Scalable Differential Privacy with Certified Robustness in Adversarial Learning

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Abstract

In this paper, we aim to develop a scalable algorithm to preserve differential privacy (**DP**) in adversarial learning for deep neural networks (**DNNs**), with certified robustness to adversarial examples. By leveraging the sequential composition theory in DP, we randomize both input and latent spaces to strengthen our certified robustness bounds. To address the trade-off among model utility, privacy loss, and robustness, we design an original adversarial objective function, based on the post-processing property in DP, to tighten the sensitivity of our model. A new *stochastic batch training* is proposed to apply our mechanism on large DNNs and datasets, by bypassing the vanilla iterative batch-by-batch training in DP DNNs. An end-to-end theoretical analysis and evaluations show that our mechanism notably improves the robustness and scalability of DP DNNs.

1. Introduction

The pervasiveness of machine learning exposes new vulnerabilities in software systems, in which deployed machine learning models can be used (a) to reveal sensitive information in private training data (Fredrikson et al., 2015), and/or (b) to make the models misclassify, such as *adversarial examples* (Carlini & Wagner, 2017). Efforts to prevent such attacks typically seek one of three solutions: **(1)** Models which preserve differential privacy (**DP**) (Dwork et al., 2006), a rigorous formulation of privacy in probabilistic terms; **(2)** Adversarial training algorithms, which augment training data to consist of benign examples and adversarial examples crafted during the training process, thereby empirically increasing the classification accuracy given adversarial examples (Kardan & Stanley, 2017; Matyasko & Chau, 2017); and **(3)** Certified robustness, in which the model classification given adversarial examples is theoretically guaranteed to be consistent, i.e., a small perturbation in the input does not change the predicted label (Cisse et al., 2017; Kolter & Wong, 2017; Salman et al., 2019).

On the one hand, *private models*, trained with existing privacy-preserving mechanisms (Abadi et al., 2016; Shokri & Shmatikov, 2015; Phan et al., 2016; 2017a;b; Yu et al., 2019; Lee & Kifer, 2018), are unshielded under adversarial examples. On the other hand, *robust models*, trained with adversarial learning (with or without certified robustness to adversarial examples), do not offer privacy protections to the training data (Song et al., 2019). That one-sided approach poses serious risks to machine learning-based systems; since adversaries can attack a deployed model by using both privacy inference attacks and adversarial examples. To be safe, a model must be *i) private to protect the training data*, **and** *ii) robust to adversarial examples*. Unfortunately, there still lacks of study on how to develop such a model, which thus remains a largely open challenge (Phan et al., 2019).

Simply combining existing DP-preserving mechanisms and certified robustness conditions (Cisse et al., 2017; Kolter & Wong, 2017; Raghunathan et al., 2018) cannot solve the problem, for many reasons. **(a)** Existing sensitivity bounds (Phan et al., 2016; 2017a;b) and designs (Yu et al., 2019; Lee & Kifer, 2018; Phan et al., 2019; Wu et al., 2019; Xu et al., 2020) have not been developed to protect the training data in adversarial training. It is obvious that using adversarial examples crafted from the private training data to train our models introduces a previously unknown privacy risk, disclosing the participation of the benign examples (Song et al., 2019). **(b)** There is an unrevealed interplay among DP preservation, adversarial learning, and robustness bounds. **(c)** Existing algorithms cannot be readily applied to address the trade-off among model utility, privacy loss, and robustness. **(d)** It is challenging in applying existing algorithms to train large DNNs given large data (i.e., scalability); since, they employ the vanilla *iterative batch-by-batch training*, in which only a single batch of data instances can be used at each training step, such that the *privacy loss* can be es-

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timated (Lee & Kifer, 2018; Phan et al., 2019; Yu et al., 2019; Wu et al., 2019; Xu et al., 2020). That prevents us from applying scalable methods, e.g., *distributed adversarial training* (Goyal et al., 2017), to achieve the same level of DP on large DNNs and datasets. Therefore, bounding the robustness of a model (which both protects the privacy and is robust against adversarial examples) *at scale* is nontrivial.

Contributions. Motivated by this open problem, we develop a novel *stochastic batch (**StoBatch**) mechanism* to: **1)** preserve DP of the training data, **2)** be provably and practically robust to adversarial examples, **3)** retain high model utility, and **4)** be scalable to large DNNs and datasets.

• In StoBatch, privacy-preserving noise is injected into inputs and hidden layers to achieve DP in learning private model parameters (**Theorem 1**). Then, we incorporate ensemble adversarial learning into our mechanism to improve the decision boundary under DP protections, by introducing a concept of *DP adversarial examples* crafted using benign examples in the private training data (**Eq. 8**). To address the trade-off between model utility and privacy loss, we propose a new DP adversarial objective function to tighten the model's global sensitivity (**Theorem 3**); thus, we reduce the amount of noise injected into our function, compared with existing works (Phan et al., 2016; 2017a;b). An end-to-end privacy analysis shows that, by slitting the private training data into *disjoint* and *fixed* batches across epochs, the privacy budget in our StoBatch is not accumulated across *gradient descent*-based training steps (**Theorems 3, 4**).

• After preserving DP in learning model parameters, we establish a new connection between DP preservation in adversarial learning and certified robustness. Noise injected into different layers is considered as a sequence of randomizing mechanisms, providing different levels of robustness. By leveraging the *sequential composition theory* in DP (Dwork & Roth, 2014), we derive a generalized robustness bound, which is a composition of these levels of robustness in both input and latent spaces (**Theorem 5** and **Corollary 1**), compared with only in the input space (Salman et al., 2019) or only in the latent space (Lecuyer et al., 2018).

• To bypass the iterative batch-by-batch training, we develop a *stochastic batch training*. In our algorithm, disjoint and fixed batches are distributed to local trainers, each of which learns DP parameters given its local data batches. A synchronous scheme can be leveraged to aggregate gradients observed from local trainers; thus enabling us to efficiently compute adversarial examples from multiple data batches at each iteration. This allows us to scale our mechanism to large DNNs and datasets, under the same DP guarantee. Rigorous experiments conducted on MNIST, CIFAR-10 (Lecun et al., 1998; Krizhevsky & Hinton, 2009), and (TinyImageNet) datasets show that our mechanism notably enhances the robustness and scalability of DP DNNs.

2. Background

In this section, we revisit DP, adversarial learning, and certified robustness. Let D be a database that contains N tuples, each of which contains data $x \in [-1,1]^d$ and a *ground-truth label* $y \in \mathbb{Z}_K$ (one-hot vector), with K possible categorical outcomes $y = \{y_1, \ldots, y_K\}$. A single *true class label* $y_x \in y$ given $x \in D$ is assigned to only one of the K categories. On input x and parameters θ, a model outputs class scores $f : \mathbb{R}^d \rightarrow \mathbb{R}^K$ that maps x to a vector of scores $f(x) = \{f_1(x), \ldots, f_K(x)\}$ s.t. $\forall k \in [1,K] : f_k(x) \in [0,1]$ and $\sum_{k=1}^{K} f_k(x) = 1$. The class with the highest score value is selected as the *predicted label* for x, denoted as $y(x) = \max_{k \in K} f_k(x)$. A loss function $L(f(x), y)$ presents the penalty for mismatching between the predicted values $f(x)$ and original values y. The notations and terminologies used in this paper are summarized in Table 1 (**Appendix A**). Let us briefly revisit DP DNNs, starting with the definition of DP.

Definition 1 *(ϵ, δ)-DP (Dwork et al., 2006). A randomized algorithm A fulfills (ϵ, δ)-DP, if for any two databases D and D' differing at most one tuple, and for all $O \subseteq Range(A)$, we have:*

$$Pr[A(D) = O] \leq e^{\epsilon} Pr[A(D') = O] + \delta \qquad (1)$$

ϵ controls the amount by which the distributions induced by D and D' may differ, δ is a broken probability.

DP also applies to general metrics $\rho(D, D') \leq 1$, where ρ can be l_p-norms (Chatzikokolakis et al., 2013). DP-preserving algorithms in DNNs can be categorized into three lines: 1) introducing noise into *parameter gradients* (Abadi et al., 2016; 2017; Shokri & Shmatikov, 2015; Yu et al., 2019; Lee & Kifer, 2018; Phan et al., 2019), 2) injecting noise into objective functions (Phan et al., 2016; 2017a;b), and 3) injecting noise into labels (Papernot et al., 2018).

Adversarial Learning. For some target model f and inputs (x, y_x), the adversary's goal is to find an *adversarial example* $x^{\text{adv}} = x + \alpha$, where α is the perturbation introduced by the attacker, such that: **(1)** x^{adv} and x are close, and **(2)** the model misclassifies x^{adv}, i.e., $y(x^{\text{adv}}) \neq y(x)$. In this paper, *we consider well-known $l_{p \in \{1,2,\infty\}}(\mu)$-norm bounded attacks (Goodfellow et al., 2014), where μ is the radius of the p-norm ball*. To improve the robustness of models, prior work focused on two directions: 1) Producing correct predictions on adversarial examples, while not compromising the accuracy on legitimate inputs (Kardan & Stanley, 2017; Matyasko & Chau, 2017; Wang et al., 2016; Papernot et al., 2016b;a; Gu & Rigazio, 2014; Papernot & McDaniel, 2017; Hosseini et al., 2017); and 2) Detecting adversarial examples (Metzen et al., 2017; Grosse et al., 2017; Xu et al., 2017; Abbasi & Gagné, 2017; Gao et al., 2017). Among existing solutions, adversarial training appears to hold the

greatest promise for learning robust models (Tramèr et al., 2017). A well-known algorithm was proposed in (Kurakin et al., 2016b). At every training step, new adversarial examples are generated and injected into batches containing both benign and adversarial examples (Alg. 2, **Appendix C**).

Certified Robustness and DP. Recently, some algorithms (Cisse et al., 2017; Kolter & Wong, 2017; Raghunathan et al., 2018; Cohen et al., 2019; Li et al., 2018; Salman et al., 2019) have been proposed to derive certified robustness, in which each prediction is guaranteed to be consistent under the perturbation α, if a robustness condition is held. Given a benign example x, we focus on achieving a robustness condition to $l_p(\mu)$-norm attacks, as follows:

$$\forall \alpha \in l_p(\mu) : f_k(x+\alpha) > \max_{i:i\neq k} f_i(x+\alpha) \quad (2)$$

where $k = y(x)$, indicating that a small perturbation α in the input does not change the predicted label $y(x)$. To achieve the robustness condition in Eq. 2, (Lecuyer et al., 2018) introduce an algorithm, called **PixelDP**. By considering an input x (e.g., images) as databases in DP parlance, and individual features (e.g., pixels) as tuples, PixelDP shows that randomizing the scoring function $f(x)$ to enforce DP on a small number of pixels in an image guarantees robustness of predictions. To randomize $f(x)$, *random noise* σ_r is injected into either input x or an arbitrary hidden layer, resulting in the following (ϵ_r, δ_r)-PixelDP condition:

Lemma 1 *(ϵ_r, δ_r)-PixelDP (Lecuyer et al., 2018). Given a randomized scoring function $f(x)$ satisfying (ϵ_r, δ_r)-PixelDP w.r.t. a l_p-norm metric, we have:*

$$\forall k, \forall \alpha \in l_p(1) : \mathbb{E} f_k(x) \leq e^{\epsilon_r} \mathbb{E} f_k(x+\alpha) + \delta_r \quad (3)$$

where $\mathbb{E} f_k(x)$ is the expected value of $f_k(x)$, ϵ_r is a predefined budget, δ_r is a broken probability.

At the prediction time, a certified robustness check is implemented for each prediction, as follows:

$$\hat{\mathbb{E}}_{lb} f_k(x) > e^{2\epsilon_r} \max_{i:i\neq k} \hat{\mathbb{E}}_{ub} f_i(x) + (1+e^{\epsilon_r})\delta_r \quad (4)$$

where $\hat{\mathbb{E}}_{lb}$ and $\hat{\mathbb{E}}_{ub}$ are the lower and upper bounds of the expected value $\hat{\mathbb{E}} f(x) = \frac{1}{n}\sum_n f(x)_n$, derived from the Monte Carlo estimation with an η-confidence, given n is the number of invocations of $f(x)$ with independent draws in the noise σ_r. Passing the check for a given input guarantees that no perturbation up to $l_p(1)$-norm can change the model's prediction. PixelDP *does not* preserve DP in learning private parameters θ to protect the training data.

3. Stochastic Batch (StoBatch) Mechanism

StoBatch is presented in Alg. 4 (**Appendix D**). Our DNN (Fig. 1a) is presented as: $f(x) = g(a(x,\theta_1),\theta_2)$, where $a(x,\theta_1)$ is a feature representation learning model with x as an input, and g will take the output of $a(x,\theta_1)$ and return the class scores $f(x)$. At a high level, there are four key components: **(1)** DP $a(x,\theta_1)$, which is to preserve DP in learning the feature representation model $a(x,\theta_1)$; **(2)** DP Adversarial Learning, which focuses on preserving DP in adversarial learning, given DP $a(x,\theta_1)$; **(3)** Certified Robustness and Verified Inferring, which are to compute robustness bounds given an input at the inference time; and **(4)** Stochastic batch training (Fig. 1b). To establish theoretical results in DP preservation and in deriving robustness bounds, let us first present our mechanism in the vanilla iterative batch-by-batch training (**Alg. 1**). The network f (Lines 2-3, Alg. 1) is trained over T training steps. In each step, a disjoint and fixed batch of m perturbed training examples and a disjoint and fixed batch of m DP adversarial examples, derived from D, are used to train our network (Lines 4-12, Alg. 1).

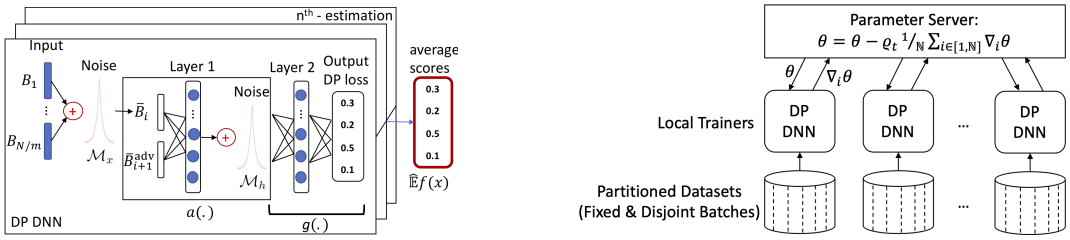
3.1. DP Feature Representation Learning

Our idea is to use auto-encoder to simultaneously learn DP parameters θ_1 and ensure that the output of $a(x,\theta_1)$ is DP, since: (1) It is easier to train, given its small size; and (2) It can be reused for different predictive models. A typical data reconstruction function (cross-entropy), given a batch B_t at the training step t of the input x_i, is as follows: $\mathcal{R}_{B_t}(\theta_1) = \sum_{x_i\in B_t}\sum_{j=1}^{d}\big[x_{ij}\log(1+e^{-\theta_{1j}h_i}) + (1-x_{ij})\log(1+e^{\theta_{1j}h_i})\big]$, where $h_i = \theta_1^T x_i$, the hidden layer $\mathbf{h}_1$ of $a(x,\theta_1)$ given the batch B_t is denoted as $\mathbf{h}_{1B_t} = \{\theta_1^T x_i\}_{x_i\in B_t}$, and $\widetilde{x}_i = \theta_1 h_i$ is the reconstruction of x_i.

To preserve ϵ_1-DP in learning θ_1 where ϵ_1 is a privacy budget, we first derive the 1st-order polynomial approximation of $\mathcal{R}_{B_t}(\theta_1)$ by applying Taylor Expansion (Arfken, 1985), denoted as $\widetilde{\mathcal{R}}_{B_t}(\theta_1)$. Then, *Functional Mechanism* (Zhang et al., 2012) **(revisited in Appendix B)** is adapted to inject noise into coefficients of the approximated function $\widetilde{\mathcal{R}}_{B_t}(\theta_1) = \sum_{x_i\in B_t}\sum_{j=1}^{d}\sum_{l=1}^{2}\sum_{r=0}^{1}\frac{\mathbf{F}_{lj}^{(r)}(0)}{r!}\big(\theta_{1j}h_i\big)^r$, where $\mathbf{F}_{1j}(z) = x_{ij}\log(1+e^{-z})$, $\mathbf{F}_{2j}(z) = (1-x_{ij})\log(1+e^{z})$, we have that: $\widetilde{\mathcal{R}}_{B_t}(\theta_1) = \sum_{x_i\in B_t}\sum_{j=1}^{d}\Big[\log 2 + \theta_{1j}\big(\frac{1}{2}-x_{ij}\big)h_i\Big]$. In $\widetilde{\mathcal{R}}_{B_t}(\theta_1)$, parameters θ_{1j} derived from the function optimization need to be ϵ_1-DP. To achieve that, Laplace noise $\frac{1}{m}Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})$ is injected into coefficients $\big(\frac{1}{2}-x_{ij}\big)h_i$, where $\Delta_{\mathcal{R}}$ is the sensitivity of $\widetilde{\mathcal{R}}_{B_t}(\theta_1)$, as follows:

$$\widetilde{\mathcal{R}}_{B_t}(\theta_1) = \sum_{x_i\in B_t}\sum_{j=1}^{d}\Big[\theta_{1j}\Big(\big(\frac{1}{2}-x_{ij}\big)h_i + \frac{1}{m}Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})\Big)\Big]$$
$$= \sum_{x_i\in B_t}\Big[\sum_{j=1}^{d}(\frac{1}{2}\theta_{1j}\overline{h}_i) - x_i\widetilde{x}_i\Big] \quad (5)$$

To ensure that the computation of $\widetilde{x}_i$ does not access the



(a) An instance of DP DNNs and verified inference

(b) An instance of stochastic batch training

Figure 1. Stochastic Batch mechanism.

original data, we further inject Laplace noise $\frac{1}{m}Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})$ into x_i. This can be done as a preprocessing step for all the benign examples in D to construct a set of *disjoint* batches $\overline{\mathbf{B}}$ of perturbed benign examples (Lines 2 and 5, Alg. 1). The perturbed function now becomes:

$$\overline{\mathcal{R}}_{\overline{B}_t}(\theta_1) = \sum_{\overline{x}_i \in \overline{B}_t} \Big[\sum_{j=1}^{d} (\frac{1}{2}\theta_{1j}\overline{h}_i) - \overline{x}_i\widetilde{x}_i \Big] \quad (6)$$

where $\overline{x}_i = x_i + \frac{1}{m}Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1}), h_i = \theta_1^T\overline{x}_i, \overline{h}_i = h_i + \frac{2}{m}Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})$, and $\widetilde{x}_i = \theta_1\overline{h}_i$. Let us denote β as the number of neurons in $\mathbf{h}_1$, and h_i is bounded in $[-1, 1]$, the global sensitivity $\Delta_{\mathcal{R}}$ is as follows:

Lemma 2 *The global sensitivity of $\widetilde{\mathcal{R}}$ over any two neighboring batches, B_t and B'_t, is: $\Delta_{\mathcal{R}} \leq d(\beta + 2)$.*

All the proofs are in **Appendix**. By setting $\Delta_{\mathcal{R}} = d(\beta+2)$, we show that the output of $a(\cdot)$, which is the perturbed affine transformation $\overline{\mathbf{h}}_{1\overline{B}_t} = \{\theta_1^T\overline{x}_i + \frac{2}{m}Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})\}_{\overline{x}_i \in \overline{B}_t}$, is (ϵ_1/γ)-DP, given $\gamma = \frac{2\Delta_{\mathcal{R}}}{m\|\overline{\theta}_1\|_{1,1}}$ and $\|\overline{\theta}_1\|_{1,1}$ is the maximum 1-norm of θ_1's columns (Operator norm, 2018). This is important to tighten the privacy budget consumption in computing the remaining hidden layers $g(a(x, \theta_1), \theta_2)$. In fact, without using additional information from the original data, the computation of $g(a(x, \theta_1), \theta_2)$ is also (ϵ_1/γ)-DP.

Similarly, the perturbation of each benign example x turns $\overline{B}_t = \{\overline{x}_i \leftarrow x_i + \frac{1}{m}Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})\}_{x_i \in B_t}$ into a $(\epsilon_1/\gamma_{\mathbf{x}})$-DP batch, with $\gamma_{\mathbf{x}} = \Delta_{\mathcal{R}}/m$. We do not use the post-processing property of DP to estimate the DP guarantee of $\overline{\mathbf{h}}_{1\overline{B}_t}$ based upon the DP guarantee of $\overline{B}_t$, since $\epsilon_1/\gamma < \epsilon_1/\gamma_{\mathbf{x}}$ in practice. So, the (ϵ_1/γ)-DP $\overline{\mathbf{h}}_{1\overline{B}_t}$ provides a more rigorous DP protection to the computation of $g(\cdot)$ and to the output layer.

Lemma 3 *The computation of the batch $\overline{B}_t$ as the input layer is $(\epsilon_1/\gamma_{\mathbf{x}})$-DP, and the computation of the affine transformation $\overline{\mathbf{h}}_{1\overline{B}_t}$ is (ϵ_1/γ)-DP.*

Departing from the vanilla Functional Mechanism, in which only *grid search*-based approaches can be applied to find DP-preserving θ_1 with a low loss $\overline{\mathcal{R}}_{\overline{B}_t}(\theta_1)$, our following Theorem 1 shows that *gradient descent*-based optimizing $\overline{\mathcal{R}}_{\overline{B}_t}(\theta_1)$ is $(\epsilon_1/\gamma_{\mathbf{x}}+\epsilon_1)$-DP in learning θ_1 given an $(\epsilon_1/\gamma_{\mathbf{x}})$-DP $\overline{B}_t$ batch. In fact, in addition to h_i, $\overline{h}_i$, $\widetilde{x}_i$, based on Lemma 3, we further show that the computation of gradients, i.e., $\forall j \in [1, d] : \frac{\delta\overline{\mathcal{R}}_{\overline{B}_t}(\theta_1)}{\delta\theta_{1j}} = \sum_{i=1}^{m}\overline{h}_i(\frac{1}{2} - \overline{x}_{ij})$, and descent operations given the $(\epsilon_1/\gamma_{\mathbf{x}})$-DP $\overline{B}_t$ batch are $(\epsilon_1/\gamma_{\mathbf{x}})$-DP, without incurring any additional information from the original data. As a result, gradient descent-based approaches can be applied to optimize $\overline{\mathcal{R}}_{\overline{B}_t}(\theta_1)$ in Alg. 1, since all the computations on top of $\overline{B}_t$ are DP, without using any additional information from the original data.

Theorem 1 *The gradient descent-based optimization of $\overline{\mathcal{R}}_{\overline{B}_t}(\theta_1)$ preserves $(\epsilon_1/\gamma_{\mathbf{x}} + \epsilon_1)$-DP in learning θ_1.*

3.2. Adversarial Learning with Differential Privacy

To integrate adversarial learning, we first draft DP adversarial examples $\overline{x}_j^{\text{adv}}$ using perturbed benign examples $\overline{x}_j$, with an ensemble of attack algorithms A and a random perturbation budget $\mu_t \in (0, 1]$, at each step t (Lines 6-11, Alg. 1). This will significantly enhances the robustness of our models under different types of adversarial examples with an unknown adversarial attack size μ.

$$\overline{x}_j^{\text{adv}} = \overline{x}_j + \mu \cdot \text{sign}\Big(\nabla_{\overline{x}_j}\mathcal{L}\big(f(\overline{x}_j, \theta), y(\overline{x}_j)\big)\Big) \quad (7)$$

with $y(\overline{x}_j)$ is the class prediction result of $f(\overline{x}_j)$ to avoid label leaking of x_j during the adversarial example crafting. Given a set of DP adversarial examples $\overline{B}_t^{\text{adv}}$, training the auto-encoder with $\overline{B}_t^{\text{adv}}$ preserves $(\epsilon_1/\gamma_{\mathbf{x}} + \epsilon_1)$-DP.

Theorem 2 *The gradient descent-based optimization of $\overline{\mathcal{R}}_{\overline{B}_t^{adv}}(\theta_1)$ preserves $(\epsilon_1/\gamma_{\mathbf{x}} + \epsilon_1)$-DP in learning θ_1.*

The proof of Theorem 2 is in **Appendix J, Result 4**. It can be extended to iterative attacks as: $\overline{x}_{j,0}^{\text{adv}} = \overline{x}_j$,

$$\overline{x}_{j,\mathtt{t}+1}^{\text{adv}} = \overline{x}_{j,\mathtt{t}}^{\text{adv}} + \frac{\mu}{T_\mu} \cdot \text{sign}\Big(\nabla_{\overline{x}_{j,\mathtt{t}}^{\text{adv}}}\mathcal{L}\big(f(\overline{x}_{j,\mathtt{t}}^{\text{adv}}, \theta), y(\overline{x}_{j,\mathtt{t}}^{\text{adv}})\big)\Big) \quad (8)$$

where $y(\overline{x}_{j,\mathtt{t}}^{\text{adv}})$ is the prediction of $f(\overline{x}_{j,\mathtt{t}}^{\text{adv}}, \theta)$, $\mathtt{t} \in [0, T_\mu - 1]$.

Second, we propose a novel DP adversarial objective function $L_{B_t}(\theta_2)$, in which the loss function $\mathcal{L}$ for benign examples is combined with an additional loss function Υ for DP

Algorithm 1 Adversarial Learning with DP

Input: Database D, loss function L, parameters θ, batch size m, learning rate ϱ_t, privacy budgets: ϵ_1 and ϵ_2, robustness parameters: ϵ_r, Δ_r^x, and Δ_r^h, adversarial attack size μ_a, the number of invocations n, ensemble attacks A, parameters ψ and ξ, and the size $|\mathbf{h}_\pi|$ of $\mathbf{h}_\pi$

1: **Draw Noise** $\chi_1 \leftarrow [Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})]^d$, $\chi_2 \leftarrow [Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})]^\beta$, $\chi_3 \leftarrow [Lap(\frac{\Delta_{\mathcal{L}2}}{\epsilon_2})]^{|\mathbf{h}_\pi|}$
2: **Randomly Initialize** $\theta = \{\theta_1, \theta_2\}$, $\mathbf{B} = \{B_1, \ldots, B_{N/m}\}$ s.t. $\forall B \in \mathbf{B} : B$ is a batch with the size m, $B_1 \cap \ldots \cap B_{N/m} = \emptyset$, and $B_1 \cup \ldots \cup B_{N/m} = D$, $\overline{\mathbf{B}} = \{\overline{B}_1, \ldots, \overline{B}_{N/m}\}$ where $\forall i \in [1, N/m] : \overline{B}_i = \{\overline{x} \leftarrow x + \frac{\chi_1}{m}\}_{x \in B_i}$
3: **Construct** a deep network f with **hidden layers** $\{\mathbf{h}_1 + \frac{2\chi_2}{m}, \ldots, \mathbf{h}_\pi\}$, where $\mathbf{h}_\pi$ is the last hidden layer
4: **for** $t \in [T]$ **do**
5: **Take** a batch $\overline{B}_i \in \overline{\mathbf{B}}$ where $i = t\%(N/m)$, $\overline{B}_t \leftarrow \overline{B}_i$
6: **Ensemble DP Adversarial Examples:**
7: **Draw Random Perturbation Value** $\mu_t \in (0, 1]$
8: **Take** a batch $\overline{B}_{i+1} \in \overline{\mathbf{B}}$, **Assign** $\overline{B}_t^{\text{adv}} \leftarrow \emptyset$
9: **for** $l \in A$ **do**
10: **Take** the next batch $\overline{B}_a \subset \overline{B}_{i+1}$ with the size $m/|A|$
11: $\forall \overline{x}_j \in \overline{B}_a$: **Craft** $\overline{x}_j^{\text{adv}}$ by using attack algorithm $A[l]$ with $l_\infty(\mu_t)$, $\overline{B}_t^{\text{adv}} \leftarrow \overline{B}_t^{\text{adv}} \cup \overline{x}_j^{\text{adv}}$
12: **Descent:** $\theta_1 \leftarrow \theta_1 - \varrho_t \nabla_{\theta_1} \overline{\mathcal{R}}_{\overline{B}_t \cup \overline{B}_t^{\text{adv}}}(\theta_1)$; $\theta_2 \leftarrow \theta_2 - \varrho_t \nabla_{\theta_2} \overline{L}_{\overline{B}_t \cup \overline{B}_t^{\text{adv}}}(\theta_2)$ with the noise $\frac{\chi_3}{m}$

Output: $\epsilon = (\epsilon_1 + \epsilon_1/\gamma_{\mathbf{x}} + \epsilon_1/\gamma + \epsilon_2)$-DP parameters $\theta = \{\theta_1, \theta_2\}$, robust model with an ϵ_r budget

adversarial examples, to optimize the parameters θ_2. The objective function $L_{B_t}(\theta_2)$ is defined as follows:

$$L_{\overline{B}_t \cup \overline{B}_t^{\text{adv}}}(\theta_2) = \frac{1}{m(1+\xi)} \Big(\sum_{\overline{x}_i \in \overline{B}_t} \mathcal{L}\big(f(\overline{x}_i, \theta_2), y_i\big) + \xi \sum_{\overline{x}_j^{\text{adv}} \in \overline{B}_t^{\text{adv}}} \Upsilon\big(f(\overline{x}_j^{\text{adv}}, \theta_2), y_j\big) \Big) \quad (9)$$

where ξ is a hyper-parameter. For the sake of clarity, in Eq. 9, we denote y_i and y_j as the true class labels y_{x_i} and y_{x_j} of examples x_i and x_j. $\overline{x}_j^{\text{adv}}$ and x_j share the same label y_{x_j}.

Now we are ready to preserve DP in objective functions $\mathcal{L}\big(f(\overline{x}_i, \theta_2), y_i\big)$ and $\Upsilon\big(f(\overline{x}_j^{\text{adv}}, \theta_2), y_j\big)$ in order to achieve DP in learning θ_2. Since the objective functions use the true class labels y_i and y_j, we need to protect the labels at the output layer. Let us first present our approach to preserve DP in the objective function $\mathcal{L}$ for benign examples. Given $\mathbf{h}_{\pi i}$ computed from the $\overline{x}_i$ through the network with W_π is the parameter at the last hidden layer $\mathbf{h}_\pi$. Cross-entropy function is approximated as: $\mathcal{L}_{\overline{B}_t}(\theta_2) \approx \sum_{k=1}^K \sum_{\overline{x}_i} \big[\mathbf{h}_{\pi i} W_{\pi k} - (\mathbf{h}_{\pi i} W_{\pi k}) y_{ik} - \frac{1}{2}|\mathbf{h}_{\pi i} W_{\pi k}| + \frac{1}{8}(\mathbf{h}_{\pi i} W_{\pi k})^2\big] \approx \mathcal{L}_{1\overline{B}_t}(\theta_2) - \mathcal{L}_{2\overline{B}_t}(\theta_2)$, where $\mathcal{L}_{1\overline{B}_t}(\theta_2) = \sum_{k=1}^K \sum_{\overline{x}_i} \big[\mathbf{h}_{\pi i} W_{\pi k} - \frac{1}{2}|\mathbf{h}_{\pi i} W_{\pi k}| + \frac{1}{8}(\mathbf{h}_{\pi i} W_{\pi k})^2\big]$, and $\mathcal{L}_{2\overline{B}_t}(\theta_2) = \sum_{k=1}^K \sum_{\overline{x}_i} (\mathbf{h}_{\pi i} y_{ik}) W_{\pi k}$.

Based on the *post-processing property of DP* (Dwork & Roth, 2014), $\mathbf{h}_{\pi \overline{B}_t} = \{\mathbf{h}_{\pi i}\}_{\overline{x}_i \in \overline{B}_t}$ is (ϵ_1/γ)-DP, since the computation of $\overline{\mathbf{h}}_{1\overline{B}_t}$ is (ϵ_1/γ)-DP (Lemma 3). Hence, the optimization of $\mathcal{L}_{1\overline{B}_t}(\theta_2)$ does not disclose any information from the training data, and $\frac{Pr(\mathcal{L}_{1\overline{B}_t}(\theta_2))}{Pr(\mathcal{L}_{1\overline{B}'_t}(\theta_2))} = \frac{Pr(\mathbf{h}_{\pi \overline{B}_t})}{Pr(\mathbf{h}_{\pi \overline{B}'_t})} \leq e^{\epsilon_1/\gamma}$, given neighboring batches $\overline{B}_t$ and $\overline{B}'_t$. Thus, we only need to preserve ϵ_2-DP in the function $\mathcal{L}_{2\overline{B}_t}(\theta_2)$, which accesses the ground-truth label y_{ik}. Given coefficients $\mathbf{h}_{\pi i} y_{ik}$, the sensitivity $\Delta_{\mathcal{L}2}$ of $\mathcal{L}_{2\overline{B}_t}(\theta_2)$ is computed as:

Lemma 4 *Let $\overline{B}_t$ and $\overline{B}'_t$ be neighboring batches of benign examples, we have the following inequality: $\Delta_{\mathcal{L}2} \leq 2|\mathbf{h}_\pi|$, where $|\mathbf{h}_\pi|$ is the number of hidden neurons in $\mathbf{h}_\pi$.*

The sensitivity of our objective function is notably smaller than the state-of-the-art bound (Phan et al., 2017b), which is crucial to improve our model utility. The perturbed functions become: $\overline{\mathcal{L}}_{\overline{B}_t}(\theta_2) = \mathcal{L}_{1\overline{B}_t}(\theta_2) - \overline{\mathcal{L}}_{2\overline{B}_t}(\theta_2)$, where $\overline{\mathcal{L}}_{2\overline{B}_t}(\theta_2) = \sum_{k=1}^K \sum_{\overline{x}_i} \big(\mathbf{h}_{\pi i} y_{ik} + \frac{1}{m} Lap(\frac{\Delta_{\mathcal{L}2}}{\epsilon_2})\big) W_{\pi k}$.

Theorem 3 *Algorithm 1 preserves $(\epsilon_1/\gamma + \epsilon_2)$-DP in the gradient descent-based optimization of $\overline{\mathcal{L}}_{\overline{B}}(\theta_2)$.*

We apply the same technique to preserve $(\epsilon_1/\gamma + \epsilon_2)$-DP in the optimization of the function $\Upsilon\big(f(\overline{x}_j^{\text{adv}}, \theta_2), y_j\big)$ over the DP adversarial examples $\overline{x}_j^{\text{adv}} \in \overline{B}_t^{\text{adv}}$. As the perturbed functions $\overline{\mathcal{L}}$ and $\overline{\Upsilon}$ are always optimized given two disjoint batches $\overline{B}_t$ and $\overline{B}_t^{\text{adv}}$, the privacy budget used to preserve DP in the adversarial objective function $L_{B_t}(\theta_2)$ is $(\epsilon_1/\gamma + \epsilon_2)$, following the *parallel composition* property (Dwork & Roth, 2014). The total budget to learn private parameters $\overline{\theta} = \{\overline{\theta}_1, \overline{\theta}_2\} = \arg\min_{\{\theta_1, \theta_2\}} (\overline{\mathcal{R}}_{\overline{B}_t \cup \overline{B}_t^{\text{adv}}}(\theta_1) + \overline{L}_{\overline{B}_t \cup \overline{B}_t^{\text{adv}}}(\theta_2))$ is $\epsilon = (\epsilon_1 + \epsilon_1/\gamma_{\mathbf{x}} + \epsilon_1/\gamma + \epsilon_2)$ (Line 12, Alg. 1).

DP at the Dataset Level. Our mechanism achieves DP at the batch level $\overline{B}_t \cup \overline{B}_t^{\text{adv}}$ given a specific training step t. By constructing *disjoint* and *fixed* batches from D, we leverage both parallel composition and post-processing properties of DP to extend the result to ϵ-DP in learning $\{\overline{\theta}_1, \overline{\theta}_2\}$ on D across T training steps. There are three key properties in our model: **(1)** It only reads perturbed inputs $\overline{B}_t$ and perturbed coefficients $\overline{\mathbf{h}}_1$, which are DP across T training steps with *a single draw of Laplace noise* (i.e., no further privacy leakage); **(2)** Given N/m disjoint batches in each epoch, $\forall \overline{x}$, $\overline{x}$ is included in *one and only one* batch, denoted $B_x \in \overline{\mathbf{B}}$. As a result, the DP guarantee to $\overline{x}$ in D is equivalent to the DP guarantee to $\overline{x}$ in B_x; since the optimization using any

other batches does not affect the DP guarantee of $\overline{x}$, even the objective function given B_x can be slightly different from the objective function given any other batches in $\overline{\mathbf{B}}$; and **(3)** All the batches are fixed across T training steps to prevent additional privacy leakage, caused by generating new and overlapping batches (which are considered overlapping datasets in the parlance of DP) in the typical training.

Theorem 4 *Algorithm 1 achieves* $(\epsilon_1+\epsilon_1/\gamma_{\mathbf{x}}+\epsilon_1/\gamma+\epsilon_2)$*-DP parameters* $\overline{\theta}=\{\overline{\theta}_1,\overline{\theta}_2\}$ *on the private training data* D *across* T *gradient descent-based training steps.*

3.3. Certified Robustness

Now, we establish the correlation between our mechanism and certified robustness. In the *inference time*, to derive the certified robustness condition against adversarial examples $x+\alpha$, i.e., $\forall\alpha\in l_p(1)$, PixelDP randomizes the function $f(x)$ by injecting *robustness noise* σ_r into either input x or a hidden layer, i.e., $x'=x+Lap(\frac{\Delta_r^x}{\epsilon_r})$ or $h'=h+Lap(\frac{\Delta_r^h}{\epsilon_r})$, where Δ_r^x and Δ_r^h are the sensitivities of x and h, measuring how much x and h can be changed given the perturbation $\alpha\in l_p(1)$ in the input x. Monte Carlo estimation of the expected values $\hat{\mathbb{E}}f(x)$, $\hat{\mathbb{E}}_{lb}f_k(x)$, and $\hat{\mathbb{E}}_{ub}f_k(x)$ are used to derive the robustness condition in Eq. 4.

On the other hand, in our mechanism, the privacy noise σ_p includes Laplace noise injected into both input x, i.e., $\frac{1}{m}Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})$, and its affine transformation h, i.e., $\frac{2}{m}Lap(\frac{\Delta_{\mathcal{R}}}{\epsilon_1})$. Note that the perturbation of $\overline{\mathcal{L}}_{2\overline{B}_t}(\theta_2)$ is equivalent to $\overline{\mathcal{L}}_{2\overline{B}_t}(\theta_2)=\sum_{k=1}^{K}\sum_{\overline{x}_i}(\mathbf{h}_{\pi i}y_{ik}W_{\pi k}+\frac{1}{m}Lap(\frac{\Delta_{\mathcal{L}2}}{\epsilon_2})W_{\pi k})$. This helps us to avoid injecting the noise directly into the coefficients $\mathbf{h}_{\pi i}y_{ik}$. The correlation between our DP preservation and certified robustness lies in the correlation between the privacy noise σ_p and the robustness noise σ_r.

We can derive a robustness bound by projecting the privacy noise σ_p *on the scale of the robustness noise* σ_r. Given the input x, let $\kappa=\frac{\Delta_{\mathcal{R}}}{m\epsilon_1}/\frac{\Delta_r^x}{\epsilon_r}$, in our mechanism we have that: $\overline{x}=x+Lap(\kappa\Delta_r^x/\epsilon_r)$. By applying a group privacy size κ (Dwork & Roth, 2014; Lecuyer et al., 2018), the scoring function $f(x)$ satisfies ϵ_r-PixelDP given $\alpha\in l_p(\kappa)$, or equivalently is $\kappa\epsilon_r$-PixelDP given $\alpha\in l_p(1)$, $\delta_r=0$. By applying Lemma 1, we have

$$\forall k,\forall\alpha\in l_p(\kappa):\mathbb{E}f_k(x)\leq e^{\epsilon_r}\mathbb{E}f_k(x+\alpha),$$
$$or\quad\forall k,\forall\alpha\in l_p(1):\mathbb{E}f_k(x)\leq e^{(\kappa\epsilon_r)}\mathbb{E}f_k(x+\alpha)$$

With that, we can achieve a robustness condition against $l_p(\kappa)$-norm attacks, as follows:

$$\hat{\mathbb{E}}_{lb}f_k(x)>e^{2\epsilon_r}\max_{i:i\neq k}\hat{\mathbb{E}}_{ub}f_i(x)\tag{10}$$

with the probability $\geq\eta_x$-confidence, derived from the Monte Carlo estimation of $\hat{\mathbb{E}}f(x)$. Our mechanism also perturbs h (Eq. 6). Given $\varphi=\frac{2\Delta_{\mathcal{R}}}{m\epsilon_1}/\frac{\Delta_r^h}{\epsilon_r}$, we further have $\overline{h}=h+Lap(\frac{\varphi\Delta_r^h}{\epsilon_r})$. Therefore, the scoring function $f(x)$ also satisfies ϵ_r-PixelDP given the perturbation $\alpha\in l_p(\varphi)$. In addition to the robustness to the $l_p(\kappa)$-norm attacks, we achieve an additional robustness bound in Eq. 10 against $l_p(\varphi)$-norm attacks. Similar to PixelDP, these robustness conditions can be achieved as randomization processes in the inference time. They can be considered as *two independent and certified defensive mechanisms* applied against two l_p-norm attacks, i.e., $l_p(\kappa)$ and $l_p(\varphi)$.

One challenging question here is: *"What is the general robustness bound, given* κ *and* φ*?"* Intuitively, our model is robust to attacks with $\alpha\in l_p(\kappa+\varphi)$. We leverage the theory of *sequential composition* in DP (Dwork & Roth, 2014) to theoretically answer this question. Given S independent mechanisms $\mathcal{M}_1,\ldots,\mathcal{M}_S$, whose privacy guarantees are $\epsilon_1,\ldots,\epsilon_S$-DP with $\alpha\in l_p(1)$. Each mechanism $\mathcal{M}_s$, which takes the input x and outputs the value of $f(x)$ with the Laplace noise only injected to randomize the layer s (i.e., no randomization at any other layers), denoted as $f^s(x)$, is defined as: $\forall s\in[1,S],\mathcal{M}_sf(x):\mathbb{R}^d\rightarrow f^s(x)\in\mathbb{R}^K$. We aim to derive a generalized robustness of any composition scoring function $f(\mathcal{M}_1,\ldots,\mathcal{M}_s|x):\prod_{s=1}^{S}\mathcal{M}_sf(x)$ bounded in $[0,1]$, defined as follows:

$$f(\mathcal{M}_1,\ldots,\mathcal{M}_S|x):\mathbb{R}^d\rightarrow\prod_{s\in[1,S]}f^s(x)\in\mathbb{R}^K\tag{11}$$

Our setting follows the sequential composition in DP (Dwork & Roth, 2014). Thus, we can prove that the expected value $\mathbb{E}f(\mathcal{M}_1,\ldots,\mathcal{M}_S|x)$ is insensitive to small perturbations $\alpha\in l_p(1)$ in Lemma 5, and we derive our composition of robustness in Theorem 5, as follows:

Lemma 5 *Given* S *independent mechanisms* $\mathcal{M}_1,\ldots,\mathcal{M}_S$*, which are* $\epsilon_1,\ldots,\epsilon_S$*-DP w.r.t a* l_p*-norm metric, then the expected output value of any sequential function* f *of them, i.e.,* $f(\mathcal{M}_1,\ldots,\mathcal{M}_S|x)\in[0,1]$*, satisfies:*

$$\forall\alpha\in l_p(1):\mathbb{E}f(\mathcal{M}_1,\ldots,\mathcal{M}_S|x)\leq e^{(\sum_{s=1}^{S}\epsilon_s)}\mathbb{E}f(\mathcal{M}_1,\ldots,\mathcal{M}_S|x+\alpha)$$

Theorem 5 *(Composition of Robustness) Given* S *independent mechanisms* $\mathcal{M}_1,\ldots,\mathcal{M}_S$*. Given any sequential function* $f(\mathcal{M}_1,\ldots,\mathcal{M}_S|x)$*, and let* $\hat{\mathbb{E}}_{lb}$ *and* $\hat{\mathbb{E}}_{ub}$ *are lower and upper bounds with an* η*-confidence, for the Monte Carlo estimation of* $\hat{\mathbb{E}}f(\mathcal{M}_1,\ldots,\mathcal{M}_S|x)=\frac{1}{n}\sum_n f(\mathcal{M}_1,\ldots,\mathcal{M}_S|x)_n=\frac{1}{n}\sum_n(\prod_{s=1}^{S}f^s(x)_n)$*.*

$$\forall x,if\ \exists k\in K:\hat{\mathbb{E}}_{lb}f_k(\mathcal{M}_1,\ldots,\mathcal{M}_S|x)>e^{2(\sum_{s=1}^{S}\epsilon_s)}\max_{i:i\neq k}\hat{\mathbb{E}}_{ub}f_i(\mathcal{M}_1,\ldots,\mathcal{M}_S|x),\tag{12}$$

then the predicted label $k = \arg\max_k \hat{\mathbb{E}} f_k(\mathcal{M}_1, \ldots, \mathcal{M}_S|x)$, *is robust to adversarial examples* $x + \alpha$, $\forall \alpha \in l_p(1)$, *with probability* $\geq \eta$, *by satisfying:* $\hat{\mathbb{E}} f_k(\mathcal{M}_1, \ldots, \mathcal{M}_S|x + \alpha) > \max_{i:i\neq k} \hat{\mathbb{E}} f_i(\mathcal{M}_1, \ldots, \mathcal{M}_S|x + \alpha)$, *which is the targeted robustness condition in Eq. 2.*

There is no η_s-confidence for each mechanism s, since we do not estimate the expected value $\hat{\mathbb{E}} f^s(x)$ independently. To apply the composition of robustness in our mechanism, the noise injections into the input x and its affine transformation h can be considered as two mechanisms $\mathcal{M}_x$ and $\mathcal{M}_h$, sequentially applied as $(\mathcal{M}_h(x), \mathcal{M}_x(x))$. When $\mathcal{M}_h(x)$ is applied by invoking $f(x)$ with independent draws in the noise χ_2, the noise χ_1 injected into x is fixed; and vice-versa. By applying group privacy (Dwork & Roth, 2014) with sizes κ and φ, the scoring functions $f^x(x)$ and $f^h(x)$, given $\mathcal{M}_x$ and $\mathcal{M}_h$, are $\kappa\epsilon_r$-DP and $\varphi\epsilon_r$-DP with $\alpha \in l_p(1)$. With Theorem 5, we have a generalized bound as follows:

Corollary 1 *(StoBatch Robustness).* $\forall x$, *if* $\exists k \in K$: $\hat{\mathbb{E}}_{lb} f_k(\mathcal{M}_h, \mathcal{M}_x|x) > e^{2\epsilon_r} \max_{i:i\neq k} \hat{\mathbb{E}}_{ub} f_i(\mathcal{M}_h, \mathcal{M}_x|x)$ *(i.e., Eq. 12), then the predicted label* k *of our function* $f(\mathcal{M}_h, \mathcal{M}_x|x)$ *is robust to perturbations* $\alpha \in l_p(\kappa + \varphi)$ *with the probability* $\geq \eta$, *by satisfying*

$$\forall \alpha \in l_p(\kappa + \varphi) : \hat{\mathbb{E}} f_k(\mathcal{M}_h, \mathcal{M}_x|x + \alpha) > \max_{i:i\neq k} \hat{\mathbb{E}} f_i(\mathcal{M}_h, \mathcal{M}_x|x + \alpha)$$

Compared with state-of-the-art robustness analysis (Salman et al., 2019; Lecuyer et al., 2018), in which either the input space or the latent space are randomized, the advantage of our robustness bound is the composition of different levels of robustness in both input and latent spaces.

3.4. Verified Inference

At the inference time, we implement a *verified inference* (Alg. 3, **Appendix D**) to return a *robustness size guarantee* for each example x, i.e., the maximal value of $\kappa + \varphi$, for which the robustness condition in Corollary 1 holds. Maximizing $\kappa + \varphi$ is equivalent to maximizing the robustness epsilon ϵ_r, which is the only parameter controlling the size of $\kappa + \varphi$; since, all the other hyper-parameters, i.e., $\Delta_{\mathcal{R}}$, m, ϵ_1, ϵ_2, θ_1, θ_2, Δ_r^x, and Δ_r^h are fixed given a well-trained model $f(x)$:

$$(\kappa + \varphi)_{max} = \max_{\epsilon_r} \frac{\Delta_{\mathcal{R}} \epsilon_r}{m\epsilon_1} \left(\frac{1}{\Delta_r^x} + \frac{2}{\Delta_r^h}\right)$$
$$\text{s.t. } \hat{\mathbb{E}}_{lb} f_k(x) > e^{2\epsilon_r} \max_{i:i\neq k} \hat{\mathbb{E}}_{ub} f_i(x) \text{ (i.e., Eq. 12)} \quad (13)$$

The prediction on an example x is robust to attacks up to $(\kappa+\varphi)_{max}$. The failure probability 1-η can be made arbitrarily small by increasing the number of invocations of $f(x)$, with independent draws in the noise. Similar to (Lecuyer et al., 2018), Hoeffding's inequality is applied to *bound* the approximation error in $\hat{\mathbb{E}} f_k(x)$ and to *search* for the robustness bound $(\kappa + \varphi)_{max}$. We use the following sensitivity bounds $\Delta_r^h = \beta \|\theta_1\|_\infty$ where $\|\theta_1\|_\infty$ is the maximum 1-norm of θ_1's rows, and $\Delta_r^x = \mu d$ for l_∞ attacks. In the Monte Carlo Estimation of $\hat{\mathbb{E}} f(x)$, we also propose a new method to draw independent noise to control the *distribution shifts* between training and inferring, in order to improve the verified inference effectiveness, without affecting the DP protection and the robustness bounds (**Appendix N**).

3.5. Distributed Training

In the vanilla iterative batch-by-batch training for DP DNNs, at each step, only one batch of examples can be used to train our model, so that the privacy loss can be computed (Lee & Kifer, 2018; Yu et al., 2019; Wu et al., 2019; Xu et al., 2020). Parameters θ_1 and θ_2 are independently updated (Lines 4-12, Alg. 1). This prevents us from applying *practical adversarial training* (Xie et al., 2019; Goyal et al., 2017), in which *distributed training using synchronized SGD* on many GPUs (e.g., 128 GPUs) is used to scale adversarial training to large DNNs. Each GPU processes a mini-batch of 32 images (i.e., the total batch size is $128 \times 32 = 4,096$).

To overcome this, a well-applied technique (Yu et al., 2019) is to fine-tune a limited number of layers, such as a fully connected layer and the output layer, under DP of a pre-trained model, i.e., VGG16, trained over a public and large dataset, e.g., ImageNet, in order to handle simpler tasks on smaller private datasets, e.g., CIFAR-10. Although this approach works well, there are several utility and security concerns: **(1)** Suitable public data may not always be available, especially for highly sensitive data; **(2)** Trojans can be implanted in the pre-trained model for backdoor attacks (Liu et al., 2018); and **(3)** Public data can be poisoned (Shafahi et al., 2018). Fine-tuning a limited number of layers may not be secure; while fine-tuning an entire of a large pre-trained model iteratively batch-by-batch is still inefficient.

To address this bottleneck, we leverage the training recipe of (Xie et al., 2019; Goyal et al., 2017) to propose a distributed training algorithm, called **StoBatch** (Fig. 1b), in order to efficiently train large DP DNNs in adversarial learning, without affecting the DP protection (Alg. 4, **Appendix D**). In StoBatch, fixed and disjoint batches $\overline{\mathbf{B}}$ are distributed to $N/(2m)$ local trainers, each of which have two batches $\{\overline{B}_{i1}, \overline{B}_{i2}\}$ randomly picked from $\overline{\mathbf{B}}$ with $i \in [1, N/(2m)]$ (Line 4, Alg. 4). At each training step t, we randomly pick $\mathbb{N}$ local trainers, each of which gets the latest global parameters θ from the parameter server. A local trainer i will compute the gradients $\nabla_i \theta_1$ and $\nabla_i \theta_2$ to optimize the DP objective functions $\overline{\mathcal{R}}$ and $\overline{L}$ using its local batch $\overline{B}_{i1}$ and ensemble DP adversarial examples crafted from $\overline{B}_{i2}$ (Lines 5-14, Alg.

4). The gradients will be sent back to the parameter server for a synchronized SGD (Lines 15-16, Alg. 4), as follows: $\theta_1 \leftarrow \theta_1 - \frac{\varrho_t}{\mathbb{N}} \sum_{i\in[1,\mathbb{N}]} \nabla_i \theta_1, \quad \theta_2 \leftarrow \theta_2 - \frac{\varrho_t}{\mathbb{N}} \sum_{i\in[1,\mathbb{N}]} \nabla_i \theta_2$. This enables us to train large DNNs with our DP adversarial learning, by training from multiple batches simultaneously with more adversarial examples, without affecting the DP guarantee in Theorem 4; since the optimization of one batch does not affect the DP protection at any other batch and at the dataset level D across T training steps (**Theorem 4**).

In addition, the *average errors of our approximation functions* are always *bounded*, and are *independent* of the number of data instances N in D (**Appendix O**). This further ensures that our functions can be applied in large datasets.

Our approach can be extended into two different complementary scenarios: **(1)** Distributed training for each local trainer i, in which the batches $\{\overline{B}_{i1}, \overline{B}_{i2}\}$ can be located across $\mathbb{M}$ GPUs to efficiently compute the gradients $\nabla_i \theta_1 = \frac{1}{\mathbb{M}} \sum_{j\in[1,\mathbb{M}]} \nabla_{i,j} \theta_1$ and $\nabla_i \theta_2 = \frac{1}{\mathbb{M}} \sum_{j\in[1,\mathbb{M}]} \nabla_{i,j} \theta_2$; and **(2)** Federated training, given each local trainer can be considered as an independent party. In this setting, an independent party can further have different sizes of batches. As long as the global sensitivities $\Delta_{\mathcal{R}}$ and $\Delta_{\mathcal{L}2}$ are the same for all the parties, the DP guarantee in Theorem 4 does hold given D be the union of all local datasets from all the parties. This can be achieved by nomalizing all the inputs x to be in $[-1, 1]^d$. This is a step forward compared with the classical federated learning (McMahan et al., 2016). We focus on the distributed training setting in this paper, and reserve the federated learning scenarios for future exploration.

4. Experimental Results

We have conducted an extensive experiment on the MNIST, CIFAR-10, and Tiny ImageNet datasets. Our validation focuses on shedding light into the interplay among model utility, privacy loss, and robustness bounds, by learning **1)** the impact of the privacy budget $\epsilon = (\epsilon_1 + \epsilon_1/\gamma_{\mathbf{x}} + \epsilon_1/\gamma + \epsilon_2)$, **2)** the impact of attack sizes μ_a, and **3)** the scalability of our mechanism. We consider the class of l_∞-bounded adversaries. *All statistical tests are 2-tail t-tests.* Please refer to the **Appendix Q** for a complete analysis of our experimental results, including **Figures 2 - 9**. The implementation of our mechanism is available in TensorFlow[1].

Baseline Approaches. Our **StoBatch** mechanism is evaluated in comparison with state-of-the-art mechanisms in: (1) DP-preserving algorithms in deep learning, i.e., **DP-SGD** (Abadi et al., 2016), **AdLM** (Phan et al., 2017b); in (2) Certified robustness, i.e., **PixelDP** (Lecuyer et al., 2018); and in (3) DP-preserving algorithms with certified robustness, i.e., **SecureSGD** given heterogeneous noise (Phan et al., 2019), and **SecureSGD-AGM** (Phan et al., 2019) given the Analytic Gaussian Mechanism (AGM) (Balle & Wang, 2018). To preserve DP, DP-SGD injects random noise into gradients of parameters, while AdLM is a Functional Mechanism-based approach. PixelDP is one of the state-of-the-art mechanisms providing certified robustness using DP bounds. SecureSGD is a combination of PixelDP and DP-SGD with an advanced heterogeneous noise distribution; i.e., "more noise" is injected into "more vulnerable" latent features, to improve the robustness. The baseline models share the same design in our experiment. Four white-box attacks were used, including **FGSM**, **I-FGSM**, Momentum Iterative Method (**MIM**) (Dong et al., 2017), and **MadryEtAl** (Madry et al., 2018). Pure robust training and analysis can incur privacy leakage (Song et al., 2019); thus, in this study, similar algorithms to (Salman et al., 2019) do not fit as comparable baselines, since they may not be directly applicable to DP DNNs.

Model Configuration (Appendix P). It is important to note that $x \in [-1, 1]^d$ in our setting, which is different from a common setting, $x \in [0, 1]^d$. Thus, a given attack size $\mu_a = 0.3$ in the setting of $x \in [0, 1]^d$ is equivalent to an attack size $2\mu_a = 0.6$ in our setting. The reason for using $x \in [-1, 1]^d$ is to achieve better model utility, while retaining the same global sensitivities to preserve DP, compared with $x \in [0, 1]^d$. As in (Lecuyer et al., 2018), we apply two accuracy metrics:

$$\textit{conventional acc} = \sum_{i=1}^{|test|} \frac{isCorrect(x_i)}{|test|}$$

$$\textit{certified acc} = \sum_{i=1}^{|test|} \frac{isCorrect(x_i)\ \&\ isRobust(x_i)}{|test|}$$

where $|test|$ is the number of test cases, $isCorrect(\cdot)$ returns 1 if the model makes a correct prediction (else, returns 0), and $isRobust(\cdot)$ returns 1 if the robustness size is larger than a given attack size μ_a (else, returns 0).

Results on the MNIST Dataset. Figure 2 illustrates the conventional accuracy of each model as a function of the privacy budget ϵ on the MNIST dataset under $l_\infty(\mu_a)$-norm attacks, with $\mu_a = 0.2$. Our StoBatch outperforms AdLM, DP-SGD, SecureSGD, and SecureSGD-AGM, in all cases, with $p < 1.32e - 4$. When the privacy budget $\epsilon = 0.2$ (a tight DP protection), there are significant drops, in terms of conventional accuracy, given the baseline approaches. By contrast, our StoBatch only shows a small degradation in the conventional accuracy. At $\epsilon = 0.2$, our StoBatch achieves 82.7%, compared with 11.2% and 41.64% correspondingly for SecureSGD-AGM and SecureSGD. This shows the ability to offer tight DP protections under adversarial example attacks in our model, compared with existing algorithms.

• Figure 4 presents the conventional accuracy as a function of μ_a, under a strong DP guarantee, $\epsilon = 0.2$. It is

[1] https://github.com/haiphanNJIT/StoBatch

clear that our StoBatch mechanism outperforms the baseline approaches in all cases. On average, our StoBatch model improves 44.91% over SecureSGD, a 61.13% over SecureSGD-AGM, a 52.21% over AdLM, and a 62.20% over DP-SGD. More importantly, thanks to the composition robustness bounds in both input and latent spaces, and the random perturbation size $\mu_t \in (0, 1]$, our StoBatch model is resistant to different attack algorithms with different attack sizes μ_a, compared with baseline approaches.

• Figure 6 demonstrates the certified accuracy as a function of μ_a. The privacy budget is set to 1.0, offering a reasonable privacy protection. In PixelDP, the construction attack bound ϵ_r is set to 0.1, which is a pretty reasonable defense. With (small perturbation) $\mu_a \leq 0.2$, PixelDP achieves better certified accuracies under all attacks; since PixelDP does not preserve DP to protect the training data, compared with other models. Meanwhile, our StoBatch model outperforms all the other models when $\mu_a \geq 0.3$, indicating a stronger defense to more aggressive attacks.

Results on the CIFAR-10 Dataset further strengthen our observations. In Figure 3, our StoBatch outperforms baseline models in all cases ($p < 6.17e-9$), especially with small privacy budget ($\epsilon < 4$), yielding strong DP protections. On average conventional accuracy, our StoBatch mechanism has an improvement of 10.42% over SecureSGD, 14.08% over SecureSGD-AGM, 29.22% over AdLM, and 14.62% over DP-SGD. Furthermore, the accuracy of our model is consistent given different attacks with different adversarial perturbations μ_a under a rigorous DP protection ($\epsilon_t = 2.0$), compared with baseline approaches (Figure 5). In fact, when the attack size μ_a increases from 0.05 to 0.5, the conventional accuracies of the baseline approaches are remarkably reduced, i.e., a drop of 25.26% on average given the most effective baseline approach, SecureSGD. Meanwhile, there is a much smaller degradation (4.79% on average) in terms of the conventional accuracy observed in our StoBatch model. Figure 7 further shows that our StoBatch model is more accurate than baseline approaches (i.e., ϵ_r is set to 0.1 in PixelDP) in terms of certified accuracy in all cases, with a tight privacy budget set to 2.0 ($p < 2.04e-18$).

Scalability and Strong Iterative Attacks. First, we scale our model in terms of *adversarial training* in the CIFAR-10 data, i.e., the number of iterative attack steps is increased to T_μ=*200 in training*, and to T_a=*2,000 in testing*. The iterative batch-by-batch DP adversarial training (Alg. 1) is infeasible in this setting, taking over 30 days for one training with 600 epochs. Thanks to the distributed training, our StoBatch takes $\approxeq$ 3 days to finish the training ($\mathbb{N} = 1$, $\mathbb{M} = 4$). More importantly, our StoBatch achieves consistent accuracies under strong iterative attacks with T_a=$\{1,000; 2,000\}$, compared with the best baseline, i.e., SecureSGD (Figure 8). On average, across attack sizes $\mu_a \in \{0.05, 0.1, 0.2, 0.3, 0.4, 0.5\}$ and steps $T_a \in \{100, 500, 1000, 2000\}$, our StoBatch achieves 45.25±1.6% and 42.59±1.58% in conventional and certified accuracies, compared with 29.08±11.95% and 19.58±5.0% of SecureSGD ($p < 2.75e-20$).

• We achieve a similar improvement over the **Tiny ImageNet** with a ResNet18 model, i.e., *a larger dataset on a larger network*, ($\mathbb{N} = 1$, $\mathbb{M} = 20$) (Figure 9). On average, across attack sizes $\mu_a \in \{0.05, 0.1, 0.2, 0.3, 0.4, 0.5\}$ and steps $T_a \in \{100, 500, 1000, 2000\}$, our StoBatch achieves 29.78±4.8% and 28.31±1.58% in conventional and certified accuracies, compared with 8.99±5.95% and 8.72±5.5% of SecureSGD ($p < 1.55e-42$).

Key observations: (1) Incorporating ensemble adversarial learning into DP preservation, tightened sensitivity bounds, a random perturbation size μ_t at each training step, and composition robustness bounds in both input and latent spaces does enhance the consistency, robustness, and accuracy of DP model against different attacks with different levels of perturbations. These are key advantages of our mechanism; **(2)** As a result, our StoBatch model outperforms baseline algorithms, in terms of conventional and certified accuracies in most of the cases. It is clear that existing DP-preserving approaches have not been designed to withstand against adversarial examples; and **(3)** Our StoBatch training can help us to scale our mechanism to larger DP DNNs and datasets with distributed adversarial learning, without affecting the model accuracies and DP protections.

5. Conclusion

In this paper, we established a connection among DP preservation to protect the training data, adversarial learning, and certified robustness. A sequential composition robustness was introduced to generalize robustness given any sequential and bounded function of independent defensive mechanisms in both input and latent spaces. We addressed the trade-off among model utility, privacy loss, and robustness by tightening the global sensitivity bounds. We further developed a stochastic batch training mechanism to bypass the vanilla iterative batch-by-batch training in DP DNNs. The average errors of our approximation functions are always bounded by constant values. Last but not least, a new Monte Carlo Estimation was proposed to stabilize the estimation of the robustness bounds. Rigorous experiments conducted on benchmark datasets shown that our mechanism significantly enhances the robustness and scalability of DP DNNs. In future work, we will test our algorithms and models in the Baidu Fedcube platform (Baidu, 2020). In addition, we will evaluate our robustness bounds against synergistic attacks, in which adversarial examples can be combined with other attacks, such as Trojans (Gu et al., 2017; Liu et al., 2018), to create more lethal and stealthier threats (Pang et al., 2020).

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