agent emergence
Teacher-student dialogue	Complex social ecosystems
Session-based interaction	Developmental trajectories

From "How to model one authentic student?" → "How to simulate authentic classroom dynamics while preserving individual uniqueness?"

EduVerse: A User-Defined Multi-Agent Simulation Space



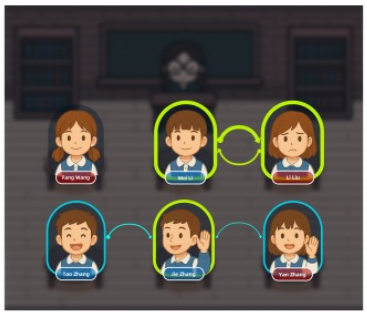
- A ***user-defined environment*** for constructing diverse classroom layouts and interaction scenarios.
- An ***agent modeling module*** based on the CIE architecture (Cognition–Interaction–Evolution) , enabling teachers and students to exhibit personalized and developmental characteristics.
- ***Interaction and evolution experiments*** for simulating instructional alignment, group interactions, and long-term learning dynamics.

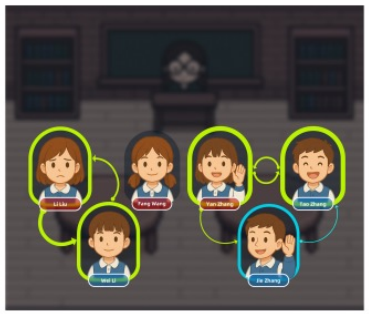
Individual Agents → Social Interactions → Classroom Emergence

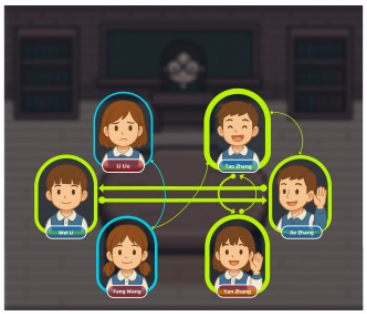
Environment Modeling: Creating Authentic Classroom Contexts

Four-Tier Hierarchical Spatial Architecture

- **Sector Level**: Functional zones (Teacher Zone, Student Zone, Activity Zone)
- **Arena Level**: Specific areas within each zone
- **Object Level**: Interactive classroom furniture and equipment
- **Item Level**: Detailed educational materials and tools





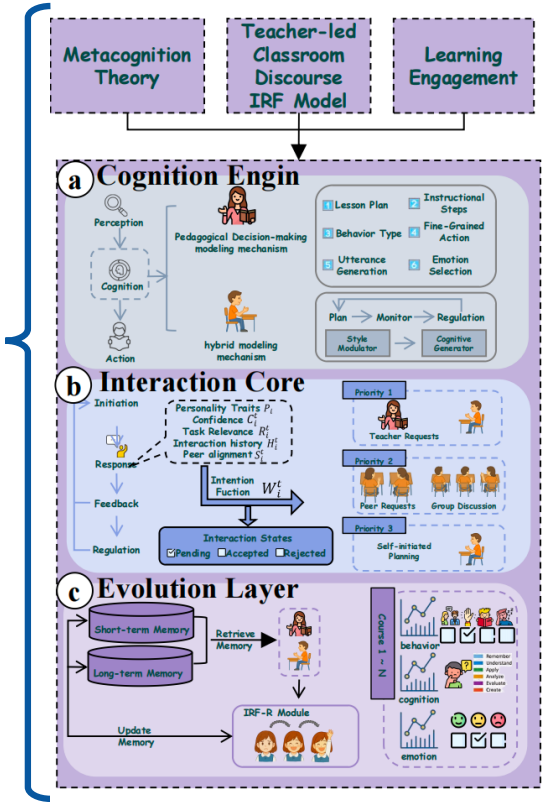


Creating an authentic spatial foundation that enables natural classroom interactions and supports diverse educational activities.

Agent Modeling: Unified Architecture with Individual Differentiation

Behavior: Questioning
Emotion: Encouragement
Content: How Mr. Zhu vividly portrayed the beauty of spring through delicate descriptions?
Feedback: Liu Li, great improvement—keep up your active participation.

Age: 13
Gender: Female
Personality: High Neuroticism
Class Role: Academic Student
Learning **Motivation:** High
Class Behavior: Often hesitant but gradually contributes well-structured summaries and personal reflections during class.
Cognitive Style: Field-dependent
Thinking Tendency: Reflective



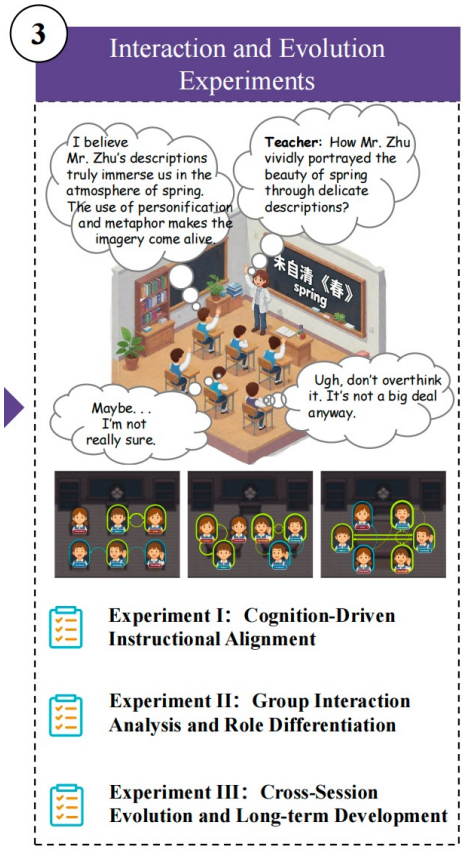
🧠 **Cognition Engine: The Thinking Brain**
Metacognitive regulation provides each agent with a personalized "thinking brain"

🤝 **Interaction Core: Social Coordination Hub**
Enhanced IRF paradigm supports "who to interact with, when to respond, how to feedback"

📈 **Evolution Layer: Developmental Trajectories**
Enables virtual students to not only "respond appropriately" but also "grow progressively"

Using a unified structure with differentiated parameters to produce identifiable and controllable personality traits in student and teacher agents, supporting multi-agent interaction and social evolution.

Experimental Validation: Three-Tier Comprehensive Evaluation



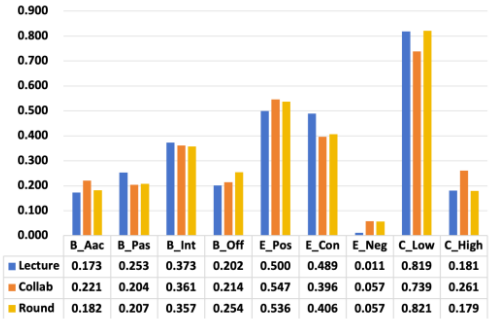
No.	Experiment Name	Objective	Method Summary
I	**Cognition-Driven Instructional Alignment**	Verify authenticity and stability of classroom interactions in user-defined environments.	Three classroom layouts (lecture, collaboration, round-table); analyze teacher–student IRF structures and personality-driven behaviors.
II	**Group Interaction and Role Differentiation**	Examine group network evolution and role changes across classroom settings.	Use interaction graphs (nodes, edges, density, centrality) to analyze group structures and student–teacher interaction patterns.
III	**Cross-Session and Long-Term Development**	Observe behavioral, emotional, and cognitive co-evolution across sessions.	Track four lessons (e.g., Spring, Dedication and Joy in Work) and measure behavioral–emotional–cognitive (BEC) dynamics.

Three interconnected experiments were designed to evaluate the feasibility and educational value of the EduVerse system, focusing on virtual students' cognition, social behavior, and learning evolution.

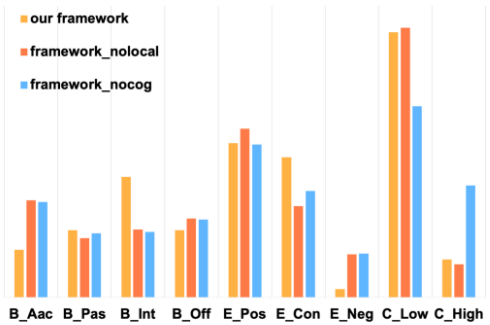
Experimental I
Can virtual student agents reproduce authentic classroom interactions?

Table 1: Average IRF (Initiation–Response–Feedback) distributions in simulated environments vs. real classrooms across three text genres.

Genre	Setting	I	R	F	IRF_rate
Lyrical Prose	Simulation	0.454	0.166	0.293	0.336
	Real Class	0.513	–	0.703	0.486
Argumentative Essay	Simulation	0.482	0.207	0.335	0.554
	Real Class	0.417	–	0.583	0.417
Foreign Fiction	Simulation	0.310	0.230	0.407	0.379
	Real Class	0.367	–	0.515	0.367



(a) **Distribution of students' BEC across environments.** Different layouts yield distinct patterns: collaborative fosters positivity and higher-order cognition, round-table increases disengagement, while lecture remains stable with passive, lower-order patterns.



(b) **Ablation study.** Removing the stylization module amplifies negative emotions, while removing the CIE module exaggerates higher-order cognition and overly active behaviors.

Figure 3: **Overall analysis of student behavior and system design.** (a) Distribution of students' behavioral–emotional–cognitive (BEC) patterns across different classroom environments. (b) Ablation study illustrating the distinct roles of stylization and CIE modules.

Answer: Yes.

- Simulated IRF (0.34–0.55) matches real classrooms (0.37–0.49)
- Agents maintain stable yet adaptive personalities
- CIE ablations confirm cognition–interaction–evolution coupling is key.

Experimental II
Do virtual students exhibit natural social structures and differentiated roles?

Table 2: Group interaction analysis across lessons and environments. Values report nodes, edges, density, and average degree of the interaction graph. **Bold** marks the highest values per lesson.

Lesson	Env.	Nodes	Edges	Density	Avg. Deg.
Foreign Fiction	*Lecture*	6	5	**0.333**	**1.667**
	Collab	5	3	0.300	1.200
	Round	6	5	**0.333**	**1.667**
Argumentative Essay	*Lecture*	5	3	0.300	1.200
	Collab	5	4	**0.400**	**1.600**
	Round	6	5	**0.333**	**1.667**
Lyrical Prose	*Lecture*	6	4	0.267	1.333
	Collab	5	3	0.300	1.200
	Round	6	5	**0.333**	**1.667**

Table 3: Distribution of students' network centrality indicators in the *Dedication and Joy* lesson across environments. Values are normalized to $[0, 1]$; **Deg.** denotes degree centrality and **Betw.** denotes betweenness centrality.

Env.	Student	In	Out	Deg.	Betw.
Lecture	Li Wei	0.25	0.25	0.50	0
	Liu Li	0.25	0.25	0.50	0
	Zhang Tao	0.00	0.25	0.25	0
	Zhang Jie	0.50	0.00	0.50	0
	Zhang Yan	0.00	0.25	0.25	0
Collab	Li Wei	0.25	0.25	0.50	0
	Liu Li	0.25	0.25	0.50	0
	Zhang Tao	0.50	0.25	0.75	0.083
	Zhang Yan	0.25	0.50	0.75	0.083
	Zhang Jie	0.25	0.25	0.50	0
Round	Li Wei	0.20	0.20	0.40	0
	Zhang Jie	0.40	0.20	0.60	0.10
	Liu Li	0.00	0.20	0.20	0
	Wang Fang	0.40	0.00	0.40	0
	Zhang Tao	0.20	0.60	0.80	0.15
	Zhang Yan	0.20	0.20	0.40	0

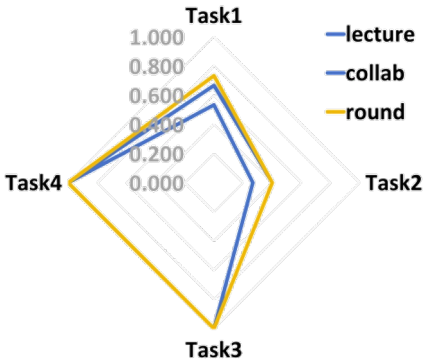


Figure 4: **Human–Agent Interaction Across Four Tasks.** Results show strong alignment with personality traits and robust instructional control, confirming that EduVerse enables seamless integration of human participants while preserving realistic classroom dynamics.

Answer: Yes.

- Interaction patterns shift from centralized to distributed as teaching moves from lecture to collaboration.
- Students show emergent role differentiation, taking spontaneous core or bridge positions.
- In the Human–Agent Interaction experiment, four subtasks were designed: peer chatting, academic responses, teacher Q&A, and teacher intervention.

Experimental III
Can EduVerse capture learning development over time?

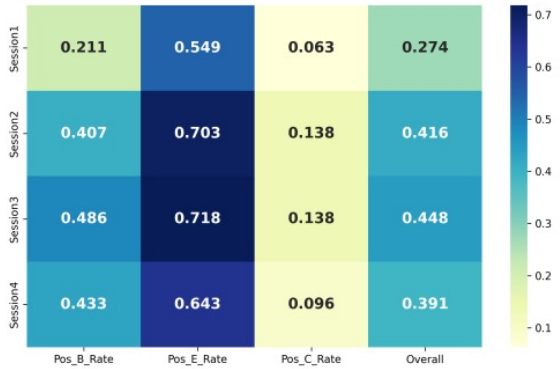


Figure 5: **Positive transition trends in cross-session evolution.** Rates of positive shifts in behavior, emotion, and cognition increase over time, with behavior improving most rapidly, emotion rising steadily, and cognition progressing gradually.

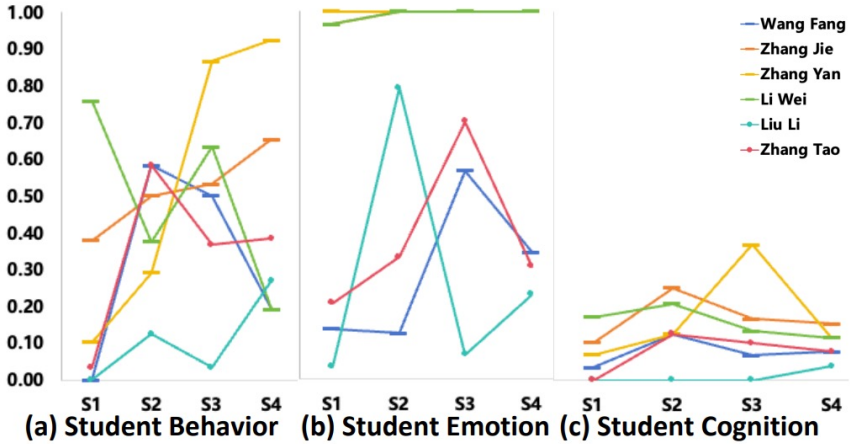


Figure 6: **Individual trajectories of positive shifts across sessions.** Students display differentiated developmental paths in behavior, emotion, and cognition, closely aligned with personality traits, validating EduVerse's capacity to model personalized learning evolution.

Answer: Yes.

- Positive transition rate increases by 11.7%.
- Behavior improves fastest, emotion rises steadily, cognition advances gradually—aligned with personality traits.

Research Summary

Our Contributions

- We ***propose EduVerse***, a user-defined, developmental multi-agent simulation framework for virtual classrooms.
- We ***introduce the CIE architecture*** to model cognitive, interactive, and evolutionary agent dynamics.
- We validate EduVerse through ***instantiated experiments*** in authentic educational settings.

Future Work

- ***Extend EduVerse to broader instructional formats***, educational levels, and more diverse classroom contexts beyond junior secondary education.
- ***Scale the framework to support larger classrooms*** and more heterogeneous student populations.

The ultimate goal is not to make AI more like students,
but to enable education itself to evolve through AI observation.

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Detailed Information： Evironment Configuration

Table A1: **Hierarchical Classroom Environment Structure**

Parameter	Description
Grid size	30×20 discrete lattice
Layout type	Lecture / Round Table / Collaborative (two tables)
Table radius	Default $= 3$ grid units
Table gap	Default $= 10$ grid units (between two tables)
Objects	Students, teacher, podium, board, tables
Peer adjacency	Edge (i, j) if $d(i, j) \leq \tau_d = 4.5$
Group adjustment	Threshold $+1.0$ if $g(i) = g(j)$
Round Table rule	Add cross-table "opposite" edges
Collaborative rule	Within-table complete graph; no inter-table edges
Perception radius	$r = 8$ grid units
Perception capacity	$\kappa = 5$ objects per student
Collision/occupancy	One object per grid cell; invalid moves rejected

Table A2: Environment configuration parameters in EduVerse. Parameters specify spatial layout, interaction rules, and perception constraints.

Detailed Information： IRF Annotation

Setting	I (Initiation)	R (Response)	F (Feedback)
S_LP	Li Wei, could you share your understanding of this sentence? The rest of you may also think about which images or characters in the text left a strong impression on you.	I think Zhu Ziqing's description is very vivid. He humanized spring, making readers feel its warmth and vitality. The contrast between "little grass" and "new leaves" makes the scene full of freshness and life.	Excellent sharing and observation! You captured the emotional tone of the classroom very well.
S_AE	Zhang Yan, could you try to create a phrase using *Take out of context*? This might help us better understand how to apply this expression.	Okay, for example, we can't just take one sentence and explain it in isolation. We need to connect it to the context.	Great example and reasoning! Keep up your analytical depth.
S_FF	This story reveals that many people chose to follow authority rather than uphold truth and justice. Based on "The Emperor's New Clothes," why do you think some people stay silent before power?	I think... maybe because they are afraid of losing status or being excluded if they tell the truth. People often go along with others to protect themselves.	Excellent reflection and teamwork! Maintain this thoughtful analysis and courage to question.
RC_LP	There's a sentence here without additional modifiers. Tiantian, what do you think makes it effective?	Hmm, it's very concise. The author used pure description to highlight the beauty of the scene.	Good, that's correct.
RC_AE	The author discusses several issues. Which one do you find most convincing? Please share your opinion. You please.	First, he emphasizes the meaning of dedication. I think this value is most inspiring.	Good point. Who would like to add to that?
RC_FF	Who can tell me what the first function of clothing is in this story? What does it symbolize?	It shows one's social status — for instance, how the emperor's clothes represent vanity and hypocrisy.	Exactly, well answered.

Table 1: Representative IRF dialogue excerpts across genres in simulated and real classroom.
Note: "Setting" refers to classroom type (**S**:Simulation or **RC**: Real Class) and Genres (**LP**: Lyrical Prose, **AE**: Argumentative Essay, **FF**: Foreign Fiction.)

Detailed Information： BEC Annotation

Table A5: BEC annotation categories used in EduVerse.

Dimension	Categories
Behavior	Note Taking (NT), Hand Raise (HR), Head Up (HU), Head Down (HD), Read Aloud (RA), Refuse Reply (RR), Stand Answer (SA), Side Talk (ST), Answer Questions (AQ), Sleep, Chat
Emotion	Positive, Negative, Confused
Cognition	Remember, Understand, Apply, Analyze, Evaluate, Create