Cognitive-Uncertainty Guided Knowledge Distillation for Accurate Classification of Student Misconceptions

Anonymous ACL submission

Abstract

Accurately identifying student misconceptions is crucial for personalized education but faces three challenges: (1) data scarcity with long-tail distribution, where authentic student reasoning is difficult to synthesize; (2) fuzzy boundaries between error categories with high annotation noise; (3) deployment paradoxlarge models overlook unconventional approaches due to pretraining bias and cannot be deployed on edge, while small models overfit to noise. Unlike traditional methods that increase diversity through large-scale data synthesis, we propose a two-stage knowledge distillation framework that mines high-value samples from existing data. The first stage performs standard distillation to transfer task capabilities. The second stage introduces a dual-layer marginal selection mechanism based on cognitive uncertainty, identifying four types of critical samples based on teacher model uncertainty and confidence differences. For different data subsets, we design difficulty-adaptive mechanism to balance hard/soft label contributions, enabling student models to inherit inter-class relationships from teacher soft labels while distinguishing ambiguous error types. Experiments show that with augmented training on only 10.30% of filtered samples, we achieve MAP@3 of 0.9585 (+17.8%) on the MAP-Charting dataset, and using only a 4B parameter model, we attain 84.38% accuracy on cross-topic tests of middle school algebra misconception benchmarks, significantly outperforming sota LLM (67.73%) and standard fine-tuned 72B models (81.25%). Our code is available at `https://anonymous.4open.science/r/acl2026_map-5847/`.

1 Introduction

Understanding how students think and solve problems remains a core challenge in educational research (Carly D. Robinson, 2021; Dyer and Sherin, 2016; Parwati and Suharta, 2020). Traditional assessment methods focusing solely on answer correctness overlook students' reasoning processes, failing to reveal cognitive obstacles or recognize partially valid thinking within incorrect answers. This limits teachers' ability to provide personalized feedback and prevents platforms from making adaptive adjustments based on actual thinking trajectories (Graesser et al., 2004; Wang et al., 2020).

This limitation is particularly acute in mathematics education, where identical incorrect answers may stem from completely different reasoning paths revealing distinct conceptual misunderstandings (Ansari et al., 2025; Sadler et al., 2013). For example, solving $2x + 3 = 11$, one student might correctly subtract 3 then divide by 2 but make a calculation error, while another might directly divide 11 by 2 due to conceptual confusion. Both produce wrong answers requiring fundamentally different interventions (Otero et al., 2025). This necessitates shifting from evaluating "answer correctness" to understanding "problem-solving approaches," which recent NLP advances now make feasible through automatic classification of student reasoning processes (Hsu et al., 2025).

However, accurate classification faces three core challenges:

Challenge 1: Data scarcity and distribution gap. Real student process data is severely limited with long-tail distribution (Hsu et al., 2025). While existing work uses LLMs to generate synthetic data (Tan et al., 2024), real student reasoning features colloquial language, reasoning jumps, and logical errors that models cannot accurately replicate. LLM-generated text's superior logic and fluency creates significant distribution gaps, limiting generalization to real scenarios.

Challenge 2: Label complexity and annotation noise. Student misconception labels are numerous with fuzzy boundaries between error types and even correct/incorrect categories (Otero

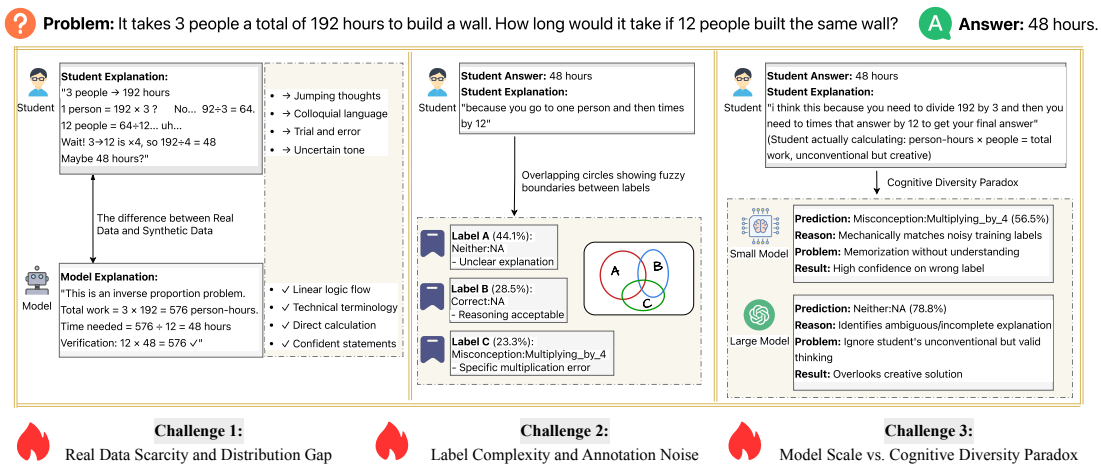


Figure 1: The overview of the key points and corresponding challenges.

et al., 2025), causing substantial annotation noise. Traditional hard-label models cannot learn subtle inter-category differences or handle inherent uncertainty, performing poorly on complex ambiguous errors.

Challenge 3: Model scale and cognitive diversity paradox. Students' diverse thinking often produces unconventional but reasonable solutions within their cognitive framework (Ansari et al., 2025). Small models meet deployment needs but overfit to noisy labels; large models possess rich knowledge but systematically overlook non-standard approaches due to pretraining bias (Shi et al., 2023), force-fitting innovative solutions into existing frameworks and misjudging error types. Educational privacy requirements and edge device limitations further prevent direct large model deployment.

Addressing these challenges, unlike traditional methods that rely on large-scale data synthesis (Tan et al., 2024), we propose a two-stage knowledge distillation framework that strategically mines high-value samples from existing data. The first stage performs standard distillation for basic task capability transfer; the second stage introduces a dual-layer marginal selection mechanism based on cognitive uncertainty, identifying Near-miss (correct but uncertain) and Hard-hard (severely incorrect) critical samples through teacher uncertainty and confidence differences, with difficulty-adaptive loss functions dynamically balancing hard/soft labels to help students distinguish complex error types while inheriting inter-class relationships. This approach produces lightweight models that accurately identify diverse student approaches while meeting practical requirements for privacy protection and edge deployment.

Our main contributions include:

- A dual-layer marginal selection mechanism based on cognitive uncertainty that precisely filters high-value real samples for incremental training, improving limited-data performance without synthetic data dependency.
- Difficulty-adaptive loss functions with dynamic soft/hard label weighting based on sample difficulty, addressing label noise and boundary ambiguity while improving discrimination of confusable categories.
- Addressing large models' diversity oversight from pretraining bias through two-stage distillation, balancing knowledge transfer with cognitive openness to maintain inclusiveness toward non-standard solutions.

2 Related Work

In this section, we first introduce the evolution in the education domain from answer scoring to process understanding, and then discuss related techniques for handling data scarcity and label noise.

2.1 Student Reasoning Assessment and Misconception Diagnosis

Educational assessment research has undergone a paradigm shift from result-oriented evaluation to process understanding. Early studies focused primarily on the automatic determination of answer correctness (Dyer and Sherin, 2016; Parwati and

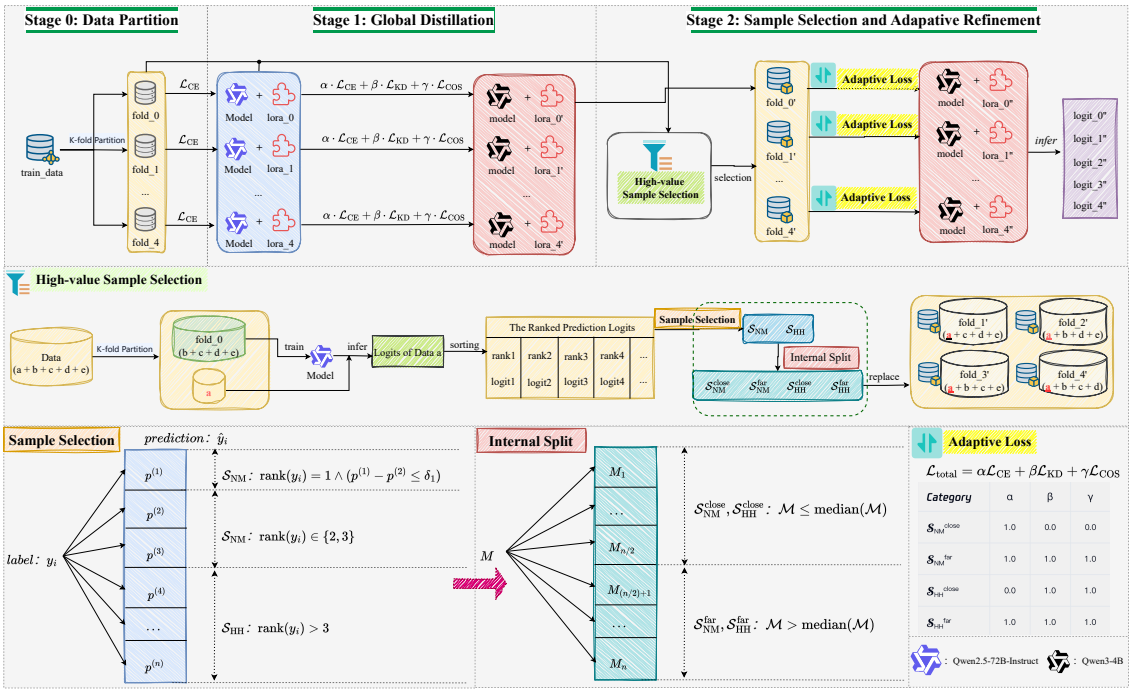


Figure 2: Overview of our two-stage distillation framework, consisting of data partitioning, two-stage knowledge distillation, and sample selection.

Suharta, 2020), achieving scoring accuracy close to human level, but lacking the ability to diagnose the underlying causes of errors. Recent work has begun to explore misconception identification. For example, Ansari et al. (2025); Hsu et al. (2025) proposed fine-grained error classification frameworks in the algebra domain, and Otero et al. (2025) summarized 55 types of algebraic misconceptions and built diagnostic benchmarks. However, these approaches still rely mainly on the final answer rather than the complete reasoning process.

Directly analyzing students reasoning processes is key to understanding cognitive barriers. Shi et al. (2023) found that even advanced language models can fail in reasoning when confronted with explanations containing irrelevant information or logical leaps, a phenomenon that mirrors characteristics commonly observed in real student responses. However, obtaining high-quality student process data is extremely challenging. Although large language models (LLMs) can generate synthetic data (Tan et al., 2024), such data tends to exhibit overly standardized expressions that differ markedly from the colloquial, non-standard reasoning of real students, resulting in poor generalization for models trained solely on synthetic data.

To address the distribution bias in synthetic data, we propose a sample selection strategy based on cognitive uncertainty. This approach accurately identifies the most critical *near-miss* and *hard-hard* samples from limited real data, which are most influential to the decision boundary, thereby avoiding reliance on synthetic data.

2.2 Sample-Efficient Learning under Label Noise

In the presence of data scarcity and label noise, the machine learning community has developed various strategies. Curriculum learning (Bengio et al., 2009; Chen et al., 2025) improves learning efficiency by arranging training in an easy-to-hard sequence; subsequent work further introduced uncertainty-based active sample selection (Houlsby et al., 2011; Gal et al., 2017; Kirsch et al., 2019), prioritizing the learning of samples with the highest information gain. The core idea behind these methods is to identify and focus on key samples that can significantly improve the decision boundary (Yuan et al., 2020; Fang et al., 2021; Yin et al., 2020).

Knowledge distillation (Hinton et al., 2015; Mansourian et al., 2025) offers another path for handling label noise. The soft labels from teacher models embed rich inter-class relational information, which can mitigate the impact of noisy

hard labels. Recent adaptive distillation methods (Chennupati et al., 2021; Song et al., 2022; Yu et al., 2025) further propose dynamically adjusting the weights of soft and hard labels based on sample difficulty, enabling more fine-grained knowledge transfer (Hao et al., 2023; Cazenavette et al., 2022; Liu et al., 2022). However, existing approaches face unique challenges in educational scenarios: biases from large model pretraining make it difficult to accept non-standard student reasoning, and direct distillation can cause small models to excessively inherit these biases (Luan et al., 2019; Hossain et al., 2025; Chen et al., 2022; Guo et al., 2020).

To address the cognitive bias issue in large models, we propose a difficulty-adaptive loss function that dynamically adjusts the weighting of soft and hard labels, allowing small models to inherit knowledge from large models while maintaining tolerance for non-standard student expressions.

3 Methodology

To address the dual challenges of "data" and "labels" in identifying students' problem-solving approaches, we propose an Adaptive Knowledge Distillation Framework for High-Value Samples. Instead of relying on synthetic data with distribution gaps, our framework accurately identifies and exploits the most valuable samples from limited authentic data through a two-stage training process of sample selection and adaptive learning, guiding models to tackle real-world ambiguity and complexity.

3.1 Problem Formulation

Our goal is to train a classification model f_s that accurately assigns student math problem-solving processes x_i (including problem description, answer, correctness, and metadata) to predefined reasoning labels y_i. The label set $\mathcal{Y}$ contains "Correct", multiple misconception categories ($\text{Misconception}_1, ..., \text{Misconception}_K$), and "Neither" for unclassifiable cases.

Given training set $\mathcal{D} = \{(x_i, y_i)\}_{i=1}^{N}$ with N real student samples, we optimize student model f_s parameters using pretrained teacher models f_t to address label noise and data sparsity. The model outputs probability distribution $p(y|x) = \text{softmax}(z/\tau)$, where $z \in R^{|\mathcal{Y}|}$ represents logits and τ is the temperature coefficient for distribution smoothing in knowledge distillation.

3.2 Stage One: Global Knowledge Distillation and Preliminary Learning

In student thinking discrimination, we face a fundamental contradiction: large models possess abundant knowledge but ignore thinking diversity due to overconfidence in prior distributions; small models are flexible but lack necessary knowledge foundations. Stage one thus uses knowledge distillation to equip small models with basic knowledge structures while maintaining openness to non-standard ideas.

We employ n-fold cross-validation to generate soft labels and prevent overfitting. Using `StratifiedKFold` (Raschka, 2020) based on label distribution, we split data into n subsets. For each fold $k \in \{1, ..., n\}$, train teacher model $f_t^{(k)}$ on $\mathcal{D} \setminus \mathcal{D}_k$ and generate soft labels $\mathbf{y}_{\text{soft}}^{(i)}$ for samples in $\mathcal{D}_k$.

We then train n student models with a loss function combining three objectives:

$$\mathcal{L} = \alpha \cdot \mathcal{L}_{\text{CE}}(f_s(x_i), y_i) + \beta \cdot \mathcal{L}_{\text{KD}}(f_s(x_i), \mathbf{y}_{\text{soft}}) + \gamma \cdot \mathcal{L}_{\text{COS}}(f_s(x_i), \mathbf{y}_{\text{soft}}) \quad (1)$$

where $\mathcal{L}_{\text{CE}}$ ensures basic classification accuracy, $\mathcal{L}_{\text{KD}}$ transfers inter-class relationships, and $\mathcal{L}_{\text{COS}}$ constrains student-teacher consistency in representation space.

3.3 Stage Two: High-Value Sample Selection and Adaptive Refinement

After initial training, we employ a two-tier margin selection mechanism to identify the most valuable samples for model enhancement, then perform targeted training on this subset using difficulty-adaptive loss functions to maximize their utilization.

3.3.1 Two-Tier Margin-Based Sample Selection

This mechanism extracts samples that most effectively reveal model weaknesses and provide maximum informational value, directly addressing data scarcity and distribution discrepancies through deep exploration of existing data rather than blind expansion.

Uncertainty-Based Difficulty Partition The most beneficial samples are not "easy" ones already mastered, but those near decision boundaries or beyond current understanding. Based on teacher model f_t predictions from stage one, we identify two high-value types:

- **Near-miss samples ($\mathcal{S}_{\text{NM}}$):** Samples with correct but low-confidence predictions, or incorrect predictions where the correct answer is "almost reached." These boundary-adjacent samples are crucial for fine-grained discrimination. Formally:

$$\mathcal{S}_{\text{NM}} = \{(x_i, y_i) : [(\hat{y}_i = y_i) \wedge (p^{(1)} - p^{(2)}) \leq \delta_1)] \vee \text{rank}(y_i) \in \{2, 3\}\} \tag{2}$$

  Here, $p^{(k)}$ represents the k-th highest predicted probability from the model, $\hat{y}_i$ denotes the predicted class, $\text{rank}(y_i)$ is the position of the true label y_i in the sorted prediction probabilities, and δ_1 is a small confidence margin threshold (e.g., 0.05).

- **Hard-hard samples ($\mathcal{S}_{\text{HH}}$):** These are samples for which the models predictions are grossly incorrect, meaning the predicted probability ranking of the true label is very low. Such samples expose fundamental knowledge gaps or severe misunderstandings of certain complex concepts.

$$\mathcal{S}_{\text{HH}} = \{(x_i, y_i) : \text{rank}(y_i) > 3\} \tag{3}$$

Through this tiered partitioning, we narrow the training focus from the entire dataset to $\mathcal{D}_{\text{selected}} = \mathcal{S}_{\text{NM}} \cup \mathcal{S}_{\text{HH}}$, achieving the first stage of concentration on high-value samples.

Fine-Grained Differentiation Based on Probability Margin Even within $\mathcal{S}_{\text{NM}}$ and $\mathcal{S}_{\text{HH}}$, there exists significant variation in sample difficulty. To enable more fine-grained adaptive learning, we introduce a composite difficulty measure that combines the prediction probability margin with distributional uncertainty. The composite difficulty metric $M(x_i, y_i)$ is defined as follows:

1. **Probability Margin:**

$$d(x_i, y_i) = |p_s(y_i|x_i) - \max_{j \in \mathcal{Y}} p_s(j|x_i)| \tag{4}$$

This reflects the models direct fitting degree to the ground truth label. A larger d indicates that the model's understanding deviates more from the true label; a smaller d suggests that the model is closer to correctly understanding it.

2. **Prediction Entropy:**

$$H(x_i) = -\sum_{j \in \mathcal{Y}} p_s(j|x_i) \log p_s(j|x_i) \tag{5}$$

This reflects the overall dispersion of the models predictions.

3. **Composite Difficulty Metric:**

$$\mathcal{M}(x_i, y_i) = d(x_i, y_i) \cdot e^{-H(x_i)} \tag{6}$$

Here, the margin $d(x_i, y_i)$ represents the prediction bias with respect to the ground truth; the entropy $H(x_i)$ adjusts the weight of the bias, with $e^{-H(x_i)}$ amplifying difficulty when entropy is low, and attenuating it when entropy is high. This metric is designed to capture two complementary dimensions of difficulty.

Based on M, we further divide $\mathcal{S}_{\text{NM}}$ and $\mathcal{S}_{\text{HH}}$ into close and far subsets according to the median:

$$\mathcal{S}_t^{\text{close}} = \{(x_i, y_i) \in \mathcal{S}_t : \mathcal{M}(x_i, y_i) \leq \text{median}(\mathcal{M}_t)\} \tag{7}$$

$$\mathcal{S}_t^{\text{far}} = \{(x_i, y_i) \in \mathcal{S}_t : \mathcal{M}(x_i, y_i) > \text{median}(\mathcal{M}_t)\} \tag{8}$$

where $t \in \{\text{NM}, \text{HH}\}$.

This dual-dimensional characterization constructed from the probability margin and prediction entropy precisely depicts different levels of sample difficulty, providing a reliable basis for subsequent adaptive loss design.

3.3.2 Difficulty-Adaptive Loss Function

To address the issues of label complexity and annotation noise, we design an adaptive loss function that dynamically fuses information from hard labels and soft labels, with its weights adjusted according to the sample categories identified in the previous section. The complete definition of the total loss is:

$$\mathcal{L}_{\text{total}} = \alpha \mathcal{L}_{\text{CE}} + \beta \mathcal{L}_{\text{KD}} + \gamma \mathcal{L}_{\text{COS}} \tag{9}$$

where $\mathcal{L}_{\text{CE}}$ is the standard cross-entropy loss based on the ground-truth (hard) label y_i; $\mathcal{L}_{\text{KD}}$ is the knowledge distillation loss that guides the student model f_s to mimic the "soft" probability distribution output by the teacher model f_t; and $\mathcal{L}_{\text{COS}}$ is the cosine embedding loss, which constrains the directional consistency between the student and teacher models in the representation space. The specific formulations are defined as:

$$\mathcal{L}_{\text{CE}} = -\log p_s(y_i|x_i) \tag{10}$$

$$\mathcal{L}_{\text{KD}} = \tau^2 \cdot \text{KL}(p_t(\cdot|x_i) \| p_s(\cdot|x_i)) \tag{11}$$

$$\mathcal{L}_{\text{COS}} = 1 - \cos\big(p_s(\cdot \mid x_i),\, p_t(\cdot \mid x_i)\big) \tag{12}$$

The key lies in the adaptive allocation strategy of the coefficients (α, β, γ) based on different sample categories. For samples with high uncertainty near the decision boundary, strong constraints from hard labels are necessary to avoid the soft-label smoothing effect. Samples near but slightly away from the boundary benefit from both the precision of hard labels and the inter-class relationships of soft labels. When predictions are close to ground-truth but exhibit significant deviations, soft labels are favored to mitigate noise impact. For extremely difficult samples, both hard- and soft-label guidance need to be strengthened. The specific weight allocation for each sample category is detailed in Appendix A.

4 Experiments and Analysis

4.1 Experimental Setup

4.1.1 Datasets

We evaluate the proposed method on two complementary benchmarks, which represent different levels of granularity in student misconception detection:

MAP-Charting dataset (King et al., 2025): This dataset contains real reasoning traces of students in multiple-choice mathematics questions. Each sample includes the problem statement, the student's answer, the correctness label, andcriticallythe student's written explanation of their reasoning process. Labels are divided into three categories: Correct, Misconception (with specific misconception types), or Neither (indicating vague or irrelevant thinking). This fine-grained dataset consists of 36,695 samples in total.

Algebra Misconceptions Benchmark (Nancy et al., 2024): This benchmark covers 55 types of algebraic misconceptions validated by 145 peer-reviewed studies. Unlike MAP-Charting, this dataset requires only the students final answer (without reasoning traces) to identify the misconception type, making it coarser-grained but easier to collect. We randomly select questions from all available topics for evaluation. This dataset contains a total of 220 samples.

4.1.2 Implementation Details

For student models, we conduct experiments on three lightweight architectures: Qwen-3-4B (Team, 2025c), Gemma-2-9B (Team, 2024a), and Llama-3.1-8B (Grattafiori et al., 2024). The teacher model is Qwen-2.5-72B (Team, 2024b). All models are fine-tuned using the AdamW optimizer with a batch size of 16 and 4 gradient accumulation steps. The learning rate for student models is set to 2×10^{-4}, with a distillation temperature $\tau = 1.0$; for the teacher model, the learning rate is 1×10^{-4}. The confidence threshold is set to $\delta_1 = 0.05$, determined from preliminary experiments. In the second-stage incremental training of the small models, apart from setting the learning rate to 1×10^{-6} and `max_grad_norm` to 4, all other configurations remain consistent with the above settings.

4.1.3 Baseline Methods

Prompting-based models: We evaluate various prompting strategies for advanced large language models, including in-context learning and chain-of-thought reasoning. Tested models include GPT-5 (Team, 2025b), Claude-4-Sonnet (Team, 2025a), DeepSeek-V3 (DeepSeek-AI et al., 2025), and Qwen-2.5-72B.

Classification-based models: We attach a classification head and fine-tune different sizes of language models, including student models (Qwen-3-4B, Gemma-2-9B, Llama-3.1-8B) and the teacher model (Qwen-2.5-72B) directly fine-tuned without distillation.

4.1.4 Evaluation Metrics

We adopt four evaluation metrics to comprehensively assess ranking quality from multiple perspectives: MAP@3, MAP@10, Accuracy, and F1@3. MAP@3 mainly measures the model's ability to identify multiple possible correct answers within the top 3 predictions; MAP@10 extends the scope to the top 10 predictions, evaluating ranking performance on a broader scale; Accuracy measures the overall correctness of predictions; F1@3 considers both precision and recall within the top 3 predictions, reflecting the models balanced performance in multi-candidate scenarios. These four metrics allow us to compare model performance in terms of local precision, overall accuracy, and ranking coverage from multiple angles.

4.2 Main Results

Table 1 shows that two-stage distillation markedly boosts MAP@3 and MAP@10 on both MAP-Charting and Algebra Misconception benchmarks, outperforming prompt-based reasoning and direct fine-tuning. In MAP-Charting, the best

Table 1: Performance comparison on two benchmark datasets. The best results in each category are shown in **bold**.

Method	MAP-Charting				Algebra Misconception Benchmark			
	MAP@3	MAP@10	Accuracy	F1@3	MAP@3	MAP@10	Accuracy	F1@3
Prompting-based Methods								
GPT-5	**0.8137**	**0.8145**	**0.7225**	**0.4626**	**0.7409**	**0.7418**	**0.6773**	**0.4091**
Claude-4-Sonnet	0.7833	0.7841	0.6914	0.4579	0.6636	0.6645	0.5636	0.3932
DeepSeek-V3	0.7665	0.7673	0.6601	0.4505	0.6485	0.6494	0.5545	0.3815
GPT-OSS-120B	0.7661	0.7669	0.6794	0.4375	0.6550	0.6559	0.5680	0.3725
Qwen-2.5-72B (prompting)	0.7285	0.7293	0.6222	0.4328	0.6280	0.6289	0.5320	0.3670
Fine-tuned-based Methods								
Qwen-2.5-72B (fine-tuned)	**0.9497**	**0.9501**	**0.9014**	**0.4993**	**0.8438**	**0.8612**	**0.8125**	**0.4375**
Qwen-3-4B (fine-tuned)	0.9472	0.9475	0.8987	0.4992	0.7552	0.7669	0.7188	0.4062
Gemma-2-9B (fine-tuned)	0.9439	0.9442	0.8919	0.4992	0.7708	0.7862	0.7188	0.4219
Llama-3.1-8B (fine-tuned)	0.9453	0.9456	0.8954	0.4990	0.7760	0.7917	0.7500	0.4062
Our Method (Two-Stage Distillation)								
Qwen-3-4B + Ours	**0.9585**	**0.9587**	**0.9198**	**0.4996**	**0.8750**	**0.8915**	**0.8438**	**0.4531**
Gemma-2-9B + Ours	0.9560	0.9562	0.9148	0.4995	0.8015	0.8155	0.7656	0.4375
Llama-3.1-8B + Ours	0.9553	0.9555	0.9134	0.4995	0.7865	0.7995	0.7564	0.4281

prompt-based GPT5 score (0.8137/0.8145) rises to 0.9497/0.9501 via direct fine-tuning of Qwen-2.5-72B, while the distilled Qwen-3-4B attains 0.9585/0.9587, about 0.9% above the teacher model and surpassing the 72B model; Gemma-2-9B and Llama-3.1-8B show similar gains. On Algebra Misconception, Qwen-3-4B improves from 0.7552/0.7669 to 0.8750/0.8915 (15.8%/16.2%), exceeding GPT5 by 18.1%/20.2%. Consistent gains across models and metrics indicate stable advantages. Overall, two-stage distillation enables lightweight students to closeand sometimes surpassthe gap with large teacher models, combining stability, generality, and efficiency.

4.3 Ablation Study

Our ablation study consists of two parts. The first part removes (ablates) the main components of the method one by one to verify the impact of different modules on model performance. The second part takes into account the multi-stage distillation training nature of our method and designs a cross-stage performance comparison experiment.

4.3.1 Ablation of Main Components

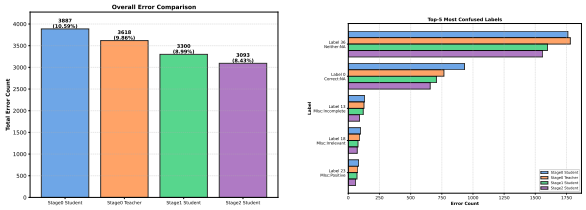
Table 2 reports ablation results for MAP@10, MAP@3, and Accuracy using the two-stage distillation scheme based on Qwen-3-4B. Removing any core component consistently lowers both MAP@10 and MAP@3, indicating stable gains across different evaluation dimensions. On the MAP-Charting dataset, the full method achieves 0.9587/0.9585 (MAP@10/MAP@3) and 0.9198 (Accuracy); removing adaptive loss or high-value sample selection reduces performance by 0.4%–0.7%, while omitting second-stage distillation causes the largest drop, with Accuracy falling by over 1.7%. On the Algebra Misconception benchmark, the full method obtains 0.8915/0.8750 and 0.8438; removing second-stage distillation reduces MAP by more than 10% and Accuracy to 0.7577. Overall, each stage of the distillation process provides significant, consistent improvements across different evaluation dimensions.

4.3.2 Performance Across Different Stages

Figures 3a and 3b respectively illustrate error count changes across five key stages (Initial Teacher, Stage-0 Student/Teacher, Stage-1 Student, Stage-2 Student) and the five most commonly confused categories. The results show that later-stage models consistently reduce total and per-category errors, confirming that multi-stage distillation effectively lowers overall error rates and enhances fine-grained classification, especially for difficult categories. For detailed analyses of the top-10 and all 37 categories, see Appendix **??**.

4.4 Efficiency Analysis

To evaluate the practical value of our method, we tested inference efficiency on 7,339 samples (Table 3). The Qwen-3-4B student model surpasses the best API model GPT5 in accuracy by 18.0 percentage points (MAP@3: 0.9599 vs 0.8137) while reducing inference time from 1.50 h to 0.008 h,



(a) Error count changes across different stage models (b) Error count changes in top-5 confused categories

Figure 3: Visualization of error counts in multi-stage distillation training.

Table 2: Ablation study results. The best result for each benchmark dataset is in **bold**.

Method Variant	MAP-Charting		
	MAP@10	MAP@3	Accuracy
Full Method	**0.9587**	**0.9585**	**0.9198**
w/o Adaptive Loss	0.9542	0.9540	0.9123
w/o Sample Selection	0.9521	0.9519	0.9085
w/o Stage-1 Distillation	0.9548	0.9546	0.9132
w/o Stage-2 Distillation	0.9495	0.9493	0.9024
Method Variant	**Algebra Misconception**		
	MAP@10	**MAP@3**	**Accuracy**
Full Method	**0.8915**	**0.8750**	**0.8438**
w/o Adaptive Loss	0.8802	0.8657	0.8321
w/o Sample Selection	0.8741	0.8603	0.8269
w/o Stage-1 Distillation	0.8823	0.8679	0.8342
w/o Stage-2 Distillation	0.8001	0.7893	0.7577

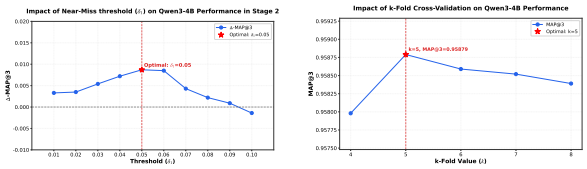
achieving a 187.5× speedup. Compared with its teacher Qwen-2.5-72B under the same hardware, it slightly improves accuracy (0.9599 vs 0.9497) and speeds up inference by 23.25× (0.008 h vs 0.186 h). Against GPT-OSS-120B, it boosts accuracy by 25.3 percentage points and is 137.5× faster, yet can run on a personal computer. These results highlight the substantial performance and efficiency gains of our method in producing accurate and lightweight student models for problem-solving strategy classification.

4.5 Parameter Analysis

In the second training stage, the class probability threshold δ is used to filter high-uncertainty samples. Based on Qwen-3-4B (Team, 2025c), experiments in the range $[0.01, 0.10]$ evaluated changes in validation MAP@3, with gain defined as $\text{MAP@3}(\delta) - \text{MAP@3}(\delta_{\text{baseline}})$. Results (Figure 4a) show $\delta = 0.05$ yields the largest improvement ($+0.012$), while $\delta = 0.10$ causes a drop (-0.004), indicating that moderate thresholds effectively select useful samples, whereas overly high thresholds risk overfitting. K-fold validation further shows performance peaks at $K = 5$, achieving **0.95879** MAP@3, suggesting this split optimally balances training coverage and validation stability.

Table 3: Inference efficiency comparison over 7,339 samples

Model	MAP@3	Time (h)	Hardware
API Models			
GPT-5	0.8137	1.50	Cloud API
Claude-4-Sonnet	0.7665	1.80	Cloud API
Self-deployment Models			
GPT-OSS-120B	0.7661	1.10	32 × H20
Qwen-2.5-72B	0.7285	1.30	32 × H20
Our Models			
Qwen-2.5-72B (teacher)†	0.9497	0.186	8 × H20
Qwen-3-4B (student)*	**0.9599**	**0.008**	**8 × H20**



(a) Impact of δ threshold (b) Impact of different K-fold

Figure 4: Results of two hyperparameter search experiments in the second stage.

5 Conclusion

This study proposes a hierarchical-difficulty-based sample selection and probability-constrained multi-scale knowledge distillation framework, achieving the high accuracy required for real-world deployment of educational AI under extremely data-scarce conditions. Leveraging a dual-level margin mechanism to precisely identify *Near-miss* (correct predictions with uncertainty) and *Hard-hard* (severely incorrect predictions) samples, and designing adaptive loss functions for different types of samples, we achieve a MAP@3 of 0.9585 (relative improvement of 17.8%) on real student data, significantly enhancing the reliability of erroneous concept diagnosis. This framework can be extended in the future to progressive difficulty scheduling and multi-task learning, improving the personalization and scalability of automated tutoring systems.

6 Limitation

Although this study demonstrates promising results in multi-stage distillation and high-value sam-

ple selection, there are still several limitations:

First, the training resource and time overhead associated with the Kfold partition. To avoid data leakage and improve the reliability of sample selection, we adopt a Kfold cross-partition approach for inference sample screening. However, the search process for the optimal K is inherently complex: each attempt to evaluate a different K value requires a complete round of global training and evaluation experiments. This high-overhead characteristic may limit the exploration of the optimal combination of K and model performance in scenarios with restricted training resources or limited training cycles, thereby constraining the methods best possible deployment performance.

Second, the limited improvement for low-value or low-quality data. Our multi-stage distillation framework is designed to continuously select the most valuable samples for adaptive refinement, thereby progressively enhancing model performance. However, when the incoming data batches are inherently of low value or poor quality, the potential for improvement offered by such methods is limited. In the presence of a large data quality gap, the model cannot achieve significant gains solely through sample selection and distillation. Therefore, in such scenarios, it is crucial to design effective high-quality data synthesis strategies, actively generating and repairing data to fill the gaps, rather than simply avoiding the challenges posed by synthetic data.

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A Adaptive Loss Weight Allocation

Table 4 presents the specific weighting strategy for the adaptive loss function based on sample categories. This mechanism organically combines sample difficulty characterization with label credibility assessment, and in particular, demonstrates a careful handling of real-world noise for $\mathcal{S}_{\text{HH}}^{\text{close}}$ samples. This is a key design choice that enhances model robustness in complex categories.

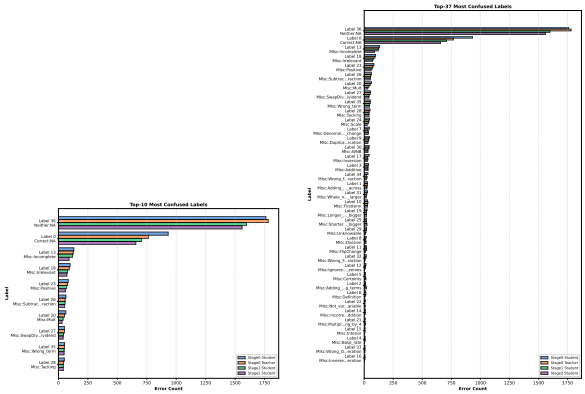
Table 4: Adaptive loss weight allocation strategy based on sample categories

Category	$\alpha(\mathcal{L}_{\text{CE}})$	$\beta(\mathcal{L}_{\text{KD}})$	$\gamma(\mathcal{L}_{\text{COS}})$
$\mathcal{S}_{\text{NM}}^{\text{close}}$	1.0	0.0	0.0
$\mathcal{S}_{\text{NM}}^{\text{far}}$	1.0	1.0	1.0
$\mathcal{S}_{\text{HH}}^{\text{close}}$	0.0	1.0	1.0
$\mathcal{S}_{\text{HH}}^{\text{far}}$	1.0	1.0	1.0

B Detailed Error Analysis Across Categories

This section provides comprehensive error analysis results for different numbers of categories. Figure 5 shows the error count changes for the top-10 most commonly confused categories and all 37 categories across different stage models.

The analysis reveals that the multi-stage distillation approach consistently reduces errors across all category groups. The improvement is particularly notable in the most frequently misclassified categories, where later-stage models demonstrate substantial error reduction compared to earlier stages.



(a) Error count changes in top-10 confused categories

(b) Error count changes in all 37 categories

Figure 5: Extended error analysis for different category groups

C LLM Model Configuration Details

Tables 5, 6 and 7 present the sampling parameters and inference configuration details for all state-of-the-art language models evaluated in our benchmark experiments.

Table 5: Sampling parameters for state-of-the-art language models (Part 1)

Model	Temperature	Max Tokens	Top-p
GPT-5	0.7	8192	0.9
DeepSeek-V3	0.3	8192	0.9
GPT-OSS-120B	0.7	8192	0.9
Claude Sonnet 4	0.3	8192	0.9
Qwen2.5-72B	0.7	8192	0.9

Table 6: Sampling parameters for state-of-the-art language models (Part 2)

Model	Repetition Penalty	Frequency Penalty	Presence Penalty
GPT-5	–	0	0
DeepSeek-V3	1.05	0	0
GPT-OSS-120B	–	0	0
Claude Sonnet 4	1.05	0	0
Qwen2.5-72B	1.05	0	0

Table 7: Inference configuration for state-of-the-art language models

Model	Batch Size	Rate Limit
GPT-5	500	2000
DeepSeek-V3	25	500
GPT-OSS-120B	500	5000
Claude Sonnet 4	500	2000
Qwen2.5-72B	50	1000

D Prompt for Experiments

To validate the effectiveness of our method, we designed three different experimental scenarios, with corresponding prompts shown below.

The first prompt presents a few-shot learning-based student explanation generation approach, which guides the LLM to generate students problem-solving process and reasoning processes based on a number of examples. The second and third prompts correspond to category prediction prompts for two benchmark tasks, respectively.

Through these three different types of prompts, we can comprehensively evaluate the models performance under both data synthesis and direct prediction modes.

Prompt: Synthetic Student Explanation Generator

You will be generating new student explanations that match a specific explanation type for a given math question. You need to simulate how different students at the same grade level might explain their reasoning when arriving at the same answer.

Here is the question, student's answer, answer correctness and an example student explanation

<question> {QUESTIONTEXT} </question>
<answer> {ANSWER} </answer>
<answer_correctness> {ANSWER CORRECTNESS} </answer_correctness>
<student_explanation> {STUDENT EXPLANATION} </student_explanation>

Here is the explanation type you need to match and related student explanations from other students:

<explanation_type> {STUDENT_EXPLANATION_TYPE} </explanation_type>
<related_explanations> {RELATED_STUDENT_EXPLANATION} </related_explanations>

You need to generate {N} new student explanations.

EXPLANATION TYPE CATEGORIES:

- **Correct:NA** – The student's reasoning process is mathematically sound and leads logically to the correct answer
- **Neither:NA** – The student's explanation is vague, unclear, or unrelated to the mathematical concepts in the question
- **Misconception:[Specific type]** – The student has a specific mathematical misconception. The specific type describes what mathematical concept they misunderstand (e.g., "Incorrect_equivalent_fraction_addition")

INSTRUCTIONS:

1. Analyze the given explanation type to understand what kind of reasoning pattern you need to replicate
2. Study the related student explanations to understand the common patterns for this explanation type
3. Generate new explanations that: – Lead to the same answer as provided – Match the specified explanation type category – Sound like they come from different students at the appropriate grade level – Show variety in wording and approach while maintaining the same underlying reasoning pattern – Are age-appropriate in language and mathematical sophistication

<scratchpad> Before generating the explanations, think through: – What grade level is this question appropriate for? – What is the specific reasoning pattern shown in the explanation type? – How do the related explanations demonstrate this pattern? – What variations in language and approach can I use while maintaining the same reasoning type? – If it's a misconception, what is the specific mathematical error being made? </scratchpad>

Generate {N} new student explanations that match the specified explanation type. Each explanation should be distinct but follow the same reasoning pattern. Present each explanation numbered and in separate tags:

<explanation_1> [First new student explanation] </explanation_1>
<explanation_2> [Second new student explanation] </explanation_2>
[Continue for all N explanations...]

Prompt: MAP-Charting dataset

SYSTEM PROMPT:
You are a mathematics education analysis expert. You need to analyze students' explanations for solving math problems, identify correct reasoning, vague statements, or specific misunderstandings, and categorize them into predefined types. Please remain professional and objective, focusing on the students' thought processes.
CLASSIFICATION PROMPT:
You will be analyzing a student's explanation for a math problem and classifying it into one of several predefined explanation types.
Here is the problem data:
<problem_data> {PROBLEM_DATA} </problem_data>
Here are the possible student explanation types with their categories and corresponding indices:
<student_explanation_types> **### General Categories**
- [0] **Correct:NA** - The student's problem-solving approach and process are correct
- [36] **Neither:NA** - The explanation is vague, unclear, or logically incomplete
Fraction Operation Misconceptions
- [1] **Misconception:Adding_across** - Adding numerators and denominators directly (e.g., 1/3 + 2/5 = 3/8)
- [7] **Misconception:Denominator-only_change** - Only denominator is changed (e.g., 1/3 + 2/5 = 3/15)
... (6 more fraction operation types)
Basic Operation Misconceptions
- [2] **Misconception:Adding_terms** - Using addition instead of multiplication (e.g., 2y = 24 interpreted as y = 22)
- [8] **Misconception:Division** - Misunderstanding division concept (e.g., confusing "of" with "œ")
... (5 more basic operation types)
Other Misconception Categories
- [9] **Misconception:Duplication** - Multiplying both numerator and denominator (e.g., 2/3 Œ 5 = 10/15)
- [19] **Misconception:Longer_is_bigger** - Believing more decimal places means larger numbers
- [22] **Misconception:Not_variable** - Not understanding variables (e.g., interpreting 2y as 2 and y)
... (18 more misconception types across various mathematical concepts) </student_explanation_types>
Your task is to determine which explanation type from STUDENT_EXPLANATION_TYPE best matches the Student Explanation provided in the PROBLEM_DATA.
The category system works as follows:
- **Correct:NA** - The student's explanation process is correct
- **Neither:NA** - The student's explanation is vague, unclear, or irrelevant to the problem
- **Misconception:[specific_type]** - The student's explanation contains a specific misunderstanding or error in reasoning (e.g., "Misconception:Incorrect_equivalent_fraction_addition")
Before providing your final answer, analyze the student's explanation carefully in scratchpad tags.
Consider:
1. What mathematical concepts or processes does the student's explanation involve?
2. Is the reasoning correct, incorrect, or unclear?
3. If incorrect, what specific type of misconception does it represent?
4. Which of the available explanation types best matches this analysis?
<scratchpad> [Your analysis here] </scratchpad>
Provide the three most likely explanation type indices in order from highest to lowest probability.
Format your answer as [idx1, idx2, idx3, ...] where idx1 is the most likely match, idx2 is the second most likely, and idx3 is the third most likely.

Prompt: Algebra Misconceptions Benchmark

SYSTEM PROMPT:
You are a mathematics education diagnostic expert specializing in misconception analysis. Your task is to analyze students' final answers to math problems, identify whether the answer reflects specific mathematical misconceptions, and categorize them into predefined misconception types. Please remain professional and objective, focusing on the students' submitted answers and the underlying errors they reveal.
CLASSIFICATION PROMPT:
You will be analyzing a student's answer to a math problem and classifying it into one of several predefined misconception types.
Here is the problem data:
<problem_data> {PROBLEM_DATA} </problem_data>
Here are the possible misconception types with their categories and corresponding indices:
<misconception_types> **### Representative Misconception Categories (55 total)**
Proportional Relationships:
- [MaE01] when students don't understand how to represent proportional relationships
- [MaE02] Students misunderstand proportional relationships, not realizing parts must be equal
Fractions:
- [MaE06] when students inaccurately simplify fractions by guessing instead of dividing
- [MaE08] incorrectly add/subtract fractions by summing numerators and denominators separately
Decimals & Negatives:
- [MaE16] mistakenly position decimal point left of sum, assuming units/tenths combine separately
- [MaE18] when students are unsure of correct sign when adding positive and negative numbers
Ratios & Percentages:
- [MaE24] struggle to understand that ratios can compare same or different units
- [MaE29] incorrectly apply single proportion formula: (smaller)/(larger) = (x/100)
Operations:
- [MaE31] incorrectly assume commutative/associative properties apply to subtraction/division
- [MaE34] incorrectly perform operations left to right, neglecting order of operations
Functions & Graphing:
- [MaE38] struggle to grasp that linear function represents consistent rate of change
- [MaE43] struggle with plotting points, reversing x- and y-coordinates
Variables & Algebra:
- [MaE46] mistakenly perceive variables as labels/units, or associate value with alphabetical position
- [MaE51] misunderstand equal sign as "the answer is" rather than relationship between quantities
- [MaE55] struggle to recognize when to combine like terms (e.g., 4x+2x+x=7x)
... (42 more misconception types covering exponents, mixed numbers, division, patterns, slopes, equations, and various algebraic concepts) </misconception_types>
Your task is to determine which misconception type best matches the Student Answer.
Before providing your final answer, analyze carefully in scratchpad tags. Consider:
1. What is the correct answer to this problem?
2. How does the student's answer differ from the correct answer?
3. What mathematical error or misconception could lead to this specific incorrect answer?
4. Which misconception types best explain the error pattern?
5. Are there alternative misconceptions that could also explain this answer?
<scratchpad> [Your analysis here] </scratchpad>
Provide the three most likely misconception type indices in order from highest to lowest probability.
Format your answer as [MaE01, MaE02, MaE03, ...] where MaE01 is the most likely match.