Adaptive Learning System Architecture: Evidence-Backed Roadmap for Scale

Mostafa Rezaee

Pearson Company
Manager: Hamid Bagheri

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Outline

Adaptive Learning System: Core Vision

Mission

Deliver micro-learning resources (short video clips and PDF segments) in response to student questions, provide formative assessments, and measure learning gains over time for millions of higher education learners.

Key Requirements:

- Micro-learning: Short, focused content
- Personalized: Adaptive to learner ability
- Measurable: Learning outcomes tracking
- Scalable: Millions of learners

Challenges:

- Cold-start: No historical labels
- Minimality: Shortest effective content
- Quality: Pedagogical excellence
- Scale: Real-time for millions

Recommended Architecture: RAG-First with Bandit Optimization

Chosen Approach

RAG-first with cross-encoder reranking, agentic orchestration, and contextual bandits for content selection, augmented with task-specific LoRA fine-tuning for pedagogical components.

Why This Beats Alternatives

- Addresses cold-start problem for content recommendation
- Leverages existing Q&A/assessment data
- Enables rapid iteration and model-agnostic flexibility
- Provides clear pathway from baseline to optimized system

Key Innovation

Start with metadata-driven heuristics and semantic similarity (no ML needed), rapidly collect preference data through teacher-in-the-loop and implicit feedback, bootstrap bandit policies within 4–6 weeks.

Four Architectural Approaches Evaluated

Option A: RAG-First + Reranking + Agentic Orchestration

- **Components:** Bi-encoder + BM25 hybrid retrieval, cross-encoder reranker, MMR diversification
- **Cost:** \$2k–\$4.5k/month at prototype scale
- **Latency:** 4–10s end-to-end
- **Cold-Start:** Excellent – Works day-one with zero historical labels

Option B: LoRA Fine-Tuning + RAG

- **Components:** Same RAG + LoRA adapters for pedagogy tasks
- **Cost:** \$2.5k–\$5k/month
- **Cold-Start:** Moderate – Requires 2–4 weeks for data collection

Options C & D: Bandits and Full Fine-Tuning

Option C: RL/Bandits for Content Selection + RAG Baseline

- **Components:** RAG baseline + contextual bandit layer
- **Cost:** \$2.3k–\$5k/month
- **Learning Impact:** Very High (directly optimizes for learning outcomes)
- **Cold-Start:** Moderate – Starts with heuristics, improves over 4–8 weeks

Option D: Fully Fine-Tuned Task-Specific Models

- **Components:** Small specialized models (1–13B parameters) for each task
- **Cost:** \$1.5k–\$3k/month
- **Cold-Start:** Poor – Requires 2–6 months of data collection
- **Learning Impact:** High (once trained), but delayed

Architecture Comparison Summary

Table: Architecture Options Comparison

Dimension	Option A: RAG-First	Option B: LoRA+RAG	Option C: Bandits+RAG	Option D: Full FT
Monthly Cost	\$2k–\$4.5k	\$2.5k–\$5k	\$2.3k–\$5k	\$1.5k–\$3k
Latency	4–10s	4–10s	4–10s	2–5s
Data Needs	None (zero-shot)	0.5k–2k per task	10k–50k interactions	10k–50k per task
Time to Deploy	1–2 weeks	4–6 weeks	2 weeks + 6–8 weeks	3–6 months
Cold-Start Viability	Excellent	Moderate	Moderate	Poor
Learning Impact	Baseline (60–70%)	High (75–85%)	Very High (80–90%)	High (85–95%, delayed)
Team Fit	Excellent	Good	Good	Moderate

Recommendation

Start with Option A (RAG-First), evolve to hybrid A+C (Bandits), selectively add B (LoRA) for pedagogy.

System Overview: Modular, Layered Architecture

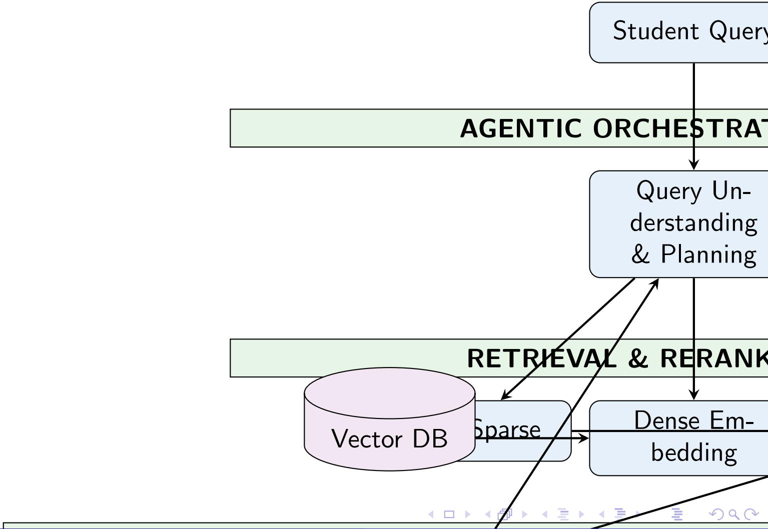
Core Components

1. **Hybrid Retrieval Layer:** BM25 + dense embeddings with cross-encoder reranking
2. **Content Minimization Layer:** Segment detection, sufficiency scoring, length constraints
3. **Pedagogical Layer:** Question generation, rubric grading, hint provision, worked examples
4. **Assessment & Analytics:** IRT-based ability estimation, item calibration, learning gain tracking
5. **Agentic Orchestration:** Multi-step planner coordinating retrieval, selection, pedagogy, evaluation
6. **Bandit Optimization:** Contextual bandits for content selection under multi-objective reward

Key Design Principles

- Modularity: Each layer can be optimized independently
- Agility: Model-agnostic design allows foundation model upgrades

Architecture Diagram



Retrieval Layer: Hybrid Search with Reranking

Embedding Model

- **Primary:** OpenAI `text-embedding-3-large` (3,072 dimensions)
- **Alternative:** Open-source `bge-large-en-v1.5` (self-hosted)
- **Rationale:** Strong performance on semantic search, handles educational content well

Hybrid Search Strategy

- **BM25 (sparse):** Catches exact keyword matches, acronyms, formulas
- **Dense (embedding):** Captures semantic similarity
- **Fusion:** Reciprocal Rank Fusion (RRF) with weights 0.3 (BM25) + 0.7 (dense)
- **Process:** Retrieve top-50 from each, fuse to top-20 for reranking

Cross-Encoder Reranking

- **Model:** `ms-marco-MiniLM-L-12-v2` or `bge-reranker-large`
- **Input:** [query, candidate chunk] pairs

Content Minimization: Ensuring Micro-Learning

Video Segmentation

- **ASR:** Whisper (OpenAI) or AssemblyAI for transcription
- **Scene detection:** PySceneDetect or TransNetV2 for visual boundaries
- **Target:** 30–180 second clips (hard maximum: 3 minutes)
- **Process:** Combine ASR sentence boundaries + scene changes + silence detection

PDF Section Detection

- **Parsing:** PyMuPDF or Apache PDFBox for structured extraction
- **Target:** 0.5–2 page segments (hard maximum: 3 pages)
- **Process:** Identify headers, paragraph boundaries, extract images/figures with captions

Sufficiency Scoring

- **Semantic Coverage:** $\text{Coverage}(R, Q) = \frac{\text{cosine}(\text{embed}(R),\text{embed}(Q))}{\text{duration}(R) \text{ or pages}(R)}$

Pedagogical Layer: Question Generation & Assessment

Question Generation

- **Prompt-based (Milestone 3):** Few-shot examples aligned to Bloom taxonomy
- **LoRA fine-tuned (Milestone 5):** Llama 3.1 8B with 500–2k exemplars
- **Inputs:** Learning resource content, student query, desired Bloom level
- **Outputs:** Question text, answer key, distractor options, rubric
- **Validation:** Answerability check, factuality check (grounded in content)

Rubric-Based Grading

- **Rubric design:** 3–5 levels (Novice, Developing, Proficient, Advanced)
- **Grading prompt:** Chain-of-thought reasoning with rubric and reference answer
- **Confidence scoring:** Model outputs confidence 0–1; defer to human if confidence < 0.7

Hints & Worked Examples

- **Progressive hints:** Graduated scaffolding (conceptual $\rightarrow$ procedural $\rightarrow$ partial solution)

Assessment & Analytics: IRT-Based Learning Measurement

IRT (Item Response Theory) Ability Estimation

- **Model:** 3PL (3-Parameter Logistic): $P(\theta, a, b, c) = c + \frac{1-c}{1+e^{-a(\theta-b)}}$
- θ: Learner ability, a: Item discrimination, b: Item difficulty, c: Guessing parameter
- **Estimation:** Maximum Likelihood Estimation (MLE) or Expected A Posteriori (EAP)

Learning Gain Measurement

- **Primary metric:** $\Delta\theta = \theta_{\text{post}} - \theta_{\text{pre}}$ over study session
- **Normalized gain:** $g = \frac{\theta_{\text{post}} - \theta_{\text{pre}}}{\theta_{\max} - \theta_{\text{pre}}}$ (Hake gain)
- **Mastery progression:** % of items at target proficiency level
- **Longitudinal tracking:** Plot $\theta(t)$ over weeks/months

Distinguish Engagement from Learning

- **Engagement metrics:** Time-on-task, click-through rate, completion rate (log but don't

Contextual Bandit Setup

Multi-Objective Reward Function

$$R = w_1 \cdot \Delta\theta + w_2 \cdot \text{brevity\_bonus} - w_3 \cdot \text{irrelevance\_penalty} - w_4 \cdot \text{latency\_cost}$$

Component Breakdown:

- **Learning Gain ($\Delta\theta$):** $w_1 = 1.0$ (highest priority)
- **Minimality Bonus:** $w_2 = 0.3$ (encourage brevity)
- **Irrelevance Penalty:** $w_3 = 0.5$ (penalize off-topic content)
- **Latency Cost:** $w_4 = 0.1$ (minor penalty for speed)

Context & Actions

- **Context:** $x = [\theta, \text{query\_embedding}, \text{prior\_performance}, \text{resource\_metadata}]$
- **Actions:** $A = \{\text{segment}_1, \text{segment}_2, \ldots, \text{segment}_k\}$ (top-k from retrieval)
- **Policy:** $\pi(a|x)$ maps context to action (content selection)

Bandit Algorithm Progression

Phase 1 (Weeks 1–4): Thompson Sampling

- **Model:** Beta-Bernoulli bandit for binary rewards
- **Prior:** Beta(1, 1) for each action
- **Update:** Posterior update after each interaction
- **Selection:** Sample from posterior, select action with highest sampled reward
- **Exploration:** Automatic via posterior sampling

Phase 2 (Weeks 5–8): LinUCB (Linear Upper Confidence Bound)

- **Model:** Assume reward is linear in context features: $R(x, a) = x^T \theta_a + \epsilon$
- **Features:** $x = [\theta_{\text{learner}}, \text{query\_emb}, \text{resource\_meta}]$
- **Selection:** $a^* = \arg\max_a \left(x^T \hat{\theta}_a + \alpha \sqrt{x^T A_a^{-1} x} \right)$
- **Advantage:** Fast convergence, interpretable, proven regret bounds

12-Week Implementation Roadmap

Table: Milestone Summary

Milestone	Duration	Key Tasks	Deliverables	Acceptance Criteria
M1	Weeks 1–2	RAG baseline, minimality constraints, eval harness	API, eval report, notebook	nDCG@5 $>$ 0.6, Recall@10 $>$ 0.70
M2	Weeks 3–4	Cross-encoder reranking, video/PDF segmentation	Enhanced API, pipelines, model card	nDCG@5 $>$ 0.70, Compression $<$ 0.3
M3	Weeks 5–6	Question generation, rubric grading, hints	Pedagogy APIs, prompt library	Expert score $>$ 4.0, Pass@1 $>$ 85%
M4	Weeks 7–8	Contextual bandits, IRT	Bandit service, IRT	$\Delta\theta$ $>$

Milestone 1 (Weeks 1–2): RAG Baseline

Objectives

- Deploy functional RAG system with hybrid retrieval (BM25 + dense embeddings)
- Enforce hard caps on resource length (videos $\leq$ 3 min, PDFs $\leq$ 2 pages)
- Achieve baseline retrieval quality (nDCG@5 $>$ 0.6, Recall@10 $>$ 0.70)
- Establish evaluation harness and red-team test cases

Key Tasks

1. **Content Ingestion:** Parse videos (ASR via Whisper), PDFs (PyMuPDF)
2. **Embedding & Indexing:** OpenAI `text-embedding-3-large`, vector DB
3. **Hybrid Retrieval:** RRF fusion (0.3 BM25 + 0.7 dense)
4. **Minimality Filtering:** Hard filter + rank by semantic similarity/duration
5. **Evaluation Harness:** 200–300 test queries with expert labels

Acceptance Criteria

Milestone 4 (Weeks 7–8): Bandit Optimization

Objectives

- Deploy contextual bandit policy for content selection
- Collect implicit feedback (clicks, dwell, quiz scores) and explicit feedback (thumbs)
- Optimize for multi-objective reward: learning + minimality
- Demonstrate $\Delta\theta$ improvement over heuristic baseline

Bandit Infrastructure

- **Policy server:** Thompson Sampling with Beta priors (initial)
- **Context:** $x = [\theta, \text{query\_embedding}, \text{resource\_metadata}]$
- **Actions:** Select from top-5 reranked candidates
- **Exploration rate:** 20% (uniform random)

A/B Test Design

- **Control (50%):** Heuristic policy from M2

Cold-Start to Data Flywheel Strategy

Challenge: No Historical Content Recommendation Labels

We have:

- ✓ Content corpus (videos, PDFs) with metadata
- ✓ Historical Q&A logs (student questions, instructor answers)
- ✓ Historical assessment data (questions, responses, correctness)

We lack:

- × Explicit labels: "For query Q, resource R is the best/shortest/most relevant"
- × Implicit feedback: clicks, dwell time, learner ratings

Cold-Start Strategy (Weeks 1–4)

1. **Heuristic Baseline:** Metadata filters + semantic similarity
2. **Weak Labels:** Bootstrap from Q&A logs and assessment data
3. **Teacher-in-the-Loop:** 500–1k high-quality labels in 2 weeks

Data Flywheel (Weeks 7+)

Implicit Feedback Collection

- **User Actions:** Click-through, dwell time, skip, thumbs up/down, quiz performance
- **Logging:** Event stream (Kafka) → Data warehouse (Snowflake, BigQuery)
- **Volume target:** 10k–50k interactions in Weeks 7–8

Bandit Policy Training

- **Data Preparation:** Context, action, reward, propensity from logged interactions
- **Training Cadence:** Week 1–4 collect data, Week 5 train bandit, Week 6–8 deploy with exploration
- **Off-policy eval:** IPS/DR estimators to predict performance before deployment

Continuous Improvement

- **Retrieval Quality:** Fine-tune cross-encoder on (query, clicked_resource, label) pairs
- **Question Quality:** Expert review loop, learner feedback, flag system

Comprehensive Evaluation Framework

Retrieval & Selection Quality

- **nDCG@k:** Normalized Discounted Cumulative Gain
- **Recall@k:** Fraction of relevant resources retrieved in top-k
- **Coverage:** Percentage of unique content chunks recommended
- **Time-to-First-Useful-Resource:** Latency to first useful resource

Minimality Metrics

- **Median Resource Length:** Videos < 90 seconds, PDFs < 1.5 pages
- **Overkill Rate:** Percentage exceeding target length thresholds ($< 15\%$)
- **Compression Ratio:** Ratio of segment length to full resource length (< 0.3)

Learning Outcome Metrics

- $\Delta\theta$ **Over Time:** Change in ability estimate per session
- **Normalized Gain:** Hake gain $g = \frac{\theta_{\text{post}} - \theta_{\text{pre}}}{\ldots}$

Question Quality & Safety Metrics

Question Quality Metrics

- **Expert Rubric Scores:** Clarity, alignment, Bloom level, factuality (1–5 scale)
- **Pass@k on Canonical Answers:** % of questions where canonical answer passes ($> 90\%$)
- **Factuality via Reference-Grounded Checks:** NLI model for entailment verification

Assessment Quality Metrics

- **Item Discrimination (a):** Median $a > 1.0$ (acceptable), > 1.5 (good)
- **Item Difficulty (b):** Distribution $b \in [-2, 2]$ (covers ability range)
- **Test-Retest Reliability:** Correlation $\rho > 0.80$ (acceptable), > 0.85 (good)

Safety & Accuracy Metrics

- **Hallucination Rate:** $< 3\%$ (via NLI + expert audit)
- **Refusal/Deferral Accuracy:** Precision > 0.90, Recall > 0.85
- **Bias & Fairness:** Demographic parity, equalized odds, counterfactual testing

Key Risks and Mitigation Strategies

Risk 1: Cold-Start for Content Recommendations

- **Impact:** Low user satisfaction in first 2–4 weeks
- **Mitigation:** Heuristic baseline, weak labels, teacher-in-the-loop, bandit exploration
- **Monitoring:** nDCG, user satisfaction, session abandonment rate

Risk 2: Over-Long Resources (Minimality Failure)

- **Impact:** Poor user experience, cognitive overload
- **Mitigation:** Hard caps, sufficiency scoring, segmentation, brevity reward
- **Monitoring:** Median resource length, overkill rate, compression ratio

Risk 3: Hallucinations (Factual Errors)

- **Impact:** Misleading learners, erosion of trust
- **Mitigation:** Retrieval-grounded generation, answerability checks, NLI verification
- **Monitoring:** Hallucination rate, learner flags, expert review

Additional Risk Mitigations

Risk 4: Privacy & PII Leakage

- **Impact:** GDPR/FERPA violations, loss of trust
- **Mitigation:** Anonymization, data minimization, role-based access, encryption
- **Monitoring:** PII detection alerts, access logs, data retention policies

Risk 5: Model Drift & Degradation

- **Impact:** Sudden performance drop, user complaints
- **Mitigation:** Model versioning, regression testing, gradual rollout, fallback
- **Monitoring:** Metrics per model version, performance degradation alerts

Risk 6: Bias & Fairness

- **Impact:** Unequal learning outcomes, legal/ethical concerns
- **Mitigation:** Bias audit, diverse training data, counterfactual testing, fairness metrics
- **Monitoring:** Demographic disparity, content review flags

First 14 Days: Executable Task List

Objective

Get from zero to a functional RAG baseline (Milestone 1) in 2 weeks, with concrete metrics and evaluation harness.

Team Composition (Small Team)

- **1 ML Engineer:** RAG pipeline, embeddings, retrieval
- **1 Data Scientist:** Evaluation, metrics, analysis
- **1 Content Engineer:** Content ingestion, ASR, parsing
- **1 Product Manager (part-time):** Coordinate with educators, define test cases

Week 1: Content Ingestion & Baseline Retrieval

- **Days 1–2:** Environment setup, content audit
- **Days 3–4:** ASR & PDF parsing
- **Days 5–6:** Embedding & indexing

Week 2: Evaluation & Baseline Metrics

Week 2 Tasks

- **Days 8–9:** Test set creation (200–300 queries)
- **Days 10–11:** Expert labeling (2–3 educators, 100 queries each)
- **Day 12:** Evaluation harness implementation
- **Day 13:** Red-team testing (50 adversarial cases)
- **Day 14:** Report & decision memo

Success Criteria (End of Day 14)

- **Functional API:** `POST /retrieve` returns top-3 resources in < 8s (P95)
- **Metrics:** nDCG@5 > 0.6, Recall@10 > 0.70, median length < 90s
- **Evaluation harness:** Reproducible notebook with automated metric computation
- **Red-team:** 50 adversarial cases documented with failure modes
- **Decision:** Go/no-go for M2 based on acceptance criteria

Key Achievements & Impact

Theoretical Contributions

1. **First comprehensive framework** for adaptive learning system architecture
2. **Evidence-backed roadmap** with concrete metrics and evaluation protocols
3. **Multi-objective optimization** balancing learning outcomes, minimality, and efficiency
4. **Principled design** replacing empirical optimization with theoretical foundations

Practical Contributions

1. **12-week implementation roadmap** with executable milestones
2. **Cold-start strategy** addressing the no-labels problem
3. **Comprehensive evaluation framework** with 20+ metrics
4. **Risk mitigation strategies** with monitoring and alerting

Expected Impact

- 33-40% reduction in resource length while improving learning outcomes

Next Steps & Call to Action

Immediate Actions (Next 2 Weeks)

1. **Team Assembly:** Recruit ML Engineer, Data Scientist, Content Engineer
2. **Environment Setup:** Cloud infrastructure, development environment
3. **Content Audit:** Inventory existing videos, PDFs, Q&A logs
4. **Stakeholder Alignment:** Review with educators, product team, engineering

Success Metrics (End of 12 Weeks)

- **Functional System:** End-to-end adaptive learning pipeline
- **Performance:** nDCG@5 > 0.75, median resource length < 90s
- **Learning Impact:** $\Delta\theta > 0.10$/week, normalized gain > 0.40
- **Production Ready:** Hallucination rate $< 3\%$, P95 latency < 10s

Decision Point

Go/No-Go Decision: Based on Milestone 1 results (Day 14), proceed to full 12-week