19 - 21 December 2025 Berlin , Germany

A Concept-Level Multidimensional Elo Model for Adaptive Educational Systems

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Abstract

Adaptive learning systems require learner models capable of capturing multidimensional knowledge and supporting real-time updates as students interact with diverse learning tasks. Traditional Elo-based approaches offer fast online adaptation but assume unidimensional skill and task difficulty, which limits their applicability in domains where items simultaneously involve multiple concepts. This paper introduces MxM-Elo, a novel many-to-many multidimensional extension of the Elo model that jointly represents students' knowledge profiles and tasks' concept-level difficulty vectors. Unlike prior multivariate variants, MxM-Elo eliminates manually assigned concept weights and derives the influence of each concept directly from its inherent difficulty within a task. The model also incorporates per-concept uncertainty, operationalized via battle counts—tracking how often each student and each task has interacted within each concept—to enable rapid parameter updates in low-information regions and stable learning when uncertainty decreases. We evaluate MxM-Elo on synthetic and real-world educational datasets and compare it against the standard Elo algorithm as well as multivariate Elo baselines. Results demonstrate that MxM-Elo improves predictive performance by 12% over the standard Elo model, while also exhibiting superior stability during long-term usage and producing richer, more interpretable estimates for guiding adaptive recommendations and open learner model visualizations. These findings highlight MxM-Elo as a robust and scalable learner modeling approach for modern adaptive learning environments where tasks and knowledge naturally span multiple interconnected concepts.

Keywords: Adaptive Learning; Elo Model; Learner Modeling; Multidimensional Difficulty; Uncertainty Estimation