SEQPATE: DIFFERENTIALLY PRIVATE TEXT GENERATION VIA KNOWLEDGE DISTILLATION

Anonymous authors
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ABSTRACT

Protecting the privacy of user data is crucial when training neural text generation models, which may leak sensitive user information during generation. Differentially private (DP) learning algorithms provide guarantees on identifying the existence of a training sample from model outputs. PATE is a DP learning algorithm that fits the large model well, such as GPT. In this paper, we propose SeqPATE that adapts PATE to text generation while satisfying DP. There are two key challenges in adapting PATE to text generation: (i) obtaining sequence-level supervision for text generation, and (ii) reducing noise required to protect privacy given the large output space (i.e. vocabulary size). For (i), we generate pseudo input and reduce the sequence generation problem to the next word prediction. For (ii), we reduce the output space with top-k and top-p selection strategy that dynamically filters the candidate words; and we refine the teacher aggregation mechanism of PATE to avoid the low agreement rates due to voting over the large output space. To limit the privacy loss, we design an efficient knowledge distillation to reduce the time of distilling from the private data. We apply SeqPATE to a simple text generation task (sentence completion) and achieves 39% and 28% gains in Bleu4 on two datasets.

1 INTRODUCTION

Recent work showed that sensitive user information in training corpora, such as address and name, can be extracted from text generation models (Carlini et al., 2019; 2020). Providing privacy guarantees to the text used to train text generation models has become a critical problem. Differential privacy (DP) provides provable guarantees against the identification of individuals in the dataset. Deep learning models with DP guarantees ensure the existence of a specific training sample cannot be detected.

The most popular DP algorithm for deep learning is Noisy-SGD (Song et al., 2013; Bassily et al., 2014; Abadi et al., 2016), which adds noise to the gradients. However, NoisySGD does not scale to models with a larger number of parameters, and it requires a per-example gradient clip, which causes non-convergence and system overheads (Zhu et al., 2020; Bu et al., 2021). Kerrigan et al. (2020) apply Noisy-SGD to text generation models (GPT-2) but it is hard to have both high utility and privacy protection due to the high dimensionality of parameters in GPT-2. PATE (Papernot et al., 2017) is a DP learning model using a teacher-student framework: a student accessing non-sensitive data distills knowledge from the aggregated predictions of multiple teachers trained on sensitive data. Calibrated noise is added to the aggregated predictions to satisfy DP. PATE can handle large models since its privacy cost derives from the knowledge distillation instead of the model parameters. PATE takes advantage of non-sensitive data which is also available in our scenario.

In this paper, we propose, SeqPATE, a DP learning algorithm for text generation that exploits both sensitive and non-sensitive data by knowledge distillation. Specifically, we adapt PATE for text generation. The adaptation is challenging due to the sequential generation and the large output space (i.e. vocabulary size) in text generation. Firstly, to obtain the sentence-level supervision for text generation, directly applying PATE needs to roll out all teachers to produce a sentence (i.e. all teachers must vote to generate a word, which is then used as the input for the next word prediction). Running inference for a large number of teachers can be costly. Secondly, the large output space results in (i) low agreement rate among teachers and (ii) large noise required by DP, both would significantly hurt task performance.

To avoid sequential generation, we generate pseudo data using a pre-trained language model such that teachers only need to provide token-level supervision given the pseudo input. To handle the large output space, we aggregate teachers' outputs by interpolating their output distributions instead of voting with argmax predictions. To reduce the noise scale, we propose strategies to dynamically filter candidate words which only keep words with large probabilities. Further, we design an efficient knowledge distillation strategy that only queries the teacher when the student has poor performance.

We evaluate our method on sentence completion, a simple but representative task of text generation. Compared to baselines including Noisy-SGD (Kerrigan et al., 2020), SeqPATE improves Bleu4 by 39% and 28% on two datasets with meaningful privacy protection [1]. We observe SeqPATE works particularly well under relatively strong privacy protection (e.g., $\varepsilon \leq 2$) compared to Noisy-SGD. Our contribution is threefold: (i) Our model significantly surpasses baselines and makes DP algorithm achieve satisfactory performance on text generation; (ii) We propose several practical strategies to enable SeqPATE to handle text generation with a sequential of classifications over larger output spaces; (iii) We are the first to adapt PATE, an effective DP algorithm, to text generation.

2 Problem Setup

Our goal is to achieve the privacy protection defined by DP in text generation: preventing attackers from inferring whether a sample or an n-gram appears in the training set. (Formal definition in Sec. 5)

PATE's assumes students are trained on unlabeled non-sensitive data. Similar to PATE, our setting contains two textual datasets: 1. a private set $\mathcal{D}^{\text{pri}}$ from a corpus with sensitive information. 2. a public set $\mathcal{D}^{\text{pub}}$ without sensitive information (e.g. incomplete or masked text spans) or data contributors (e.g. volunteers) have no objection to publishing their data. Algorithms are required to protect the privacy on the private set and can ignore the privacy protection on the public set. The final goal is to do well on the private set during inference.

Text generation is to generate a sequence of words $S = \{w_1, w_2, \ldots, w_l\}$. Our application is a simple text generation task, sentence completion, which aims to generate the remaining part of a sentence $w_{1:l}$ given its prefix $p_{1:l'}$, where $w_{1:l}$ and $p_{1:l'}$ are the abbreviation of $\{w_1, w_2, \ldots, w_l\}$ and $\{p_1, p_2, \ldots, p_{l'}\}$ respectively. $p_{1:l'}$ and $w_{1:l}$ compose a complete sentence. We collect some input prefixes $p_{1:l'}$ to compose the public set $\mathcal{D}^{\text{pub}}$ and the original samples (complete sentences) compose the private set $\mathcal{D}^{\text{pri}}$. Such a setting fits for some real-world text generation applications: in dialog systems, the training samples from online services consist of questions and responses. The questions from customer service staffs or service robots can be public and the response from users carrying individual information should be private. In writing assistants where a sample has an input prompt and an essay body, the prompt can be public but the body written by data contributors is private.

3 Background on DP and PATE

Differential privacy (DP) (Dwork et al., 2014) is a quantifiable definition of privacy that provides provable guarantees on identifications of individuals in the dataset. ML algorithms with DP guarantee ensure that each individual training sample has a degree of *plausible deniability*, i.e., the trained model is *just as likely as* to have been trained on an alternative dataset *without* that sample.

PATE, designed for classification tasks, takes advantage of an unlabeled public dataset $\mathcal{D}^{\text{pub}}$ and also trains on a labeled private $\mathcal{D}^{\text{pri}}$ in a semi-supervised scenario. PATE is model-agnostic and treats models as black-boxes. PATE (Papernot et al., 2017) achieves DP via a teacher-student framework with M teacher models and a student model, where the student learns from the private data via knowledge distillation through teachers. PATE consists of three parts,

- **Teacher models** are trained on the private set $\mathcal{D}^{\text{pri}}$. $\mathcal{D}^{\text{pri}}$ is shuffled and divided into M disjoint subsets, and m-th subset serves as the training set for m-th teacher model f_ϕ^m.
- **Teacher aggregation** merges teachers' outputs. After teachers' training, each teacher f_ϕ^m conducts the prediction (classification) on student's training set $\mathcal{D}^{\text{pub}}$. To satisfy DP, PATE aggregates M

[1] We choose $\varepsilon = 2$. Researchers usually consider ε value in a range of $(0.1, 5)$ for meaningful protection.

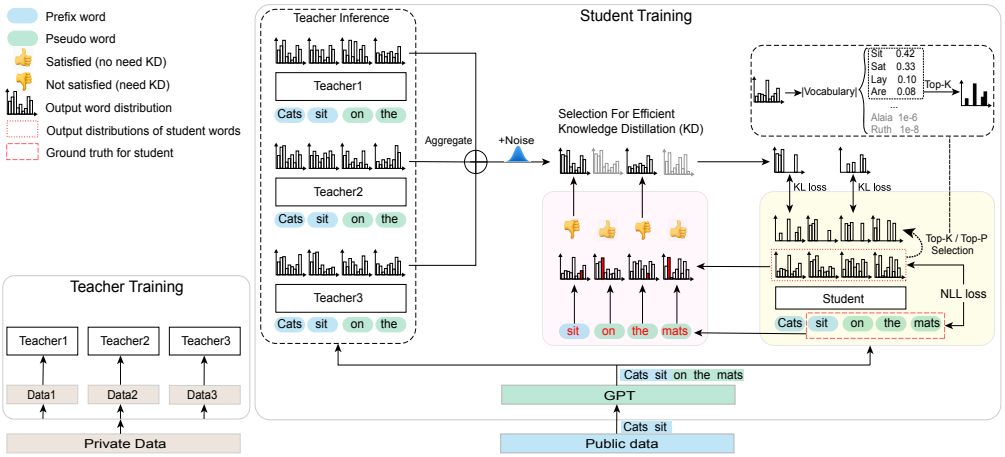

Figure 1: Overview of SeqPATE. SeqPATE trains teachers on the private data; it conducts student training and teacher inference on pseudo sentences generated by GPT based on the public data. The student is supervised by the aggregation of teacher output distributions and benefits from efficient knowledge distillation (pink block) and top-k / top-p selection (white block in the top right corner).

teachers' by voting with their top-1 predictions. PATE adds noise to aggregated teacher outputs so that attackers cannot access the exact outputs to infer original information in samples.

- **A student model** f_θ is trained on the public set $\mathcal{D}^{\text{pub}}$ and distills knowledge from private set without accessing the private samples via the teachers. In this way, the sensitive information in the private set is preserved even if the student's architecture and parameters are public or reverse-engineered by an adversary. We publish only the student model for prediction.

4 Approach

Fig. 1 shows an overview of the SeqPATE. Given the public prefix (e.g., "Cats sit"), we first generate pseudo inputs by completing the prefix using a pre-trained language model (e.g., "Cats sit on the mats") (Sec. 4.1). Teachers' output distributions are then averaged to provide word-level supervision on the pseudo inputs (Sec. 4.2). To reduce the noise over large output space and limit the privacy loss, we propose top-k / top-p selection to dynamically filter the unimportant candidates and efficient knowledge distillation to reduce the number of teacher queries (Sec. 4.3). Our training algorithm is shown in Appendix A.

4.1 Student Model

Conventional text generation models generate step-by-step and left-to-right. Naively applying PATE to the paradigm requires to roll out all the teachers to obtain the supervision at every step, where all the teachers aggregate to generate a word at each step and the word acts as the next input for all teachers. It means we should conduct all teachers' inferences simultaneously and interdependently, which is costly in both computation (involving hundreds of teachers) and privacy costs.

Hence, in SeqPATE, we employ GPT to generate pseudo sentences and conduct teacher inference and student training on the pseudo sentences. Firstly, given a prefix in $\mathcal{D}^{\text{pub}}$, we employ the public released pre-trained GPT to conduct the inference to complete a pseudo sentence. All the generated pseudo sentences compose the student's training set, denoted as $\tilde{\mathcal{D}}^{\text{pub}}$. Secondly, we conduct teacher inference and student training on the samples $S = \{w_1, w_2, \ldots, w_{|S|}\}$ from $\tilde{\mathcal{D}}^{\text{pub}}$. As the conventional training of text generation, the student learns to generate a word $\hat{w}_i$ at i-th step given its previous words $w_{1:i-1}$. Our teachers conduct the inference to generate $\hat{w}_i$ using the input $w_{1:i-1}$ from sample S at i-th step. Then, each teacher provides its output for aggregation. All teachers shares the same inputs with the student so that the outputs of teachers and student are aligned and comparable.

4.2 TEACHER AGGREGATION

PATE aggregates teacher results by taking the majority vote of the predicted labels from all teachers. However, this aggregation strategy does not fit for the large output space in text generation, because the number of votes for each candidate may be very low due to low agreement. For example, multiple candidates may tie for the top-1 prediction.

Therefore, we aggregate M teachers' results by averaging their output distributions, where each teacher model is trained on one of the disjoint subset divided from the private set $\mathcal{D}^{\text{pri}}$. At i-th step on teacher inference, the m-th teacher model f_ϕ^m predicts a word $\hat{w}_i$ with a probability $p_\phi^m(\hat{w}_i)$. Then, our model aggregates all teachers' probabilities by averaging $p_\phi(\hat{w}_i) = \frac{1}{M}\sum_{m=1}^{M} p_\phi^m(\hat{w}_i)$.

Like most DP algorithms, our model adds noises so that the privacy impact can be analyzed and bounded. Different from PATE that adds noise on vote numbers, we add noise on the aggregation of teachers' output distributions. Following (Papernot et al., 2018), we apply the Gaussian mechanism which add iid $\mathcal{N}(0, \sigma^2)$ to each coordinate, where σ controls the strength of privacy protection (more details in Sec. 5).

4.3 SUPERVISION ON THE STUDENT MODEL

Reducing Output Space via Top-k or Top-p Selection. Recall that the teacher outputs a distribution over all words in the vocabulary, and noise must be added to each coordinate to satisfy DP. To reduce the output dimension (hence the amount of noise), we only assign probability mass to a subset of candidates W_i. For all teachers and the student, we assign zero probability mass to any candidates not in W_i and re-normalizing distribution as shown in Eq. 1, where $g(\cdot)$ is the normalizing function The operation makes the words not in W_i never occur in student's training and teachers' supervision, so those words do not need noise to provide protection.

$$g(p(\hat{w}_i \mid w_{1:i-1})) = \begin{cases} \dfrac{p(\hat{w}_i \mid w_{1:i-1})}{\sum_{w \in W_i} p(w \mid w_{1:i-1})} & \text{if } \hat{w}_i \in W_i \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

We determine the subset W_i by two selection strategies: top-k and top-p. Eq. 1 shows the top-k selection at i-th step, where we select the top-k candidates according to the probability generated by the student model. Further, inspired by neucleus sampling (Holtzman et al., 2019), we propose a top-p selection strategy that chooses the minimum k where the cumulative probability of the top-k words is larger than a constant close to 1 (e.g. 0.95) such that the candidate set cover a large proportion of the distribution. We note that candidate selection is based on the student model's output on public or already released input, thus not affecting the privacy guarantee. This choice helps to improve the privacy-utility tradeoff by adaptively allocating the available privacy budgets to release that information more relevant for the task.

Efficient Knowledge Distillation. Reducing the number of queries from teachers results in better privacy protection. Therefore, we acquire teacher supervision only when the student has poor performance. Concretely, we measure student's performance on each token by comparing its output distribution with the ground truth token (from $\tilde{\mathcal{D}}^{\text{pub}}$). Concretely, let r_{w_i} be the rank of the ground truth token w_i in the student's predicted distribution, that is, the number of tokens with higher or equal probability. The student model acquires the teachers' supervision only if r_{w_i} is larger than certain threshold r_c. We note that the selection of tokens relies only on the student and is independent of the teachers, thus the selection does not cause additional privacy loss.

Training Objectives. Different from the semi-supervised setting in PATE, our student model is supervised by both teachers' aggregation and labels from the public set, since the text generation corpus is naturally labeled, unlike in classification tasks. Even if the training set $\tilde{\mathcal{D}}^{\text{pub}}$ provides only pseudo samples, the labels from that sample are also useful given that the number of teacher queries is limited due to privacy concerns. The student's loss function consists of two parts as shown in Eq. 2,

- $\mathcal{L}_i^{\text{KL}}$ shows the supervision from teachers. The student learns from teachers by minimizing KL divergence between student's output distribution p_θ and aggregation of teacher output distributions p_ϕ.
- $\mathcal{L}_i^{\text{NLL}}$ shows the supervision from the pseudo public set $\tilde{\mathcal{D}}^{\text{pub}}$ generated by GPT. As conventional language models, our student model is trained by negative log-likelihood (NLL) loss on $\tilde{\mathcal{D}}^{\text{pub}}$. The words w_i in the training sample is naturally the label for the student model $f_\theta(w_{1:i-1})$ at i-th step.

$$\begin{aligned}
\mathcal{L}_i^{\text{KL}} &= \text{KL}\left(g(\frac{1}{M}(\sum_{m=1}^{M} p_\phi^m(\cdot \mid w_{1:i-1}) + \mathcal{N}(0,\sigma^2))) \,\|\, p_\theta(\cdot \mid w_{1:i-1}) \right), \\
\mathcal{L}_i^{\text{NLL}} &= -\log p_\theta(w_i \mid w_{1:i-1}), \qquad \mathcal{L} = \sum_{S\in\tilde{\mathcal{D}}^{pub}} \sum_{i=1}^{|S|} (\mathcal{L}_i^{\text{NLL}} + \lambda \mathcal{L}_i^{\text{KL}}).
\end{aligned} \tag{2}$$

where $\mathcal{L}_i$ is loss at i-th step, $|S|$ denotes the length of sentence S, and λ balances the two terms and the noise scale σ will be discussed in Sec. 5. $g(\cdot)$ is the re-normalization function used in Eq. 1 that selects the top-k words according to the student's outputs and re-normalizes on the aggregation of teacher outputs with noise. [2]. According to the efficient knowledge distillation, at each step, the loss $\mathcal{L}_i$ is the combination of $\mathcal{L}_i^{\text{NLL}}$ and $\mathcal{L}_i^{\text{KL}}$) if the student needs supervision; otherwise, $\mathcal{L}_i = \mathcal{L}_i^{\text{NLL}}$.

5 Privacy Analysis

5.1 Preliminary of Differential Privacy

Let $\mathcal{D}$, $\mathcal{D}'$ denote two neighboring datasets which differ at only one individual.

Definition 1 (Differential privacy). *For $\varepsilon > 0$ and $\delta \geq 0$, a randomized algorithm $\mathcal{M} : \mathcal{X}^n \to \mathcal{Y}$ is (ε, δ)-differentially private if for any neighboring datasets $\mathcal{D} \sim \mathcal{D}'$ and any $S \subseteq \mathcal{Y}$,*

$$\mathsf{Pr}[\mathcal{M}(\mathcal{D}) \in S] \leq e^\varepsilon \cdot \mathsf{Pr}[\mathcal{M}(\mathcal{D}') \in S] + \delta$$

The definition ensures that it is information-theoretically impossible for an adversary to infer whether the input dataset is $\mathcal{D}$ or $\mathcal{D}'$ even with arbitrary side information. The definition is also *future proof* thanks to its closure to post-processing.

Lemma 2 (Post-processing). *If $\mathcal{M}$ obeys (ε, δ)-DP, then for any function f, $f \circ \mathcal{M}$ is also (ε, δ)-DP.*

One notable properties of DP is that it automatically protects the privacy of groups of multiple units.

Lemma 3 (Group privacy). *An (ε, δ)-DP mechanism $\mathcal{M}$ on individuals is $(k\varepsilon, \frac{e^{k\varepsilon}-1}{e^\varepsilon - 1}\delta)$-DP on groups of size k for all integer $k \geq 1$.*

Lemma 4 (Analytical Gaussian mechanism (Balle & Wang, 2018)). *For a numeric query $f : \mathcal{X}^n \to \mathbb{R}^d$ over a dataset $\mathcal{D}$, the randomized algorithm that outputs $f(\mathcal{D}) + Z$ where $Z \sim \mathcal{N}(0, \sigma^2 I_d)$ satisfies $(\varepsilon, \delta(\varepsilon))$-DP for all $\varepsilon \geq 0$ and $\delta(\varepsilon) = \Phi(\frac{\Delta}{2\sigma} - \frac{\varepsilon\sigma}{\Delta}) - e^\varepsilon \Phi(-\frac{\Delta}{2\sigma} - \frac{\varepsilon\sigma}{\Delta})$. where $\Delta := \Delta_2^{(f)} = \max_{\mathcal{D}\sim\mathcal{D}'} \|f(\mathcal{D}) - f(\mathcal{D}')\|_2$ is the global L2 sensitivity of f and Φ is the CDF function of $\mathcal{N}(0,1)$.*

The above is (ε, δ)-DP of a single Gaussian mechanism, and the following lemma shows that we can use the same result for an adaptive composition of a sequence of Gaussian mechanisms.

Lemma 5 (Composition of Gaussian mechanisms (Dong et al., 2019)). *The adaptive composition of a sequence of Gaussian mechanism with noise level $\sigma_1, \sigma_2, \ldots$ and global L2 sensitivity $\Delta_1, \Delta_2, \ldots$ satisfies $(\varepsilon, \delta(\varepsilon))$-DP for all $\varepsilon \geq 0$ and $\delta(\varepsilon) \leq \delta_{\mathcal{M}}(\varepsilon)$ where $\mathcal{M}$ is a Gaussian mechanism with noise multiplier $\sigma/\Delta = \left(\sum_i (\Delta_i/\sigma_i)^2\right)^{-1/2}$.*

Specifically, the adaptive composition of k identical Gaussian mechanism with noise multiplier σ satisfies the same privacy guarantee of that of a single Gaussian mechanism with a noise multiplier $\sigma/\sqrt{k}$. By fixing k and ε, we can calibrate the noise by choosing an appropriate σ in our algorithm.

[2] Mathematically, the input of the $g(\cdot)$ may be negative and we re-normalize it to 0. Practically, we observed being negative is extremely rare since the M is very big (2000) and the first term dominates the input of $g(\cdot)$

5.2 Differential Privacy on Sentence Level

Recall that we partition the private dataset to M disjoint subsets, and train a teacher model on each subset. Let vector $x_i \in \mathbb{R}^{|\mathcal{V}|}$ denote the probability distribution predicted by the i-th teacher model for a specific word, where $|\mathcal{V}|$ is the vocabulary size. The function $f(\mathcal{D}) := \sum_{i=1}^{M} x_i$ is the sum of the probability distribution predicted by all teachers. Since the partition is disjoint and the dataset has no repeating sample, changing one data point (a sentence) will only affect one teacher model. For neighboring datasets $\mathcal{D}$, $\mathcal{D}'$, let j denote the index of different teacher models, i.e., $x_j \in \mathcal{D}$ and $x'_j \in \mathcal{D}'$ are different. Then, the sensitivity Δ in Lemma 4 & 5 is (Detailed deduction in Appendix B),

$$\Delta := \Delta_2^{(f)} = \|f(\mathcal{D}) - f(\mathcal{D}')\|_2 \leq \|x_j - x'_j\|_2 \leq \sqrt{2},$$

Then, adding noise calibrated in Lemma 5 to each coordinate is sufficient to preserve (ε, $\delta(\varepsilon)$)-DP for $f(\mathcal{D})$. Finally, as we extract top-k coordinates of $f(\mathcal{D})$ (Sec. 4.3), the privacy guarantee also holds according to the post-processing property. Intuitively, the information about whether a sample (a sentence) occurs in the training set is protected and the protection satisfies (ε, $\delta(\varepsilon)$)-DP.

5.3 Differential Privacy on User level and their Secret N-grams

The above analysis focuses on DP of sentences level, but the privacy guarantee also applies to individual users (who contributed many sentences) as well as preventing *secret n-grams* (words or phrases), such as SSN number, phone number, and addresses from being memorized (or generated *as is*) by the model. Recall that the teachers' training data are partitioned by users, adding or removing a user (and all her sentences) will only affect one teacher, thus the same privacy guarantee we derive for sentences applies to the user-level too.

As for a secret n-gram t that occurs s_t times ($s_t \geq 1$) in the private data, we may obtain DP guarantee for each t separately[3]. Our distillation approach enjoys stronger guarantee than naively applying the group privacy lemma. The latter would suggest s_t times higher privacy loss, while our approach depends only on the total number of teachers affected, which is bounded by $\tilde{s}_t := \min\{s_t, \#\text{ of users who know } t\}$. $\tilde{s}_t$ is often 2 or 3 (e.g., husband and wife, parents and child), even if s_t is large. Clearly, adding or removing n-gram t will result in a sensitivity $\sqrt{2}\tilde{s}_t$, and the exact $(\varepsilon, \delta(\varepsilon, \tilde{s}_t))$-DP for n-grams can be obtained according to Lemma 4 & 5, where $\delta(\varepsilon, \tilde{s}_t) = \Phi(\frac{\tilde{s}_t}{\sqrt{2}\sigma} - \frac{\varepsilon\sigma}{\sqrt{2}\tilde{s}_t}) - e^{\varepsilon}\Phi(-\frac{\tilde{s}_t}{\sqrt{2}\sigma} - \frac{\varepsilon\sigma}{\sqrt{2}\tilde{s}_t})$. Intuitively, the information about whether an n-gram t (a word or a phrase) occurs in the private set is protected with $(s_t\varepsilon, \delta(\varepsilon, s_t))$-DP.

How does DP prevent memorization? Lastly, we remark that the protection against unintended memorization of a model follows from the definition of DP. Consider the attack by (Carlini et al., 2019), which uses a language model to predict the second part of a secret n-gram using a prefix. By the closure to post-processing, the prediction also satisfies DP. Take $\mathcal{S}$ to be the undesirable event that the model correctly generates the rest of the secret n-gram t. The definition of DP implies that the probability of $\mathcal{S}$ to happen when t is part of the training data is at most e^{ϵ} larger than the probability of an alternative model trained without t in the data. The chances for the latter model to generate a long sequence of t is astronomically small, thus DP implies that the probability of $\mathcal{S}$ under the former model needs to be just as small.

6 Experiments

6.1 Experimental Setting

We evaluate our model on two datasets. AirDialog dataset (Wei et al., 2018) consists of 1M utterances from custom service dialog about flight booking; Europarl_v6 dataset [4] consists of 2M English sentences collected from European Parliament. We use the pre-trained GPT-2 (Radford et al., 2018) model for all baselines, our teachers, and the student. Before student's training, we conduct additional fine-tuning on the public data $\tilde{\mathcal{D}}^{\text{pub}}$ via NLL loss to provide initialization for student's training. We

[3] A formal definition of this is called personalized differential privacy, first seen in (Ghosh & Roth, 2011)

[4] www.statmt.org/europarl

evaluate the quality of generated texts with *PPL* (Perplexity, the lower the better) and *B-n* (Bleu-n, the higher the better) (Papineni et al., 2002) and evaluate the strength of privacy protection with *P-n*, which indicates how many generated n-grams can be found in the private set (lower score indicates a better protection). (See details about datasets, settings, and metrics in Appendix C to E).

6.2 Overall Performance

		AirDialog							Europarl_v6						
		PPL	B-1	B-2	B-3	B-4	P-3	P-4	PPL	B-1	B-2	B-3	B-4	P-3	P-4
No Protect	Pri-GPT	3.88	42.49	28.26	21.51	17.16	0.94	0.91	23.25	12.97	4.55	1.77	0.86	0.85	0.65
Public Data Only	Pub-GPT	63.16	5.85	1.18	0.31	0.10	0.09	0.03	57.40	12.42	3.61	1.02	0.35	0.51	0.29
	Pub-GPT+$\tilde{\mathcal{D}}^{pub}$	19.39	7.58	2.11	0.71	0.25	0.14	0.06	45.40	13.28	4.31	1.38	0.52	0.62	0.38
DP Algorithms ($\varepsilon = 2$)	DP-SGD	20.39	7.30	2.36	0.95	0.42	**0.32**	0.18	40.69	12.37	4.04	1.22	0.43	0.70	0.47
	DP-SGD+$\tilde{\mathcal{D}}^{pub}$	17.65	7.90	2.69	1.14	0.56	0.33	0.19	40.46	12.26	3.99	1.20	0.42	**0.69**	0.46
	SeqPATE (Ours)	**13.67**	**11.56**	**4.35**	**1.82**	**0.78**	**0.32**	**0.17**	**37.80**	**13.64**	**4.40**	**1.43**	**0.55**	**0.69**	**0.45**

Table 1: The overall performance on the two datasets. All DP algorithms satisfy $(2, 10^{-9})$-DP.

Table 1 shows the performance of the two datasets. Pri-GPT is the GPT model trained on the private set $\mathcal{D}^{pri}$ without privacy protection, acting as an upper bound on the task performance. The high *P-n* scores show most generated n-grams may come from $\mathcal{D}^{pri}$, indicating a serious issue of privacy leaks in current text generation models. Pub-GPT uses the pre-trained GPT model to our setting without fine-tuning. Pub-GPT+$\tilde{\mathcal{D}}^{pub}$ is further fune-tuned on the pseudo data and outperforms Pub-GPT, indicating the pseudo dataset helps in this task. The two baselines do not involve any information from the private data, so the *P-n* is the upper bound and the performance is the worst (note that our goal is to do well on $\mathcal{D}^{pri}$ in inference).

DP learning algorithms are our main baselines. DP-SGD (Noisy-SGD) (Abadi et al., 2016; Kerrigan et al., 2020) is trained on $\mathcal{D}^{pri}$ and DP-SGD+$\tilde{\mathcal{D}}^{pub}$ further fine-tunes the DP-SGD model on the pseudo dataset $\tilde{\mathcal{D}}^{pub}$. The small gap between the two methods demonstrates DP-SGD cannot utilized the public data (unlabeled data) so well. Our method, SeqPATE, significantly outperforms the DP baselines (+39.3% and +28.0% in Bleu4) while ensuring the same strength of privacy protection in terms of the *P-n* and ε. Note that, we conduct the experiments based on the sentence level privacy of $\varepsilon = 2$ mentioned in Sec. 5.2, and our trained model also protects users' *secret n-grams* t mentioned in Sec. 5.3 with DP but the strength of the protection is reduced linearly (in terms of ε) as the value $\tilde{s}_t$ defined in Sec. 5.3 goes up. In short, the model satisfies $(\varepsilon, \delta(\varepsilon, \tilde{s}_t))$-DP for the n-gram t ($\varepsilon = 2$). SeqPATE does better in empirical metrics on privacy compared to DP-SGD even if $\varepsilon = 2$ is the same theoretically; this provides empirical evidence of our discussion in Sec. 5.3 on providing stronger guarantees for n-grams that appear more than once.

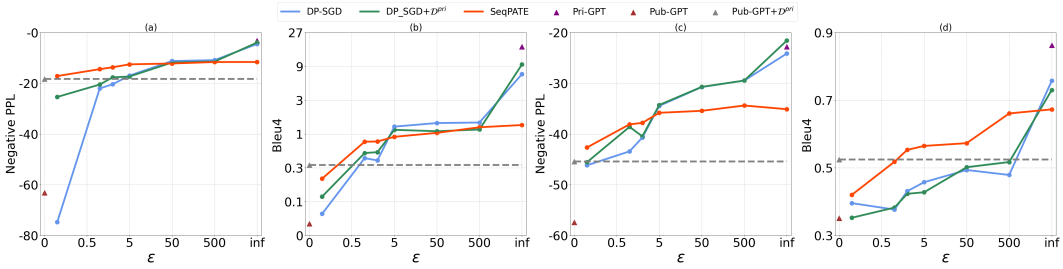

Figure 2: The private-utilty tradeoff reflected in the Bleu-4 and negative PPL on different ε.

The curves in Fig 2 show the private-utility tradeoff of all DP algorithms in AirDialog (subfigure a & b) and Europarl_v6 (subfigure c & d) dataset [5]. DP with $\varepsilon \in (0.1, 5)$ is considered to provide meaningful protection, and we observe that SeqPATE outperforms DP-SGD in this range. SeqPATE does not work better than DP-SGD when $\varepsilon \geq 5$. The reason is DP-SGD approaches Pri-GPT as ε approaches infinity (i.e. the noise approaches 0). However, SeqPATE with an infinite ε is still weaker than Pri-GPT because each teacher in SeqPATE is trained on a small partition of the full data. The grey

[5]For non-DP methods, we consider ε to be zero for baselines that do not use sensitive data and ε to be infinity for baseline without privacy protection.

lines show the performance of Pub-GPT+$\tilde{\mathcal{D}}^{pri}$ and the area above the line indicates the DP methods outperform Pub-GPT+$\tilde{\mathcal{D}}^{pri}$, which making use of private data with DP algorithm outperforms the popular deep learning algorithm trained on public data only. It means the DP algorithm is practical for some real-world application with mass of private data but have not used it due to the privacy concern, e.g. dialogue between the customer service staff and users. Our method always retches that area when $\varepsilon \geq 1$ but DPSGD hardly exceeds the grey line, the very trivial baseline, with $\varepsilon \leq 5$, it indicates DP-SGD is a little bit far from the practical use.

	AirDialog			Europarl_v6		
	PPL	B-4	P-4	PPL	B-4	P-4
SeqPATE	13.67	0.78	0.17	37.80	0.55	0.45
−Merge P	14.72	0.69	0.16	45.37	0.54	0.40
−KL	14.74	0.69	0.16	45.53	0.55	0.39
−NLL	13.60	0.74	0.18	38.09	0.54	0.45
−Effi KD	14.35	0.58	0.19	37.10	0.53	0.46
−Gaussian	13.69	0.60	0.16	38.24	0.50	0.43
−All	15.73	0.60	0.16	45.36	0.52	0.40

Table 2: Ablation studies.

	AirDialog			Europarl_v6		
	PPL	B-4	P-4	PPL	B-4	P-4
top-p	13.67	0.78	0.17	37.80	0.55	0.45
top-k=1	18.37	0.25	0.09	46.25	0.53	0.45
top-k=10	14.57	0.79	0.21	45.90	0.55	0.40
top-k=50	13.50	0.70	0.18	37.91	0.53	0.40
top-k=100	13.96	0.76	0.19	38.48	0.57	0.50
top-k=200	14.65	0.72	0.17	39.55	0.53	0.46

Table 3: Analyses about top-k and top-p strategies.

6.3 Ablation Studies and Further Analyses

In the ablation studies (Table 2), SeqPATE mainly outperforms its variants shown in row 2 to 7 verifying the effectiveness of our strategies, where $-X$ represents SeqPAET's variant without the strategy X. −Merge P is the variant aggregating the teachers by voting instead of merging the probabilities. Its bad performance shows the voting is not suitable for text generation with a large output space where the voting leads to low agreement rates. −KL means the student learns from the aggregation of teachers' top-1 predictions via NLL loss instead of from KL loss. The sharp performance drop on −KL indicates the importance of KL loss. NLL loss makes a little contribution to SeqPATE as the performance of −NLL slightly decreases. The reason is we have pre-trained on student's dataset via NLL loss before student's training. The promotion caused by efficient knowledge distillation (Effi KD) on AirDialog is larger than that on Europarl_v6, which shows the "clever" student (e.g. models on AirDialog with low PPL and high Bleu4) benefits more from this strategy since it can sharply save the privacy cost and spend the cost when the student needs.. −Gaussian means we use Laplace mechanism as PATE (Papernot et al., 2017) instead of Gaussian mechanism, which shows Gaussian mechanism works better. −All indicates discarding all above strategies, which is similar to but not equivalent to the original PATE (the difference is PATE needs to roll out all teachers as mentioned in Sec. 4.1, which makes PATE cannot work on text generation). The poor performance of −All also verifies original PATE are not adaptive to text generation. We note that the differences on Bleu4 of Europarl_v6 are small since the lower bound performance, row 3 of Table 1, is close to our full model.

Table 3 shows the performance of the top-p and top-k selection strategies (Sec. 4.3). As shown in row 1, our full model employs the top-p selection (the threshold $\mu = 0.95$) surpasses most variants with manually chosen k (row 2 to 6). Selection with too small k ($k = 1$ & $k = 10$) implies discarding too much useful information from the supervision ($k = 1$ is difference from −KL in Table 2, which uses Top-1 of teachers' results). Selection with too large k results in involving more useless noise: the candidates with very small probabilities should be rarely sampled during generation but random noise may increase their probabilities, so models may generate those words mislead by the noise. Supervisions on top-k candidates with $k = 50$ and $k = 100$ obtains relatively good performances.

Table 4 & 5 in Appendix shows more teachers lead to better results since the noise assigned on each teacher drops linearly as the teacher number goes up (as Eq. 2). We choose $\varepsilon = 2$ for all results in Table 2 to 5 and the P-n for all results in a dataset are roughly in a same level, except some methods (e.g. top-k=1 in Table 3) perform very bad in all metrics. It verifies SeqPATE has a stable strength of privacy protection if we fix ε (no matter which variant and hyper-parameters do we use).

7 Related Work

Privacy protection is becoming crucial in deep learning models. Research in this area can be categorized into three directions (Liu et al., 2021). Encryption approaches are to add encryption on

training data (Brickell et al., 2007; Bost et al., 2015) or machine learning (ML) models (Aono et al., 2017). Aggregation approaches generally come along with distributed training where many parties join the training of an ML model with the purpose of maintaining the privacy of the dataset from each party (Shokri & Shmatikov, 2015; Konečnỳ et al., 2016). Obfuscation approaches reduce the precision of the data or model by importing noise into the original input (Zhang et al., 2018), model parameters (Rubinstein et al., 2012), or model gradients (Abadi et al., 2016; McMahan et al., 2018).

As a sub-topic of the obfuscation approach, differential privacy (DP) (Dwork et al., 2014) formally defines and quantifies privacy. ML models with DP guarantee (Wang et al., 2015; Park et al., 2016; Ziller et al., 2021) prevents the existence of individual training examples from being detected (Carlini et al., 2019). Some researchers protect the privacy of empirical risk minimization (ERM) classifier (Chaudhuri et al., 2011) and SVM (Rubinstein et al., 2012) with DP. Following (Song et al., 2013), DP-SGD (Abadi et al., 2016) achieves DP on deep learning models by applying the noise to the clipped gradients. (Bu et al., 2020). Pichapati et al. (2019) adaptively clip the gradient on DP-SGD. PATE (Papernot et al., 2017) transfers the knowledge from teacher models trained on private data with injected noise to a student model. KNN-PATE (Zhu et al., 2020) refines PATE by accessing only the k-nearest neighbors from the private set instead of the whole private set. The above approaches are not customized for text generation models.

One direction of privacy protection in text generation is to protect author-level (user-level) information. The methods prevent the attackers from inferring the attribute (e.g. gender, age) of authors (Li et al., 2018) and the relation between sensitive information and authors (Mireshghallah et al., 2021). Shokri et al. (2017) and Song & Shmatikov (2019) infer the membership (whether a given user's data is used to train a model) given a black-box model. Another direction is to prevent attackers extract sensitive information in the training set by analyzing the generated outputs (Nakamura et al., 2020; Kerrigan et al., 2020), which is an urgent need since Carlini et al. (2020) achieve the extraction. To tackle this issue, regularization, including dropout (Srivastava et al., 2014) and quantization (Hubara et al., 2017) restricts the model capacity to avoid models memorizing too much original text from the privacy training set (Carlini et al., 2019). Anonymization methods (Maeda et al., 2016; Suzuki et al., 2017) detects sensitive spans in training sets and replace the spans with non-sensitive texts. Our application falls into the second direction. The above methods are on non-DP algorithms, which makes sense intuitively but do not provides quantifiable and provable guarantees for privacy protection.

Some researchers apply DP to text generation. For user-level privacy, ER-AE (Bo et al., 2021) augments the semantic information in the generated text to hide authors' writing styles for authorship anonymization. McMahan et al. (2018) propose a recurrent language model with a DP guarantee against the identification of the users. As far as we know, Kerrigan et al. (2020), adapt DP-SGD to text generation, is the only one work with DP guarantees matching our setting, which requires models to prevent the (not the user-level) sensitive training data being extracted from text generation models.

8 Conclusion

In this paper, we propose, SeqPATE, a framework to protect the privacy of the training data for text generation model with DP guarantees. SeqPATE achieves a good privacy-performance tradeoff by utilizing both private and public data. As an extension of PATE, SeqPATE can handle the sequential generation paradigm with large output space on each step and thus is adaptive for text generation models. We avoid rolling out the teachers by providing pseudo samples for teacher inference and student training and aggregate teachers by merging probabilities instead of voting. We further reduce the output space by top-k and top-p selection and limit the privacy loss via an efficient knowledge distillation. SeqPATE improves the baselines a lot and makes the private data useful to text generation with a meaningful strength of privacy protection. In the future, we will apply SeqPATE to some real-world applications, e.g. dialog systems and writing assistant.

9 Reproducibility Statement

We've submitted our source code as the supplementary material. We introduce the two datasets we used in Appendix C, where we introduce the details about the dataset and also append the link or citation of the dataset. For all our experiments, we adopt *autodp* (Wang et al., 2019) — an open-source library that implements the analytical Gaussian mechanism for privacy accounting and calibration.

The experimental setting and hyper-parameters can be found in Appendix D. Since we propose a new metric in our experiments, we introduce the new metric with detailed equations in Appendix E.

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A Algorithm for the Training of SeqPATE

The pseudo codes of SeqPATE's training is at Algorithm 1.

Algorithm 1 Training of SeqPATE (Full Version)

Require: $\mathcal{D}^{pri}, \mathcal{D}^{pub}$: datasets, GPT: a pre-trained GPT model.
$\{f_\phi^m\}_{m=1}^M$: M teacher models, f_θ: a student model, f_Θ: a student model for self pre-training,
$\{\phi^m\}_{m=1}^M \leftarrow GPT, \Theta \leftarrow GPT$ # Initialize teachers and the student for self pre-training.
GPT generates a pseudo dataset $\tilde{\mathcal{D}}^{pub}$ based on $\mathcal{D}^{pub}$.
$\{\mathcal{D}_m^{pri}\}_{m=1}^M \leftarrow \mathcal{D}^{pri}$ # Divide private dataset into m subsets.
for all m in M **do**
  Train teacher f_ϕ^m on $\mathcal{D}_m^{pri}$
end for
Teachers $\{\phi^m\}_{m=1}^M$ conduct inference on $\tilde{\mathcal{D}}^{pub}$ to get $p_\phi^m(w_i \mid w_{1:i-1})$ required in Eq. 2 for all samples.

Train f_Θ on $\tilde{\mathcal{D}}^{pub}$ # self pre-training for the student.
$\theta \leftarrow \Theta$ # Initialize the student model.

while not converge **do**
  for all batch of samples $\{S\}^{\text{batchsize}}$ in $\tilde{\mathcal{D}}^{pub}$ **do**
    Student f_θ conducts feed-forward.
    for all sample S in the batch $\{S\}^{\text{batchsize}}$ **do**
      for all token w_i in sample S **do**
        $p_\phi(w_i \mid w_{1:i-1}) = \frac{1}{M}\sum_{m=1}^M p_\phi^m(w_i \mid w_{1:i-1})$ # Aggregate teachers' outputs
        Select only (adaptive) top K predicted tokens as student's output.
        Obtain $\mathcal{L}_i^{\text{KL}}$ and $\mathcal{L}_i^{\text{NLL}}$ as Eq. 2. # Noise is added into $\mathcal{L}_i^{\text{KL}}$ to protect the privacy.
        Get $\mathcal{L}$ by combining $\mathcal{L}_i^{\text{KL}}$ and $\mathcal{L}_i^{\text{NLL}}$ # Efficient knowledge distillation.
      end for
    end for
    Update ϕ respect to $\mathcal{L}$.
  end for
end while

B Detailed Deduction of the Sensitivity in Sentence Level DP

We obtain Eq. 3 from Sec. 5.2.

$$\Delta_2^{(f)} = \|f(\mathcal{D}) - f(\mathcal{D}')\|_2 \leq \|x_j - x_j'\|_2 = \left(\sum_{v=1}^{|\mathcal{V}|}(x_{jv} - x_{jv}')^2\right)^{1/2} \tag{3}$$

We know $(x_{jv} - x'_{jv})^2$ is smaller than $|x_{jv} - x'_{jv}|$ since $|x_{jv} - x'_{jv}| \in (0, 1)$ for each v. Hence, we have,

$$\left(\sum_{v=1}^{|\mathcal{V}|}(x_{jv} - x'_{jv})^2\right)^{1/2} \leq \left(\sum_{v=1}^{|\mathcal{V}|}|x_{jv} - x'_{jv}|\right)^{1/2} \leq \left(\sum_{v=1}^{|\mathcal{V}|}|x_{jv} + x'_{jv}|\right)^{1/2}$$

We know $|a + b| = a + b$ when $a, b \in (0, 1)$, so we have,

$$\left(\sum_{v=1}^{|\mathcal{V}|}|x_{jv} + x'_{jv}|\right)^{1/2} = \left(\sum_{v=1}^{|\mathcal{V}|}x_{jv} + \sum_{v=1}^{|\mathcal{V}|}x'_{jv}\right)^{1/2} = \Big(1 + 1\Big)^{1/2} \leq \sqrt{2},$$

In summary, the upper bound of the sensitivity is,

$$\Delta_2^{(f)} = \|f(\mathcal{D}) - f(\mathcal{D}')\|_2 \leq \|x_j - x'_j\|_2 = \sqrt{2},$$

C Details about the Datasets

The AirDialog dataset (Wei et al., 2018) consists of 402,038 dialogues and each dialogue consists of more than two utterances. We treat each utterance as a sentence in our sentence completion task. We obtain Europarl_v6 dataset from a machine translation benchmark [6] and we only use the monolingual English dataset with 2,015,440 raw sentences.

For the above datasets, we filter the short sentence with less than eight tokens. Then, the first four tokens act as the prefix, and the rest of the tokens acts as the output (ground-truth). We split each datasets into a private set $\mathcal{D}^{\text{pri}}$ and a public set $\mathcal{D}^{\text{pub}}$. For the AirDialog dataset, the private set contains 0.95M/5K/50K samples for training/validation/testing and the public set contains 40K/5K for training/validation. For the Europarl_v6 dataset, the private set contains 1.72M/10K/50K samples for training/validation/testing and the public set contains 40K/5K for training/validation. The vocabulary size for the two datasets is set to 50K and we replace the tokens out of the vocabulary with a special token.

D Details about the Experimental Setting

All the comparing algorithms use the same base model, the GPT-small, which has 12 stacked layers as mentioned in the original paper (Radford et al., 2018). All the comparing methods are initialized by the pre-trained GPT model [7] before training. We used the Adam optimization scheme (Kingma & Ba, 2015) and we adjust the initial learning rate for all the comparing methods with a range of 0.01 $\sim$ 0.00001. We set the batch size as 32 for all the comparing baselines. We truncate the sentences with the maximal sentence length of 40. In the top-p strategy, the threshold μ is 0.95. The factor λ balancing the KL loss and NLL loss mentioned in Eq. 2 and Eq. **??** is 20. The default number of teacher models is 2,000.

E Details about the Evaluation Metrics

To measure the quality of generation, PPL is a widely used metrics in text generation, especially language modeling, which measures the perplexity of generating the next token. B-n (Bleu-n) (Papineni et al., 2002) measures the degree of the n-gram matching between the generated results and the ground-truth text.

To measures the strength of privacy protection, we note that factor ε in DP indicates the strength of privacy protection according to the DP theorem. To give an intuitive understanding of the protection on text generation scenario, we propose a new metric, P-N, indicating how many generated n-grams can be found in the private set $\mathcal{D}^{pri}$. We define $N_{\mathcal{Y}}$ as the set of unique n-grams in a generated

[6] The description is in www.statmt.org/europarl; the data comes from statmt.org/wmt11/training-monolingual.tgz

[7] link of GPT-2

	AirDialog						
	PPL	Blue1	Blue2	Blue3	Blue4	Pri3	Pri4
teacher=1	19.66	8.52	2.48	0.84	0.30	0.10	0.04
teacher=10	18.29	8.27	2.38	0.81	0.29	0.14	0.06
teacher=200	16.86	9.01	2.70	0.96	0.33	0.16	0.07
teacher=2000	13.67	11.56	4.35	1.82	0.78	0.32	0.17

Table 4: Analysis about SeqPATE's performance with different teacher number in on AirDialog dataset.

	Europarl_v6						
	PPL	Blue1	Blue2	Blue3	Blue4	Pri3	Pri4
teacher=1	44.64	12.33	3.64	1.11	0.40	0.56	0.32
teacher=10	44.22	12.67	3.73	1.16	0.43	0.58	0.33
teacher=200	43.55	13.10	4.06	1.29	0.49	0.60	0.36
teacher=2000	37.80	13.64	4.40	1.43	0.55	0.69	0.45

Table 5: Analysis about SeqPATE's performance with different teacher number in on Europarl_v6 dataset.

sentence $\mathcal{Y}$ and define $N_{\mathcal{D}^{pri}}$ as the set of unique n-grams in the private data $\mathcal{D}^{pri}$. As shown in Eq. 4, P-N is the ratio of the n-grams that occurs in the two sets over n-grams occurs only in $N_{\mathcal{Y}}$ weighted by *idf*, where the *idf* is the inverse frequency of this n-gram indicating the sensitivity of this n-gram (Rare n-grams are likely to be sensitive information, such as SSN number and address). P-N ranges from 0 to 1 and lower P-N indicates the more strong privacy protection.

For the choice of value N, we note that P-N with a very small value of N can hardly reflect the privacy loss since the uni-grams and bi-grams are very easy to be generated even if the model did not meet it from the private dataset $\mathcal{D}^{pri}$. For example, the N=1 does not make sense because it only reflects the vocabulary overlapping between two datasets. Thus, we choose 3 and 4 as the value of N.

$$
\begin{aligned}
N_{\mathcal{Y}} &= \{\text{n-gram} \in \mathcal{Y}\} \\
N_{\mathcal{D}^{pri}} &= \{\text{n-gram} \in \mathcal{D}^{pri}\} \\
\text{P-N} &= \frac{\sum_{n \in N_{\mathcal{Y}} \cap N_{\mathcal{D}^{pri}}} idf_n}{\sum_{m \in N_{\mathcal{Y}}} idf_m}
\end{aligned} \tag{4}
$$

F Analyses about the Number of Teacher Models

Table 4 and Table 5 shows the analysis about SeqPATE's performance with different teacher number on our two datasets.

G Ethical Considerations

This paper aims to protect privacy in training the text generation models, so our paper is designed for tackling some ethical issues about privacy concerns in some existing text generation models (e.g. GPT-2). In terms of motivation and the algorithm, our paper would not cause ethical issues.

However, we should also consider some special situations where someone intentionally applies our model to illegal applications. Someone may employ text generation models to create fake news or misinformation and protect himself or herself from being detected with our model. We know large ε (e.g. $\varepsilon = 500$) cannot provide a meaningful protection. We should carefully use our model and cannot assume the model is perfect no matter what parameters do we use. One possible unethical application is to collect the data from users who believe our model can fully protect the data they contribute their private data regardless of the strength of privacy protection (in terms of the value of ε).

Hence, we kindly remind the researchers who will use this model to pay more attention on the strength of the privacy protection. Further, we should prevent some researchers to collect the data from users who do not have an all-sidely understanding of our algorithm, and the data collectors should make it clear that the potential risk in releasing data to our model. In the future, we will add some constraints to our model so that our model cannot generate text for illegal application (e.g. fake news).