On the Practicality of Differential Privacy for Knowledge Tracing

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ABSTRACT

The application of machine learning techniques to educational datasets has great potential to improve our understanding of learning processes. However, there are privacy concerns in the community about the datasets and models that are being developed using student exercise logs. This limits the potential of AI in education. Differential privacy provides a mathematical framework that limits what can be inferred about an individual in a data set. In this study, we apply differential privacy techniques to knowledge tracing models and analyze the privacy-utility trade-off across three distinct privacy accounting methods. Our assessment offers insights into the practical challenges of implementing privacy-preserving knowledge tracing. We define differential privacy at the user level, where protection extends to a student's entire sequence of interactions. Our study shows that knowledge tracing models respond differently to privacy constraints, with deep knowledge tracing models maintaining competitive performance under differential privacy. We address important considerations for application of differential privacy, including optimal hyperparameter selection and evaluation of privacy accounting methods that balance strong privacy guarantees with model performance.

Keywords

Differential Privacy Knowledge Tracing Moments Accountant Sequential Composition

1. INTRODUCTION

Working with educational data requires protecting the privacy of the student. The simplest approach is to anonymize the data by removing names, social security numbers, or other direct identifiers. However, such data may still be vulnerable to reidentification methods, which leverage correlations, summary statistics, or other knowledge to infer personal information from anonymized data[5, 17]. For example, in an anonymized dataset of test scores on multiple subjects, someone who knows a student's score in one subject could use that knowledge to determine their scores in the other subjects. Differential privacy (DP) goes beyond anonymization to provide strong, statistical guarantees for privacy via randomization [4]. DP is widely used in a growing number of industries. Apple leverages local differential privacy to enhance user-level privacy in personalized services such as suggestions and health analytics applications. Microsoft incorporates DP in its Azure platform, which enables privacy-preserving data analysis for cloud-based services. The US Census Bureau also uses DP techniques to protect the confidentiality of respondents, as part of the new Disclosure Avoidance system. The implementation adds controlled noise at different geographic levels and demonstrates how privacy protection can be applied while maintaining the utility of demographic analysis [18]. In this paper, we investigate the application of DP to educational data mining, focusing specifically on knowledge tracing. Knowledge tracing is the task of modeling student knowledge states from their interaction history to predict performance on future questions. This is a core task in educational data mining with applications in adaptive learning systems, personalized feedback, and educational resource optimization.

Numerous studies investigate potential threat scenarios and the risks of reidentifying individuals in educational datasets [26] [22] [10] [23] [24] [14] [21]. Others explore various perturbation approaches in differential privacy [13].

However, very little of this work focuses on specific applications, such as knowledge tracing, or the unique challenges of applying differential privacy to deep learning in education. Knowledge tracing is different from other differential privacy settings because of the dynamic, sequential nature of knowledge tracing tasks, where each interaction potentially reveals sensitive information about a student's learning progress and cognitive states. We address this gap by examining the unique challenges of applying dif- ferential privacy to knowledge tracing tasks by examining a broader spectrum of differential privacy theories and tech- niques. Our research makes several distinct contributions.

- We discuss how differential privacy can be applied to the knowledge tracing setting, including defining the problem formally.
- We use existing tools to implement differentially private versions of three knowledge tracing methods: (1)BKT [25] which is a well-established probabilistic learner

Anika Kabir, and Daniel Lowd. On the Practicality of Differential Privacy for Knowledge Tracing. In Caitlin Mills, Giora Alexandron, Davide Taibi, Giosuè Lo Bosco, and Luc Paquette (eds.) Proceedings of the 18th International Conference on Educational Data Mining, Palermo, Italy, July, 2025, pp. 619–624. International Educational Data Mining Society (2025).

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https://doi.org/10.5281/zenodo.15870248

modeling approach; (2) DKT [19], which uses recurrent neural networks to capture complex patterns in student interaction sequences; and (3) MonaCoBERT [11], a transformer-based approach that leverages contextual representations for knowledge tracing.

- We evaluate private knowledge tracing methods on six datasets in order to (1) determine which private method is most accurate; (2) compare the performance of private and non-private methods; (3) explore the tradeoff between greater privacy (smaller epsilon) and greater accuracy (higher AUC); (4) compare the guarantees offered by different DP accounting methods, namely Privacy Random Variable, Rényi Differential Privacy, and Gaussian Differential Privacy(GDP).

Overall, our findings show that we can offer DP guarantees for knowledge tracing, with DKT offering the strongest performance overall and performing nearly as well in the private setting as in the non-private setting(for $\epsilon < 8$)

2. DP KNOWLEDGE TRACING

We now provide brief background on differential privacy (DP), while explaining how these concepts can be applied to the knowledge tracing setting.

2.1 Differential Privacy

The definition of Differential Privacy [4] centers around the notion of neighboring datasets, where D and D' belong to the set $\mathcal{S}$ of all *Datasets*. The probability of a specific event resulting from a query on the dataset D is compared to the outcome for a query on dataset D'. Differential Privacy ensures that these probabilities differ by at most a factor of e^{ϵ}, making it infeasible to distinguish whether an individual's data was included or excluded based solely on the query results. Therefore, the privacy level is quantified by the exponential privacy parameter ϵ, a non-negative real number that measures the degree of privacy protection.

Definition 1. A mechanism $\mathcal{M}$ is (ϵ, δ)-differentially private if for all pairs of **adjacent datasets** D and D', where D' differs from D by one data point x, and for all subsets $S \subseteq \text{Range}(\mathcal{M})$, the following inequality holds:

$$\Pr[\mathcal{M}(D) \in S] \leq e^{\epsilon} \cdot \Pr[\mathcal{M}(D') \in S] + \delta. \quad (1)$$

The δ term accounts for privacy failures in ways that cannot be accounted for in $\epsilon - DP$. The δ represents a small probability of exceeding the privacy loss bound set by δ [3] [16].

THEOREM 1 (SEQUENTIAL COMPOSITION). *If $F_1(x)$ satisfies ϵ_1-differential privacy, and $F_2(x)$ satisfies ϵ_2-differential privacy, then the mechanism $G(x) = (F_1(x), F_2(x))$ satisfies $(\epsilon_1 + \epsilon_2)$-differential privacy [6].*

This means that when multiple queries are performed on the same dataset, the total privacy budget is the sum of the individual budgets.

2.2 Problem Definition

We now discuss how DP can be applied to knowledge tracing. The knowledge tracing task aims to model a student's evolving knowledge state from their interaction history. The knowledge tracing task can be formalized as follows:given a sequence of observed student interaction consisting of questions q_i and responses r_i, the objective is to estimate the student's latent knowledge state to predict their correct/incorrect answers on subsequent questions. Model performance is evaluated through binary classification metrics, where Area Under the ROC Curve (AUC) quantifies the model's ability to discriminate between correct and incorrect responses. Root Mean Square Error (RMSE) is used to measure the magnitude of the prediction error on the test set. Given a test-set of users' question and response sequences $y_{s,q} \in \{0, 1\}$ and predictions $\hat{p}_{s,q}$ from the model, the task is to predict the probability of a correct response for the next question in the sequence based on previous performance.

Definition 2. A knowledge tracing mechanism $\mathcal{M}$ is (ϵ, δ)-differentially private if for all pairs of **adjacent datasets** D and D', where D' differs from D by the addition or removal of **one user's entire sequence of interactions** $(q_1, r_1) \ldots (q_i, r_i)$, and for all subsets $S \subseteq \text{Range}(\mathcal{M})$, the following inequality holds:

$$\Pr[\mathcal{M}(D) \in S] \leq e^{\epsilon} \cdot \Pr[\mathcal{M}(D') \in S] + \delta. \quad (2)$$

Therefore, knowledge tracing can be defined as a randomized mechanism that adheres to (ϵ, δ) **-differential privacy**. This turns out to be a very strong definition of privacy, one that works even against an attacker who knows every single student in the dataset $\mathcal{D}$ and the hypothetical student that might or might not be in the dataset $\mathcal{D}'$.

2.3 Moments Accountant

We now briefly describe the moments accountant method, a foundational privacy accounting technique, that yields better bounds for deep learning [1]. The privacy loss random variable 3 quantifies how output probabilities of mechanisms differ between adjacent datasets d and d'.

Definition 3. For neighboring datasets d, d', a mechanism $\mathcal{M}$, auxiliary input aux, and outcome o, the privacy loss is defined as:

$$c(o; \mathcal{M}, \text{aux}, d, d') \triangleq \log \frac{\Pr[\mathcal{M}(\text{aux}, d) = o]}{\Pr[\mathcal{M}(\text{aux}, d') = o]} \quad (3)$$

$$\alpha_{\mathcal{M}}(\lambda; \text{aux}, d, d') \triangleq \log \mathbb{E}_{o \sim \mathcal{M}(\text{aux}, d)}[\exp(\lambda c(o; \mathcal{M}, \text{aux}, d, d'))] \quad (4)$$

The λth moment (4) of the privacy loss for a mechanism $\mathcal{M}$, denoted as $\alpha_{\mathcal{M}}(\lambda; \text{aux}, d, d')$, is defined as the logarithm of the moment generating function evaluated at λ [1]. Tracking log moments of this random variable allows composition across training steps, providing the foundation for privacy accounting and enabling us to report precise budgets. In the formal expression, $c(o; \mathcal{M}, \text{aux}, d, d')$ represents the privacy loss for output o, aux is auxiliary input, and d and d' are neighboring databases.

2.4 Rènyi Differential Privacy

Rényi Differential Privacy(RDP) [15] provides a theoretical framework for privacy accounting, formalizing the concept of moments accountant method. RDP measures privacy loss using Rényi divergence between output distributions.

Definition 4. For probability distributions P and Q, the Rényi divergence of order $\alpha > 1$ is defined as:

$$D_\alpha(P \parallel Q) = \frac{1}{\alpha - 1} \log \mathbb{E}_{x \sim Q} \left[\left(\frac{P(x)}{Q(x)} \right)^\alpha \right] \tag{5}$$

A randomized mechanism f satisfies (α, ϵ)-RDP if for any adjacent datasets D, D':

$$D_\alpha(f(D) \parallel f(D')) \leq \epsilon \tag{6}$$

This approach provides tight composition bounds and allows tracking privacy budget during training.

3. EMPIRICAL EVALUATION

3.1 Datasets

Six benchmark datasets were used in training knowledge tracing tasks. The ASSISTments datasets are an extensive collection of anonymized student data from the ASSISTments learning platform [7], for selected school years [1]. The datasets adhere to privacy protocols, with the personally identifiable information removed. The Algebra datasets were a part of the 2010 KDD Cup Educational Data Mining Challenge [2]. The competition included two Algebra developmental datasets for two separate academic years. EdNET consists of large scale student interaction logs collected from Scala, an intelligent tutoring system [2]. Knowledge tracing datasets typically contain fields that capture various aspects of student interactions with educational platforms. These generally include student identifiers and unique IDs for questions or exercises attempted. An important field is skill or knowledge component , which links each problem to specific concepts or topics. Each interaction may have specific time stamps and correctness indicating performance.

3.2 Procedure

We evaluate a standard BKT model on the six datasets. The evaluation uses procedures described in the literature[19] [9], using five-fold cross-validation and computing single AUC values from accumulated predictions. The parameters of the Bayesian Knowledge Tracing model, an instance of Hidden Markov Model, used in Yudelson, Koedinger, and Gordon [25] are $\lambda = \{\Pi, A, B\}$, where Π is the Priors matrix, A is the Transitions matrix, and B is the Emissions matrix. The model is defined by two key probability distributions that describe the probability of transitioning between states and the probability of observations from states. These parameters are optimized to maximize the likelihood of observed student performance data, enabling the model to track students' knowledge states and predict performance. We train BKT on a per-skill basis, treating each skill's data as an independent set. If we have K disjoint datasets $\mathcal{D}_1, \mathcal{D}_2, \ldots, \mathcal{D}_K$, where each dataset $\mathcal{D}_k$ contains distinct and non-overlapping data, and each dataset $\mathcal{D}_k$ is independently analyzed with a mechanism satisfying ϵ_k-differential privacy, then the privacy budget for the overall dataset $\mathcal{D} = \bigcup_{k=1}^{K} \mathcal{D}_k$ remains the same as the privacy budget for each individual dataset. That is,

$$\epsilon_{\text{dataset}} = \max\{\epsilon_k : k \in \{1, 2, \ldots, K\}\}.$$

If all mechanisms are run with the same privacy parameter ϵ, then:

$$\epsilon_{\mathcal{D}} = \epsilon.$$

We employed the Opacus library, a framework for privacypreserving deep learning. The experiments closely followed the best practices described in [20] [8].For MonacoBERT, a batch size of 2048 was used. For the Deep Knowledge Tracing model, a smaller batch size of 1024 was sufficient for achieving good AUC. Since higher batch sizes reduce the noise scale in gradient estimates and directly improve model utility while maintaining robustness, these batch size choices were critical to achieving good performance under differential privacy constraints. The clipping norms were chosen to match the distribution of per-example gradient magnitudes [12].

3.3 Results and Discussion

We evaluated four models across six datasets, comparing their performance in private and non-private settings. Results for all datasets are shown in Table 1. Deep Knowledge Tracing (DKT) emerged as the best performer across most datasets. The model was trained for 600 epochs with a gradient clipping threshold of 0.5 and a noise multiplier of 6.0, with early stopping employed to ensure the selection of the best validation AUC. Both DKT and DKT+ exhibit minimal degradation under differential privacy settings.

In the non-private setting, the deep learning methods demonstrate strong predictive performance. For the Assistments2009 dataset, DKT achieved an AUC of 0.80 in the non-private setting and maintained a competitive AUC of 0.79 when privacy-preserving constraints were applied. Similar trends were observed for Algebra 2005 and Algebra 2006, where DKT demonstrated high AUC. The model also showed promising results on EdNet, achieving an AUC of 0.72 non-private and 0.69 in private setting. Therefore, results demonstrate that Deep Knowledge Tracing, which leverages recurrent neural networks to model student performance, can maintain strong predictive capability under differential privacy. Differentially private DKT-plus shows performance comparable to DKT. In the Assistments2009 dataset, it achieves the same AUC of 0.80 in non-private settings and 0.78 under privacy constraints. For experiments under non-private settings, MonaCoBERT shows consistent performance with AUC scores ranging from 0.71 to 0.81 and 0.68 to 0.75 in private settings. Therefore, the results indicate that DKT and DKT+ are resilient to differential privacy constraints. MonaCoBERT, despite achieving strong performance in non-private settings, experiences a large decline in AUC [3]. Fig-

[1]https://sites.google.com/site/assistmentsdata/home/2009-2010-assistment-data

[2]https://pslcdatashop.web.cmu.edu/KDDCup

[3]In a few cases, the RMSE of the private model is better than its non-private counterpart. After performing more runs, we found that RMSE can vary substantially with different random noise. RMSE evaluates numeric calibration; AUC, which evaluates ranking performance, is more stable.

Table 1: Results for Different Datasets

(a) Assistments2009

KT Models	Non-private		Private		
	AUC	RMSE	AUC	RMSE	ϵ
BKT	0.71	0.4147	0.69	0.5761	7.15
DKT	**0.80**	0.4073	0.79	0.4527	6.46
DKT+	**0.80**	0.4195	0.78	0.4928	6.23
MonaCoBERT	0.79	0.4136	0.75	0.4853	6.81

(b) Assistments2012

KT Models	Non-private		Private		
	AUC	RMSE	AUC	RMSE	ϵ
BKT	0.62	0.6145	0.57	0.5935	8.25
DKT	0.71	0.5558	0.70	0.5748	7.12
DKT+	0.70	0.5476	0.70	0.5621	6.74
MonaCoBERT	**0.77**	0.4532	**0.71**	0.4872	6.81

(c) Assistments2017

KT Models	Non-private		Private		
	AUC	RMSE	AUC	RMSE	ϵ
BKT	0.59	0.6236	0.54	0.6672	8.14
DKT	**0.72**	0.4765	0.70	0.4784	7.15
DKT+	**0.72**	0.4462	**0.71**	0.4622	6.95
MonaCoBERT	0.71	0.4340	0.68	0.4776	7.85

(d) EdNet

KT Models	Non-private		Private		
	AUC	RMSE	AUC	RMSE	ϵ
BKT	0.64	0.5715	0.59	0.5927	7.95
DKT	0.72	0.5754	**0.69**	0.6012	7.22
DKT+	0.73	0.5681	**0.69**	0.6125	7.55
MonaCoBERT	**0.81**	0.5449	0.68	0.5421	7.18

(e) Algebra2006

KT Models	Non-private		Private		
	AUC	RMSE	AUC	RMSE	ϵ
BKT	0.70	0.4285	0.69	0.5065	6.99
DKT	**0.80**	0.4634	**0.78**	0.4865	7.45
DKT+	**0.80**	0.4372	**0.78**	0.4741	6.96
MonaCoBERT	**0.80**	0.4382	0.74	0.4886	6.72

(f) Algebra2005

KT Models	Non-private		Private		
	AUC	RMSE	AUC	RMSE	ϵ
BKT	0.71	0.5105	0.68	0.5467	6.99
DKT	**0.81**	0.4552	**0.79**	0.3932	6.21
DKT+	0.80	0.4671	0.78	0.4210	7.62
MonaCoBERT	**0.81**	0.3928	0.75	0.3425	6.20

ure 1 demonstrates the performance of the models under privacy constraints, $\epsilon = 1.0$ through 10.0. In this method, a target privacy budget ϵ is specified, and Opacus adjusts the noise multiplier σ during training to achieve the desired privacy level. The relationship between epsilon ϵ and model performance using three different privacy accounting methods: Rényi Differential Privacy, Gaussian Differential Privacy, and Privacy Random Variable are shown in Figure 2. The graph tracks the three accounting mechanisms over 600 training epochs, revealing different relative budgets.

4. CONCLUSION

In this work, we implement differential privacy with a focus on user-level sequence protection. We demonstrated that good privacy guaranties can coexist with utility. We employ several privacy accounting techniques to compare cumulative privacy losses. Empirical results in educational datasets demonstrated a reasonable trade-off in AUC and privacy budgets. This study provides a foundation for privacy-preserving knowledge tracing. This paves the way for a wider application of privacy-preserving AI in education.

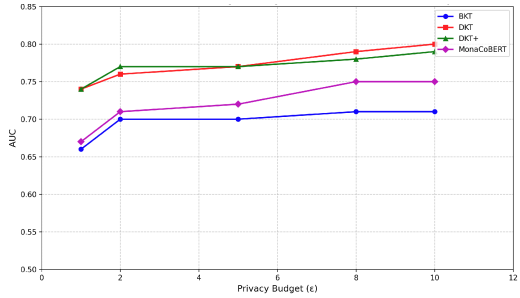

Figure 1: Comparison of Knowledge Tracing model under DP

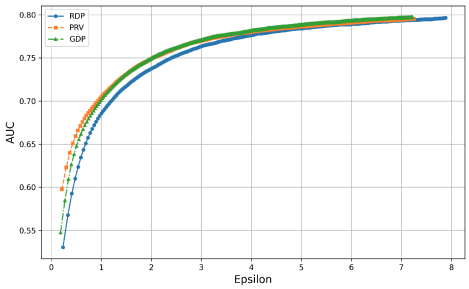

Figure 2: Budgets for Privacy Accountants during training time

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