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研究課題名（和文）パーソナライズド学習を支援する学習者知識モデルに関する研究

研究課題名（英文）Research on Learner Knowledge Models for Supporting Personalized Learning

研究代表者
孫　媛（Sun, Yuan）

国立情報学研究所・情報社会相関研究系・准教授

研究者番号：００２４９９３９

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研究成果の概要（和文）：オンライン学習の普及とパーソナライズド学習へのニーズの拡大を背景に、我々は認知診断モデルと知的学習支援システムの学習ログを用いて、学習者の知識状態の動的評価法を研究した。データ駆動型のQ-matrix生成手法、学習者データから推定されたドメイン知識の前提関係を利用した専門家定義のQ-matrixの改良、そして認知診断と知識追跡モデルの融合により、学習者の知識状態と学習過程を同時に把握する新たなモデルの開発などを行った。これらにより，学習者知識状態評価精度の向上，大規模オンライン学習のスケーラビリティ確保が可能となり，広範な教育分野への応用，パーソナライズド学習の推進に寄与することが期待される。

研究成果の学術的意義や社会的意義
我々の研究は、認知診断モデルの開発に行列分解法や深層学習を活用するというこれまでにない枠組みを提示した。これにより、教育心理学や心理測定学の領域に新たな知識の構築と進歩を促し、学習者の知識習得状況と学習過程への理解を進展させることが期待できる。また、教育現場において、開発したモデルと手法を活用することで学習者一人ひとりの理解度や学習過程を詳細に把握できれば、個別化された学習支援、教育の個別化を実現できる。特に、オンライン学習環境の普及に伴い大量の学習データが取得されるようになれば、それを有効利用し、教室単位での活用にとどまらず、教育格差の是正や生涯学習の推進などにも繋げうる可能性を有している。

研究成果の概要（英文）：In response to growing online learning and personalized learning needs, we aimed to dynamically diagnose learner knowledge state, employing Intelligent Tutoring Systems learning logs. We proposed a comprehensive framework merging learner and domain modeling, inferring domain knowledge structure directly from learner data. Our method enhanced the crucial Q-matrix using a data-driven approach, simultaneously gauging learner knowledge states. Blending cognitive diagnostic and knowledge tracing models, we captured learners' knowledge state and learning process concurrently. Harnessing deep learning, we improved knowledge state representation during performance modeling while maintaining interpretability. The enhanced evaluation accuracy and scalability make our approach adaptable to large-scale online environments, promising broader educational applications than traditional methods, and fostering personalized learning.

研究分野：教育心理学

キーワード：認知診断　Q-matrix　項目反応データ　知識追跡モデル　パーソナライズド学習

１．研究開始当初の背景

Education's transformation into the digital realm has seen the proliferation of Intelligent Tutoring Systems (ITSs), paving the way for personalized learning experiences. A significant pivot in this evolution has been the shift from traditional outcome-based assessments to the burgeoning field of Cognitive Diagnostic Assessment (CDA). Unlike conventional testing paradigms, CDA delves into a comprehensive analysis of a learner's knowledge state, thereby providing a supportive framework for the learning process rather than simply evaluating the learning outcomes. It serves as an invaluable asset within ITSs, guiding the design of adaptive, personalized strategies that optimize knowledge acquisition.

The rise of online learning has ushered in an era of sophisticated ITSs, designed to cater to a diverse range of learner needs and proficiencies. These platforms typically engage learners through a sequence of personalized learning activities, such as problem-solving exercises, allowing them to build knowledge at their own pace and style. Critical to these adaptive services is the role of learner knowledge assessment—a technique designed to model learner performance and uncover their latent proficiency in mastering specific knowledge domains.

The potency of learner knowledge assessment lies in its capacity to facilitate the optimization of learning processes. The derived assessment information forms the backbone of many real-world ITSs, informing the generation of adaptive learning materials tailored to individual student needs. It further allows the strategic alignment of content to students' knowledge states—content that does not resonate with a student's current knowledge state can be deferred or skipped entirely, thereby enhancing learning efficiency and sustaining student engagement.

The escalating popularity of online educational platforms has led to an unprecedented influx of learning logs. These voluminous datasets offer a rich source for constructing advanced models for accurate learner knowledge assessment—a research area that is currently receiving extensive attention across interdisciplinary domains, including education, psychology, computer science, and cognitive science.

However, this growth has not been without challenges. Unraveling learners' latent knowledge states from ITS learning logs is a complex endeavor, given the intricate interplay of numerous factors intrinsic to the learner and the learning domain. Current CDA models, like the deterministic inputs, noisy "and" gate model (DINA), offer a static perspective, which falls short in accommodating the dynamic nature of a learner's knowledge construction process.

In response to this shortcoming, researchers in educational data mining have proposed data-driven knowledge tracing (KT) techniques. These offer a dynamic lens to track the evolution of learners' knowledge proficiency over extended periods. Yet, existing approaches often consider only a portion of information from either the learner or the learning domain during the learning process, leaving a gap in achieving a comprehensive, precise prediction of learner performance in KT.

In this project, we venture into this uncharted territory, exploring the possibility of resolving the KT task by integrating both learner and domain modeling, in an endeavor to create a more robust, precise, and dynamic learner knowledge assessment framework.

２．研究の目的

The primary objective of this project is to address the dynamic aspect of learner knowledge assessment, an essential component in bolstering personalized learning experiences. The endeavor seeks to chronicle the evolution of each learner's knowledge state, effectively capturing their mastery over distinct concepts within a learning domain.

To create a more nuanced and detailed representation of a learner's knowledge evolution, our focus is on developing advanced learner knowledge models. These models will leverage the extensive historical learning logs amassed from various online learning platforms. The ultimate aim is to refine our understanding of the dynamic process of knowledge acquisition, thereby facilitating more tailored and effective learning experiences.

３．研究の方法

Our methodological approach starts with implementing a data-driven automated learning technique for the Q-matrix, crucial for assessing knowledge acquisition states, and an algorithm for concurrent evaluation of learners' knowledge states. The focus is on dynamically tracking the learner's knowledge progression throughout their prolonged online learning experience. We form comprehensive learner models using prominent public datasets, basing our approach mainly on learning log data analysis. Through analyzing these logs, we discern and quantify the impacting factors from both the learner and learning domain on learning performance. This analysis aids us in comprehending and capturing the influence of these factors on knowledge acquisition during learning. After identifying and quantifying these factors, we perform a learner knowledge assessment, synthesizing all identified factors, allowing us to accurately trace the evolution of learners' knowledge states over time. We carry out our research mainly in three aspects: integration of multiple factors from the learner and learning domain for knowledge tracing; enhancement of knowledge tracing via a knowledge structure-augmented Q-matrix refinement process; and development of an interpretable model for diagnosing learner knowledge.

４．研究成果

(1) Q-matrix Learning in Cognitive Diagnostic Assessment

Utilizing the fundamental principle of Boolean Matrix multiplication, we analytically expressed the Boolean Description Function (BDF), illustrating the relationship between a learner's ideal response pattern to items and their knowledge state based on the Q-matrix. Additionally, we proposed a Q-matrix-generated Auto Encoder (QAE) model, an artificial neural network used for unsupervised learning, with the obtained Q-matrix serving as a constraint condition.

The proposed approach, characterized by the ability to handle large-scale data due to its use of deep learning methods and to incorporate the expert judgment-based Q-matrix as a constraint condition in the QAE model, preserves the interpretability of the cognitive diagnostic model. We applied this method to simulation data and real data of a cognitive diagnostic test on fractions that we developed, and conducted comparative experiments with conventional cognitive diagnostic models and matrix factorization methods. As a result, our proposed QAE model demonstrated superior accuracy and robustness in Q-matrix automated learning.

(2) Enhanced Integration of Influential Factors for Knowledge Tracing

We propose an innovative approach based on a deep factorization machine for learner knowledge assessment that effectively models multiple influential factors. This technique delves into a comprehensive exploration of the factors that play a pivotal role in knowledge acquisition and harnesses the wealth of information obtained from learners' interactive activities to make highly precise predictions about learner knowledge progression.

Our approach is embodied in a novel knowledge tracing model we've coined KTM-DLF. This model dynamically traces the evolution of learners' knowledge acquisition over an extended period. It does this by explicitly modeling learners' cognitive behaviors, such as learning and forgetting, in addition to the difficulty level of the learning items.

To model learners' learning and forgetting behaviors, we consider aspects such as their memory decay and the benefits derived from exercise attempts. Additionally, we introduce a new concept of cognitive item difficulty, representing the cognitive challenges presented by different learning items to different individuals. To effectively model this user-oriented difficulty, we've designed a method that adaptively accounts for these cognitive challenges. Through a series of empirical analyses, we have demonstrated the effectiveness of our KTM-DLF model and highlighted the profound impact of these factors on learner knowledge assessment.

(3) Amplifying Knowledge Tracing through Knowledge Structure-Augmented Q-Matrix Refinement

We put forward a model fortified by knowledge structure, realized through graph

representation learning, for the purpose of precise learner knowledge assessment. This model seeks to discern the structure of domain knowledge from learner response data, utilizing these inferences to enrich the existing data by refining the original Q-matrix - a graph illustrating the relationship between questions and skills. This refinement process effectively alleviates issues of data sparseness.

Our proposed model learns the dense embeddings of both questions and skills through enhanced graph representation, amalgamating these with other distinguishing features to craft a comprehensive representation of each question. In doing so, we rectify the information deficit inherent in existing skill-level models which often neglect unique information intrinsic to individual questions and their interrelations. Incorporating the dual processes of knowledge structure inference and Q-matrix refinement into the knowledge assessment process allows for a more holistic and precise assessment. A thorough evaluation confirms the superior performance and interpretability of this model in dynamically representing learning performance and extracting the underlying knowledge structure from data.

(4) Interpretable Learner Knowledge Diagnosis

We introduce a method for interpretable learner knowledge assessment that is enhanced by knowledge interaction, which we implement through sequential modeling. Our innovative model, the Knowledge Interaction-Enhanced Dynamic Cognitive Diagnostic Assessment (KIEDCDA), dynamically traces the changes in each learner's knowledge state as they engage in various exercise activities. This model skillfully combines the powerful auxiliary memory capabilities of the key-value memory network with the interpretability of Item Response Theory (IRT) to illuminate learner performance. This is achieved by enhancing the representation of the knowledge state during learner performance modeling, and explicating learner performance in terms of knowledge proficiency and item characteristics, including difficulty and discrimination.

We further enrich our model by incorporating the concept of knowledge interaction amongst knowledge concepts. This enhancement allows us to better exploit the long-term dependencies present in the exercise sequences. As a result of this multifaceted approach, our model is capable of outputting learner knowledge proficiency at varying degrees of granularity, as well as detailing item characteristics. Consequently, our model facilitates the interpretation of results and provides a more comprehensive and nuanced understanding of a learner's knowledge trajectory.

５．主な発表論文等

〔雑誌論文〕　計13件（うち査読付論文　13件／うち国際共著　11件／うちオープンアクセス　8件）

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３．雑誌名 Proceedings of the 30th International Conference on Computers in Education (ICCE2022)	６．最初と最後の頁 124-134
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究協力者	井上　俊哉 (Inoue Shunya)		
研究協力者	孫　翼 (Sun Yi)		
研究協力者	甘　文斌 (Gan Wenbin)		

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関