Efficient Private Algorithms for Learning Halfspaces

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Abstract

We present new differentially private algorithms for learning a large-margin halfspace. In contrast to previous algorithms, which are based on either differentially private simulations of the statistical query model or on private convex optimization, the sample complexity of our algorithms depends only on the margin of the data, and not on the dimension.

1 Introduction

In a classification problem, we are given labeled examples from some unknown distribution, and the goal is to learn a classifier that accurately labels future examples from the same distribution. In many applications, each of these examples represents the highly sensitive privacy information of some individual. Although the goal of classification is to learn about the distribution, and not about the examples per se, many natural learning algorithms have the unfortunate side effect of revealing all or part of some of the labeled examples. For example, support vector machines represent the learned classifier as a set of support vectors, which are just labeled examples from the input!

The now-standard approach for ensuring privacy in machine learning is differential privacy (DP) [Dwork et al., 2006], which, informally, requires that no individual labeled example in the input significantly influences the learned classifier. Starting with some of the earliest work in differential privacy [Blum et al., 2005, Kasiviswanathan et al., 2008], there is a large body of literature showing that nearly every classification problem can be solved with differential privacy, albeit with large overheads in both sample complexity and running time. It is thus central to understand for which problems these overheads can be eliminated, and for which they are inherent.

In this paper we study the classical problem of learning a large-margin halfspace. That is, the examples are unit vectors $x \in \mathbb{R}^d$ labeled with $y \in \{\pm 1\}$, and we assume that $y = \text{sign}(\langle w, x \rangle)$ for some unknown unit vector $w \in \mathbb{R}^d$. Further, no example falls too close to the boundary of the halfspace, meaning that $y \cdot \langle w, x \rangle \geq \gamma$, where $\gamma$ is called the margin. When $d$ is large, assuming a large margin enables learning the halfspace with sample complexity independent of $d$.

Many results in differential privacy either explicitly or implicitly give private algorithms for learning a large-margin halfspace (see the related work for a detailed discussion). [Blum et al., 2005] gave a differentially private implementation of the classical Perceptron algorithm for learning a large-margin halfspace, however their implementation requires sample complexity $\text{poly}(d)$, which is
Sample Complexity | Running Time | Privacy
---|---|---
Theorem 2 | $\frac{1}{\alpha \varepsilon \gamma^2}$ | $\text{poly}(d, \frac{\log(1/\beta \delta)}{\alpha \varepsilon \gamma})$ | $(\varepsilon, \delta)$
Theorem 4 | $\frac{1}{\alpha \varepsilon \gamma^2}$ | $2^{\tilde{O}(1/\gamma^2)} \cdot \text{poly}(d, \frac{\log(1/\beta \delta)}{\alpha \varepsilon})$ | $(\varepsilon, 0)$

Table 1: Sample complexity and running time bounds for our algorithms. For simplicity, each of these bounds suppresses polylogarithmic factors of $\alpha, \beta, \varepsilon, \delta, \gamma$.

precisely what the large-margin assumption is meant to avoid. A distinct line of work, beginning with Chaudhuri et al. [2011], studies differentially private algorithms for empirical loss minimization problems. Although learning a large-margin halfspace can be achieved via minimizing the Hinge loss, generic algorithms for differentially private loss minimization inherently require $\text{poly}(d)$ samples [Bun et al., 2014, Bassily et al., 2014].

1.1 Results

In this work we give two new differentially private algorithms for learning a large margin halfspace. The key feature of our algorithms is that the sample complexity depends only on the margin, the desired accuracy of the learner, and the desired level of privacy, and not on the dimension. More precisely, our sample complexity is (ignoring constants and logarithmic factors) $1/\alpha \varepsilon \gamma^2$ where $\alpha$ is the desired error and $\varepsilon$ is the desired privacy. In contrast, without privacy the sample complexity is roughly $1/\alpha \gamma^2$, so our sample complexity is comparable to that of non-private algorithms except when $\varepsilon$ is very small.

Our first algorithm runs in polynomial time in all the parameters and satisfies the standard notion of $(\varepsilon, \delta)$-DP. Our second algorithm’s running time grows exponentially in the inverse-margin $1/\gamma$, but the algorithm satisfies the very strong special case of $(\varepsilon, 0)$-DP (so-called pure DP). Our results are described in more detail in Table 1.

The main technique in both of our algorithms is to use random projections to reduce the dimensionality of the space to $\approx 1/\gamma^2$. After projection, we can learn using either a differentially private algorithm for minimizing Hinge loss or by using the exponential mechanism over a net of possible halfspaces. We note that using either of these techniques on its own, without the projection, would fail to find an accurate classifier without $\text{poly}(d)$ samples.

We also prove a lower bound showing that any $(\varepsilon, 0)$-differentially private algorithm for learning a large-margin halfspace (with constant classification error) requires $\Omega(1/\varepsilon \gamma^2)$ samples (unless $d = O(1/\gamma^2)$). This lower bound is presented in Theorem 4.

1.2 Related Work

Blum et al. [2005] gave a differentially private implementation of the classical Perceptron algorithm, based on a general differentially private simulation of algorithms in the statistical queries model [Kearns, 1993]. Their algorithm can be improved using more recent statistical queries algorithms by Feldman et al. [2017], but this approach still requires $\text{poly}(d)$ samples. The foundational work of Kasiviswanathan et al. [2008] studied differentially private PAC learning, and gave a generic private PAC learner, but they did not consider margin-based learning guarantees.

An alternative approach is to leverage algorithms for differentially private convex optimizing to identify a halfspace minimizing the Hinge loss. Differentially private convex optimization is now the subject of a large body of literature that is too large to survey here. Notably Bassily et al.
We consider a distribution $D$ and assume without loss of generality that $1$ at least $\beta$ error, that is, there exists a $\beta$ distribution $D$ such that one can input a halfspace such that if the data has large margin with respect to that halfspace, then the structure outputs an estimate of how many points are labeled positively. One could use such a data structure to learn a large-margin halfspace, however, their algorithm has sample complexity poly($d$), and the resulting learning algorithm would also not be computationally efficient.

Similar to our work, there have been other applications of random projections in differential privacy. One example is the above query release algorithm from Blum et al. [2008], which is conceptually similar to our purely differentially private algorithm. In a very different setting, the work of Jain and Thakurta [2013] demonstrated that certain random projection matrices automatically preserve privacy, however there is no technical relationship between their results and ours. Kenthapadi et al. [2012] also used the Johnson-Lindenstrauss transform to achieve better utility and computational efficiency for privately estimating distances between users, but again there is no technical relationship between their results and ours.

2 Preliminaries

2.1 Learning Halfspaces

We consider a distribution $D$ over $\mathcal{X} \times \{\pm 1\}$, where $\mathcal{X} \subseteq \mathbb{R}^d$. We denote by $B^d_2$ the ball in $\mathbb{R}^d$ with center $0$ and radius $1$ with respect to the euclidean norm $\| \cdot \|_2$. We assume that all examples are normalized so that $\mathcal{X} = B^d_2$.

A linear threshold function is defined as $f_{w,\theta}(x) = \text{sign}(\langle w, x \rangle - \theta)$, where $x, w \in \mathbb{R}^d$ and $\theta \in \mathbb{R}$. We assume without loss of generality that $\theta = 0$ so $f_w(x) = \text{sign}(\langle w, x \rangle)$\footnote{We can simulate a non-zero threshold by letting $\tilde{x} = [x, 1]$, running the algorithm with the scaled margin, and returning $f_{w,-w,1}$, where $\tilde{w} = [w, w, 1]$ is the output of the algorithm. This would only increase the dimension of the space by $1$.}

We call a vector $w$ a hypothesis. The error of a threshold function defined by hypothesis $w$ on distribution $D$ is

$$\text{err}_D(f_w) = \Pr_{(x, y) \sim D} [f_w(x) \neq y] = \Pr_{(x, y) \sim D} [\text{sign}(\langle w, x \rangle) \neq y] = \Pr_{(x, y) \sim D} [y \cdot \langle w, x \rangle < 0].$$

As in the PAC learning model, introduced by Valiant [1984], where PAC stands for probably approximately correct, the goal is to find a hypothesis $w$ such that $\text{err}_D(f_w) \leq \alpha$ with probability at least $1 - \beta$, for given parameters $\alpha$ and $\beta$. We assume that there exists a hypothesis with zero error, that is, there exists a $w^* \in B^d_2$ such that $y \cdot \langle w^*, x \rangle > 0 \forall (x, y)$.

More specifically, we assume that $w^*$ maximizes the margin, which is defined as

$$\gamma = \min_{x \in \mathcal{X}} \frac{|\langle w^*, x \rangle|}{\|w^*\|_2 \cdot \|x\|_2}.$$ 

Equivalently, $\gamma \leq |\cos(w^*, x)| \forall x$, where the right hand side is the distance of a scaled point $x$ from the halfspace $\langle w^*, x \rangle = 0$. It follows that $\gamma \in (0, 1]$ and it is assumed that $\gamma$ is known in advance.
Our goal is to design algorithms which, given enough data points drawn from a distribution $D$ over a linearly separable set with margin $\gamma$, return a hypothesis which has error at most $\alpha$ with respect to the distribution, with probability at least $1 - \beta$. More formally, we aim to design an $(\alpha, \beta, \gamma)$-PAC learner with low sample complexity.

**Definition 2.1** ($(\alpha, \beta, \gamma)$-PAC learner). Let $D$ be a distribution over $\mathcal{B}_d^2 \times \{\pm 1\}$ such that there exists $w^* \in \mathcal{B}_d^2$ for which

$$\Pr_{(x,y) \sim D} [y\langle w^*, x \rangle \geq \gamma] = 1.$$  

We call such a distribution $D$ a distribution with margin $\gamma$.

An algorithm $A$ is an $(\alpha, \beta, \gamma)$-PAC learner for halfspaces in $\mathbb{R}^d$ with margin $\gamma$ and sample complexity $n$ if, given a sample set $S \sim D^n$ from any distribution $D$ with margin $\gamma$, it outputs a classifier $A(S) = \hat{w} \in \mathcal{B}_d^2$ such that

$$\Pr_{(x,y) \sim D} \left[ y = \text{sign}(\langle \hat{w}, x \rangle) \right] \geq 1 - \alpha$$

holds with probability at least $1 - \beta$.

### 2.2 Differential Privacy

We design algorithms which draw a sample set $S$ and output a hypothesis $w \in \mathbb{R}^d$. In addition to finding a good hypothesis, our algorithms must satisfy differential privacy (DP) guarantees. Differential privacy is a property that a randomized algorithm satisfies if its output distribution does not change significantly under the change of a single data point.

More formally, let $S, S' \in S^n$ be two data sets of the same size. We say that $S, S'$ are neighbors, denoted as $S \sim S'$, if they differ in at most one data point.

**Definition 2.2** (Differential Privacy, Dwork et al. [2006]). A randomized algorithm $A : S^n \rightarrow O$ is $(\varepsilon, \delta)$-differentially private if for all neighboring data sets $S, S'$ and all measurable $O \subseteq O$,

$$\Pr[A(S) \in O] \leq \exp(\varepsilon) \Pr[A(S') \in O] + \delta.$$  

Algorithm $A$ is $(\varepsilon, 0)$-differentially private if it satisfies the definition for $\delta = 0$.

A useful property of differential privacy is that it is closed under post-processing.

**Lemma 1** (Post-Processing, Dwork et al. [2006]). Let $A : S^n \rightarrow O$ be a randomized algorithm that is $(\varepsilon, \delta)$-differentially private. For every (possibly randomized) $f : O \rightarrow O'$, $f \circ A$ is $(\varepsilon, \delta)$-differentially private.

### 3 An Efficient Private Algorithm

Both the algorithm of this and the next section draw a sample set $S \sim D^n$ and perform dimension reduction from a $d$-dimensional to an $m$-dimensional space, which allows them to run in the reduced space for the remainder of the execution.
Algorithm 1 $A_{\alpha, \beta, \varepsilon, \delta, \gamma}(S)$

1: Choose a random matrix $A \in \mathbb{R}^{m \times d}$, where $m = O\left(\frac{\log(1/\beta JL)}{\gamma^2}\right)$, $\beta JL = \alpha \beta^2 / 64n$, and

$$A_{ij} = \begin{cases} +1/\sqrt{m} & \text{w.p. } 1/2 \\ -1/\sqrt{m} & \text{w.p. } 1/2 \end{cases}$$

2: Define $S_A \leftarrow \{(Ax/\|Ax\|_2, y) \mid (x, y) \in S\}$.
3: Define the hypothesis set $C \leftarrow \mathcal{B}_{2m}^d$.
4: Define the $\frac{100}{86}$-Lipschitz loss function $\ell : C \times (\mathcal{B}_{2}^m \times \{\pm 1\}) \rightarrow \mathbb{R}$ as

$$\ell(w; (x, y)) = \begin{cases} 1 & \text{if } y \cdot \langle w, x \rangle < \frac{96\gamma}{100} \\ \frac{96}{86} - \frac{y \cdot \langle w, x \rangle}{86\gamma/100} & \text{otherwise} \end{cases}.$$ 

5: Let $\hat{w} \leftarrow \mathcal{F}(S_A, \ell, (\varepsilon, \delta), C)$.
6: Return $\hat{w}^\top A$.

Algorithm $\mathcal{F}$ is any differentially private empirical risk minimization algorithm. It takes as input a sample set $D$, a loss function $\ell$ with Lipschitz constant $L$, differential privacy parameters $(\varepsilon, \delta)$, and a convex hypothesis space $C$, and returns a hypothesis with low empirical risk on the sample set $D$. We can instantiate algorithm $\mathcal{F}$ with the noisy stochastic gradient descent algorithm of Bassily et al. [2014] so that it has the following guarantee. The full algorithm is presented in Appendix A for completeness.

**Theorem 1** (Bassily et al. [2014]). There exists an algorithm $\mathcal{F}$ that is $(\varepsilon, \delta)$-differentially private and returns a hypothesis $\hat{w}$ for which, with probability at least $1 - \beta/4$, it holds that

$$\mathcal{L}(\hat{w}; D) - \min_{w \in C} \mathcal{L}(w; D) = \frac{\sqrt{mL\|C\|_2}}{\varepsilon} \cdot \text{polylog}\left(n, \frac{1}{\beta}, \frac{1}{\delta}\right),$$

where $\mathcal{L}(w; D) = \sum_{(x, y) \in D} \ell(w; (x, y))$ is the total loss of a hypothesis $w$ on the data set $D$.

For the following proofs, we denote $x_A := \frac{Ax}{\|Ax\|_2}$ for any $x \in \mathcal{B}_2^d$. It holds that $x_A \in \mathcal{B}_{2m}^d$ and the modified sample set can be also written as $S_A = \{(x_A, y) \mid (x, y) \in S\}$.

The lemma that follows guarantees that the transformation of a point $x \mapsto Ax$, with high probability, only changes its euclidean norm by a small multiplicative factor.

**Lemma 2** (Distributional Johnson-Lindenstrauss Lemma, Achlioptas [2003]). Let $A \in \mathbb{R}^{m \times d}$ be a random matrix such that $m = O\left(\frac{\log(1/\beta JL)}{\gamma^2}\right)$ and

$$A_{ij} = \begin{cases} +1/\sqrt{m} & \text{w.p. } 1/2 \\ -1/\sqrt{m} & \text{w.p. } 1/2 \end{cases}$$

Then, for every $x \in \mathbb{R}^d$, it holds that:

$$\Pr_A \left[ \|Ax\|_2^2 - \|x\|_2^2 \leq \frac{\gamma}{100} \|x\|_2^2 \right] \geq 1 - \beta JL.$$
Since the transform leaves the norm of a point \( x \) almost unchanged, one would expect that the corresponding transformed and normalized hypothesis \( \mathbf{w}_A^* := A\mathbf{w}^*/\|A\mathbf{w}^*\|_2 \) would still have a large enough margin with respect to the corresponding point \( x_A \). The following lemma defines the probability that a point \( x \) belongs in the set of points \( \mathcal{G}_A \), which are “good” for a fixed matrix \( A \), in the sense that their norm remains almost unchanged and the margin of their corresponding points \( x_A \) from \( \mathbf{w}_A^* \) is close to the original.

**Lemma 3.** For every given matrix \( A \), let \( \mathcal{G}_A \subseteq \mathcal{X} \times \{\pm 1\} \) be the set of data points \((x, y)\) that satisfy the following two statements:

1. \( \|Ax\|_2^2 - \|x\|_2^2 \leq \frac{2}{100} \|x\|_2^2 \) and
2. \( \mathbf{w}_A^* = \frac{A\mathbf{w}^*}{\|A\mathbf{w}^*\|_2} \) has margin at least \( 96\gamma/100 \) on \((x_A, y)\), i.e., \( y \cdot \langle \mathbf{w}_A^*, x_A \rangle \geq 96\gamma/100 \).

It holds that

\[
\Pr_{(x, y) \sim D}[(x, y) \in \mathcal{G}_A] \geq 1 - 4\beta_{JL}.
\]

For the proof of Lemma 3, we express an inner product as \( \langle \mathbf{w}^*, x \rangle = \frac{1}{2} \| x + \mathbf{w}^* \|_2^2 - \frac{1}{4} \| x - \mathbf{w}^* \|_2^2 \) and use the guarantee of the Distributional Johnson-Lindenstrauss Lemma on vectors \( x, \mathbf{w}^*, x - \mathbf{w}^*, x + \mathbf{w}^* \). By union bound, we get that with probability at least \( 1 - 4\beta_{JL} \), \( x_A \) has margin \( 96\gamma/100 \) with respect to \( \mathbf{w}_A^* \). The proof is in Appendix A.

In the following, we provide the privacy and sample complexity guarantees of our algorithm.

**Theorem 2** (Sample complexity). Algorithm \( \mathcal{A}_{\alpha, \beta, \varepsilon, \delta, \gamma} \) is an \((\alpha, \beta, \gamma)\)-learner with sample complexity

\[
n = \frac{1}{\alpha \varepsilon \gamma^2} \cdot \text{polylog} \left( \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\delta}, \frac{1}{\varepsilon}, \frac{1}{\gamma} \right).
\]

**Proof of Theorem 2**. The first step of the algorithm is to sample matrix \( A \) uniformly at random from \( U = \left\{ \pm \frac{1}{\sqrt{m}} \right\}^{m \times d} \). From Lemma 3, it follows that \( \mathbb{E}_A \left[ \Pr_{(x, y) \sim D}[(x, y) \notin \mathcal{G}_A] \right] \leq 4\beta_{JL} \). And, by Markov’s inequality,

\[
\Pr_A \left[ \Pr_{(x, y) \sim D}[(x, y) \notin \mathcal{G}_A] \geq \beta' \right] \leq \frac{\mathbb{E}_A \left[ \Pr_{(x, y) \sim D}[(x, y) \notin \mathcal{G}_A] \right]}{\beta'} \leq \frac{4\beta_{JL}}{\beta'}.
\]

We set \( \beta' = \alpha \beta/4n \). Then, substituting \( \beta_{JL} = \frac{\alpha \beta^2}{64m} \), we get that with probability at least \( 1 - \beta/4 \),

\[
\Pr_{(x, y) \sim D}[(x, y) \in \mathcal{G}_A] \geq 1 - \beta'.
\]

Therefore, with probability \( 1 - \beta/4 \), the sampled matrix \( A \) satisfies inequality (2), that is, a point \((x, y) \sim D \) is in \( \mathcal{G}_A \) with probability at least \( 1 - \beta' \). Furthermore, by union bound, \( \forall (x, y) \in S \) it holds that \((x, y) \in \mathcal{G}_A \), with probability at least \( 1 - n\beta' \geq 1 - \beta/4 \).

For the remainder of the proof, we condition on the event that:

1. \( \Pr_{(x, y) \sim D}[(x, y) \in \mathcal{G}_A] \geq 1 - \beta' \) holds for \( A \) and
2. \( S \subseteq \mathcal{G}_A \), that is, \( \mathbf{w}_A^* \) has margin at least \( 96\gamma/100 \) on \( S_A \).

This event occurs with probability at least \( 1 - \beta/4 - \beta/4 = 1 - \beta/2 \).
Claim 2.1. If \( n = \frac{1}{\alpha \gamma} \cdot \text{polylog} \left( \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\delta}, \frac{1}{\gamma} \right) \), then for the hypothesis \( \hat{w} \) returned by \( F \), with probability \( 1 - \beta/4 \), it holds that

\[
\frac{1}{n} \sum_{(x_A,y) \in S_A} \mathbb{1}\{y \cdot \langle \hat{w}, x_A \rangle < \frac{\gamma}{10}\} \leq \frac{\alpha}{4}.
\]  

(3)

Proof of Claim 2.1. Since \( w_A^* \) has margin at least \( 96\gamma/100 \) for all points in \( S_A \), it holds that \( \min_{{w \in C}} \mathcal{L}(w; S_A) \leq \mathcal{L}(w_A^*; S_A) = 0 \). Substituting \( \|C\|_2 = 2 \), \( L = 100/86\gamma \), and \( m = O \left( \frac{\log(n/\alpha \beta)}{\gamma^2} \right) \) into (1), dividing by \( n \), and simplifying the expression, we get that with probability at least \( 1 - \beta/4 \),

\[
\frac{1}{n} \mathcal{L}(\hat{w}; S_A) = \frac{1}{n \in \gamma^2} \cdot \text{polylog} \left( n, \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\delta} \right).
\]  

(4)

It also holds that:

\[
\frac{1}{n} \sum_{(x_A,y) \in S_A} \mathbb{1}\{y \cdot \langle \hat{w}, x_A \rangle < \frac{\gamma}{10}\} = \frac{1}{n \in \gamma^2} \cdot \text{polylog} \left( n, \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\delta} \right).
\]

By the latter and inequality (1), it follows that with probability at least \( 1 - \beta/4 \),

\[
\frac{1}{n} \sum_{(x_A,y) \in S_A} \mathbb{1}\{y \cdot \langle \hat{w}, x_A \rangle < \frac{\gamma}{10}\} = \frac{1}{n \in \gamma^2} \cdot \text{polylog} \left( n, \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\delta} \right).
\]

Therefore, for \( n = \frac{1}{\alpha \gamma} \cdot \text{polylog} \left( \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\delta}, \frac{1}{\gamma} \right) \) with probability at least \( 1 - \beta/4 \),

\[
\frac{1}{n} \sum_{(x_A,y) \in S_A} \mathbb{1}\{y \cdot \langle \hat{w}, x_A \rangle < \frac{\gamma}{10}\} \leq \frac{\alpha}{4}.
\]

This completes the proof of the claim.

Claim 2.2. If \( n = \frac{1}{\alpha \gamma} \cdot \text{polylog} \left( \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\delta}, \frac{1}{\gamma} \right) \), then with probability \( 1 - \beta/2 \), the error of the returned classifier \( \hat{w}^\top A \) on distribution \( D \) is

\[
\Pr_{(x,y) \sim D} \left[ y \cdot \langle \hat{w}^\top A, x \rangle < 0 \right] \leq \alpha.
\]

(5)

Proof of Claim 2.2. Let \( D_A \) denote the probability distribution with domain \( B_2^n \times \{\pm 1\} \), from which a sample \((x_A, y) \in S_A\) is drawn. Let us also denote by \( D |_{G_A} \) distribution \( D \) restricted on \( G_A \). In our conditioned probability space, \( S_A \sim D_A^n \), where the probability density function of \( D_A \) would be defined as

\[
\Pr_{(x_A,y) \sim D_A} \left[ x_A = x' \land y = y' \right] = \Pr_{(x,y) \sim D |_{G_A}} \left[ Ax = x' \land y = y' \right].
\]

Let \( \mathcal{H} = \{h : \{x_A \mid (x, y) \in G_A\} \rightarrow \{\pm 1\} \text{ s.t. } h(x) = \text{sign}(\langle w, x \rangle) \text{ for some } w \in B_2^n\} \) be a concept class of threshold functions in \( B_2^n \). By Theorem 3.4 of [Anthony and Bartlett 2009], \( \text{VCdim}(\mathcal{H}) = m + 1 \).
By the generalization bound of Theorem 5.7 of [Anthony and Bartlett 2009], it holds that:

\[
\Pr_{S \sim D_n^A} \left[ \exists h \in \mathcal{H} : \text{err}_D(h) > 2 \frac{1}{n} \sum_{(x,y) \in S_A} 1\{h(x_A) \neq y\} + \frac{\alpha}{4} \right] \leq 4 \Pi_H(2n) \exp(-\alpha n/32)
\]

where the growth function \(\Pi_H(2n) \leq (2n)^{m+1} + 1\), by Theorem 3.7 of [Anthony and Bartlett 2009].

Using \(m = O\left(\frac{\log(1/\alpha\beta)}{\gamma^2}\right)\), it holds that if \(n = \frac{1}{\alpha^2 \gamma^2} \text{polylog}\left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}\right)\) then \(4 \Pi_H(2n) \exp(-\alpha n/32) \leq \beta/4\). Therefore, with probability at least \(1 - \beta/4\),

\[
\text{err}_{D_n}(f_{\hat{w}}) \leq 2 \cdot \frac{1}{n} \sum_{(x,y) \in S_A} 1\{y \cdot (\hat{w}, x_A) < 0\} + \frac{\alpha}{4}
\]  

(6)

By Claim 2.1, \(\frac{1}{n} \sum_{(x,y) \in S_A} 1\{y \cdot (\hat{w}, x_A) < 0\} \leq \frac{1}{n} \sum_{(x,y) \in S_A} 1\{y \cdot (\hat{w}, x_A) < \frac{1}{10}\} \leq \frac{\alpha}{4}\) holds with probability \(1 - \beta/4\), if \(n = \frac{1}{\alpha^2 \gamma^2} \text{polylog}\left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}\right)\).

Therefore, by inequality (6), if \(n = \frac{1}{\alpha^2 \gamma^2} \text{polylog}\left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}\right)\), then with probability at least \(1 - \beta/4 - \beta/4 = 1 - \beta/2\),

\[
\text{err}_{D_n}(f_{\hat{w}}) \leq 2 \cdot \frac{\alpha}{4} + \frac{\alpha}{4} = \frac{3\alpha}{4}.
\]

Equivalently, with probability at least \(1 - \beta/2\),

\[
\Pr_{(x,y) \sim D_{\mathcal{G}_A}} [y \cdot (\hat{w}^\top A, x) < 0] = \Pr_{(x,y) \sim D_A} [y \cdot (\hat{w}, x_A) < 0] = \text{err}_{D_n}(f_{\hat{w}}) \leq \frac{3\alpha}{4}.
\]

Since, by Condition 1., \(\Pr_{(x,y) \sim D} [(x,y) \notin \mathcal{G}_A] \leq \beta' \leq \frac{\alpha}{4}\), it follows that with probability at least \(1 - \beta/2\),

\[
\Pr_{(x,y) \sim D} [y \cdot (\hat{w}^\top A, x) < 0] \leq \Pr_{(x,y) \sim D_{\mathcal{G}_A}} [y \cdot (\hat{w}^\top A, x) < 0] \cdot (1 - \beta') + 1 \cdot \beta'
\]

\[
\leq \frac{3\alpha}{4} \cdot (1 - \beta') + \beta'
\]

\[
\leq \frac{3\alpha}{4} + \frac{\alpha}{4} \leq \alpha.
\]

This completes the proof of the claim. \(\square\)

Accounting for the probability that we are not in the conditioned space, we conclude that if \(n = \frac{1}{\alpha^2 \gamma^2} \text{polylog}\left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}\right)\), then with probability at least \(1 - \beta/2 - \beta/2 = 1 - \beta\), \(\text{err}_{D}(f_{\hat{w}^\top A}) \leq \alpha\).

This completes the proof of the theorem. \(\square\)

**Theorem 3** (Privacy guarantee). Algorithm \(A_{\alpha,\beta,\epsilon,\delta,\gamma}\) is \((\epsilon, \delta)\)-differentially private.

**Proof of Theorem 3** By Lemma 11, \((\epsilon, \delta)\)-differential privacy is closed under post-processing. Therefore it suffices to show that an algorithm \(\mathcal{N}\) that is the same as \(A_{\alpha,\beta,\epsilon,\delta,\gamma}\) except that it returns \(\hat{w}\) instead of \(\hat{w}^\top A\), is \((\epsilon, \delta)\)-DP.

Let \(S\) and \(S'\) be two neighboring data sets such that \(S = S' \setminus \{(x', y')\} \cup \{(x, y)\}\). Let \(U = \left\{ \pm \frac{1}{\sqrt{m}} \right\}^{m \times d}\). If we fix a matrix \(A \in U\), the sample sets \(S\) and \(S'\) would correspond to \(\mathcal{F}\)'s inputs
\[ S_A \text{ and } S_A' = S_A \setminus \{(x_A', y')\} \cup \{(x_A, y)\}, \text{ respectively. Recall from Theorem 1 that algorithm } \mathcal{F} \text{ is } (\epsilon, \delta)\text{-DP.} \]

For any measurable set \( R \subseteq \mathbb{R}^m \), it holds that
\[
\Pr[N(S) \in R] = \sum_{A \in U} \Pr[A] \cdot \Pr[\mathcal{F}(S_A) \in R \mid A]
\leq \sum_{A \in U} \Pr[A] \cdot (\exp(\epsilon) \Pr[\mathcal{F}(S_A') \in R \mid A] + \delta)
\]
(by Theorem 1)
\[
= \exp(\epsilon) \sum_{A \in U} \Pr[A] \cdot \Pr[\mathcal{F}(S_A') \in R \mid A] + \delta \sum_{A \in U} \Pr[A]
\]
\[
= \exp(\epsilon) \Pr[N(S') \in R] + \delta.
\]

Therefore, \( N \) is \((\epsilon, \delta)\)-DP, and so is \( A_{\alpha, \beta, \epsilon, \delta, \gamma} \).

\section{A Purely Differentially Private Algorithm}

As previously, algorithm \( A_{\alpha, \beta, \epsilon, \gamma} \) takes as input a sample set \( S \sim D^n \) and performs dimension reduction from the \( d \)-dimensional space to an \( m \)-dimensional space. In this reduced space, the algorithm defines a net of hypotheses and uses the Exponential Mechanism \cite{McSherry2007} to choose a good hypothesis with respect to the sample set.

The Exponential Mechanism is a well-known algorithm, which serves as a building block for many differentially private algorithms. The mechanism is used in cases where we need to choose the optimal output with respect to some utility function on the data set. More formally, let \( O \) denote the range of the outputs and let \( u : S^n \times O \rightarrow \mathbb{R} \) be the utility function which maps the data set - output pairs to utility scores.

An important notion in differential privacy is that of the sensitivity of a function. Intuitively, it represents the maximum change that the change of a single data point can incur on the output of the function, and as a result, it drives the amount of uncertainty we need in order to ensure privacy. The sensitivity of the utility function, which is only with respect to the data set, is defined as
\[
\Delta u = \max_{o \in O} \max_{S, S' \in S^n} \max_{S \sim S'} |u(S, o) - u(S', o)|.
\]

**Definition 4.1** (Exponential Mechanism, \cite{McSherry2007}). Let data set \( S \in S^n \), range \( O \), and utility function \( u : S^n \times O \rightarrow \mathbb{R} \). The Exponential Mechanism \( \mathcal{M}_E(S, u, O) \) selects and outputs an element \( o \in O \) with probability proportional to \( \exp(\frac{\epsilon \cdot u(S, o)}{2 \Delta u}) \).

The Exponential Mechanism has the following guarantees.

**Lemma 4** (Privacy and Accuracy of the Exponential Mechanism, \cite{McSherry2007}). The Exponential Mechanism is \((\epsilon, 0)\)-differentially private and with probability at least \( 1 - \delta \)
\[
|\max_{o \in O} u(S, o) - u(\mathcal{M}_E(S, u, O))| \leq \frac{2 \Delta u}{\epsilon} \ln\left(\frac{|O|}{\delta}\right).
\]
Algorithm 2 $\mathcal{A}_{\alpha, \beta, \varepsilon, \gamma}(S)$

1: Choose a random matrix $A \in \mathbb{R}^{m \times d}$, where $m = O\left(\frac{\log(1/\beta JL)}{\gamma^2}\right)$, $\beta JL = \alpha \beta^2 / 64 n$, and

$$A_{ij} = \begin{cases} 
+1 / \sqrt{m} & \text{w.p. 1/2} \\
-1 / \sqrt{m} & \text{w.p. 1/2}.
\end{cases}$$

2: Define $S_A \leftarrow \{(Ax/\|Ax\|_2, y) \mid (x, y) \in S\}$.
3: Let $W$ be a $\frac{\gamma}{10}$-Net of $\mathbb{R}^m$.
4: Define the utility function $u : (B^m_2 \times \{\pm 1\})^n \times W \rightarrow [-1, 0]$

$$u(D, w) = -\frac{1}{n} \cdot \sum_{(x, y) \in D} 1\{y \cdot \langle w, x \rangle < \frac{\gamma}{10}\}.$$ 

5: $\hat{w} \leftarrow \mathcal{M}_E(S_A, u, W)$
6: return $\hat{w}^\top A$.

In the following we provide the sample complexity and privacy guarantees of our algorithm.

**Theorem 4 (Sample Complexity).** Algorithm $\mathcal{A}_{\alpha, \beta, \varepsilon, \gamma}$ is an $(\alpha, \beta, \gamma)$-learner with sample complexity

$$n = \frac{1}{\alpha \varepsilon^2} \cdot \text{polylog}\left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\varepsilon}, \frac{1}{\gamma}\right).$$

The proof of Theorem 4 is very similar to that of the previous section, except for the bound on the empirical loss of the learned classifier. We prove this part here, and the full proof can be found in Appendix B.

**Claim 4.1.** If $n = \frac{1}{\alpha \varepsilon^2} \cdot \text{polylog}\left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\varepsilon}, \frac{1}{\gamma}\right)$, then with probability $1 - \beta/4$, for hypothesis $\hat{w}$ returned by the Exponential Mechanism it holds that

$$\frac{1}{n} \sum_{(x, y) \in S_A} 1\{y \cdot \langle \hat{w}, x \rangle < \frac{\gamma}{10}\} \leq \frac{\alpha}{4}. \quad (7)$$

**Proof of Claim 4.1.** Every point in $B^m_2$ is within $\gamma/10$ from a center of $W$. Let $w^*_c$ be the center within $\gamma/10$ from $w^*_A$, that is,

$$\|w^*_A - w^*_c\|_2 \leq \gamma/10. \quad (8)$$

Recall that in our conditioned probability space,

$$y \cdot \langle w^*_c, x \rangle \geq 96\gamma/100 \quad (9)$$

holds for all $(x, y) \in S_A$. Therefore, for all $(x, y) \in S_A$,

$$y \cdot \langle w^*_c, x \rangle = y \cdot \langle w^*_A, x \rangle - y \cdot \langle w^*_A - w^*_c, x \rangle \geq y \cdot \langle w^*_A, x \rangle - \|w^*_A - w^*_c\|_2 \cdot \|x\|_2 \geq 96\gamma/100 - \gamma/10 = 86\gamma/10 > \gamma/10.$$ \hspace{1cm} \text{by inequalities (8), (9)}

It follows that

$$\max_{w \in W} u(S_A, w) \geq u(S_A, w_c^*) = -\frac{1}{n} \sum_{(x, y) \in S_A} 1\{y \cdot \langle w, x \rangle < \frac{\gamma}{10}\} = 0. \quad (10)$$
By Lemma 4 and inequality (10), with probability at least $1 - \frac{\beta}{4}$, it holds that:

$$\frac{1}{n} \sum_{(x_A, y) \in S_A} 1\{y \cdot (\hat{w}, x_A) < \frac{\gamma}{10}\} \leq \frac{2}{n\varepsilon} (\ln(|W|) + \ln(4/\beta))$$

(11)

It is a well-known result that the covering number of an $m$-dimensional unit ball by balls of radius $\gamma/10$ is at most $O\left(\left(\frac{1}{\gamma/10}\right)^m\right)$. Therefore, substituting $m = O\left(\log\left(\frac{n}{\alpha \beta \gamma^2}\right)\right)$, it follows that

$$\ln |W| = \frac{1}{\gamma^2} \cdot \text{polylog}\left(n, \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}\right).$$

Thus, by inequality (11), if $n = \frac{1}{\alpha \varepsilon \gamma^2} \cdot \text{polylog}\left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}, \frac{1}{\varepsilon}\right)$ then with probability at least $1 - \frac{\beta}{4}$,

$$\frac{1}{n} \sum_{(x_A, y) \in S_A} 1\{y \cdot (\hat{w}, x_A) < \frac{\gamma}{10}\} \leq \frac{\alpha}{4}.$$

This completes the proof of the claim. 

Theorem 5 (Privacy guarantee). Algorithm $A_{\alpha, \beta, \varepsilon, \gamma}$ is $(\varepsilon, 0)$-differentially private.

Proof of Theorem 5 The sensitivity of the utility function is

$$\Delta u = \max_{w \in W} \max_{Z, Z' \in (X \times \{\pm 1\})^n} \max_{Z \sim Z'} |u(Z, w) - u(Z', w)| \leq \frac{1}{n}.$$

It follows by Lemma 4 that $M_E$ is $(\varepsilon, 0)$-DP.

By Lemma 4, $(\varepsilon, 0)$-differential privacy is closed under post-processing. Therefore it suffices to show that an algorithm $N$ that is the same as $A_{\alpha, \beta, \varepsilon, \gamma}$ except that it returns $\hat{w}$ instead of $\hat{w}^\top A$, is $(\varepsilon, 0)$-DP.

Let $S$ and $S'$ be two neighboring sample sets such that $S = S' \setminus \{(x', y')\} \cup \{(x, y)\}$. Let $U = \left\{\pm \frac{1}{\sqrt{m}}\right\}^{m \times d}$. If we fix a matrix $A \in U$, the sample sets $S$ and $S'$ would correspond to $M_E$’s inputs $S_A$ and $S'_A = S_A \setminus \{(x'_A, y')\} \cup \{(x_A, y)\}$, respectively. For any measurable set $R \subseteq \mathbb{R}^m$, it holds that

$$\Pr[N(S) \in R] = \sum_{A \in U} \Pr[A] \cdot \Pr[M_E(S_A) \in R | A]$$

$$\leq \sum_{A \in U} \Pr[A] \cdot \exp(\varepsilon) \Pr[M_E(S'_A) \in R | A] \quad \text{(since $M_E$ is $(\varepsilon, 0)$-DP)}$$

$$= \exp(\varepsilon) \sum_{A \in U} \Pr[A] \cdot \Pr[M_E(S'_A) \in R | A]$$

$$= \exp(\varepsilon) \Pr[N(S') \in R].$$

Therefore, $N$ is $(\varepsilon, 0)$-DP, and so is $A_{\alpha, \beta, \varepsilon, \gamma}$. 

5 A Sample Complexity Lower Bound for Pure Differential Privacy

In this section we prove a lower bound on the sample complexity of any $(\varepsilon, 0)$-differentially private algorithm for learning a large-margin halfspace.
Theorem 6. Any \((\varepsilon, 0)\)-differentially private \((\frac{1}{10}, \frac{1}{10}, \gamma)\)-learner for halfspaces in \(\mathbb{R}^{\Omega(1/\gamma^2)}\) requires \(\Omega(1/\varepsilon \gamma^2)\) samples.

Proof. Our proof uses a standard packing argument. We construct distributions \(D^{(1)}, \ldots, D^{(K)}\) over \(\mathbb{B}_2^d \times \{\pm 1\}\) for \(d = 1/1000\gamma^2\) and \(K = 2^{d/20}\). We will construct these distributions so that no classifier is simultaneously accurate for two distinct distributions \(D^{(i)}\) and \(D^{(j)}\). This will imply that \(n = \Omega(\log(K)/\varepsilon) = \Omega(1/\varepsilon \gamma^2)\) samples are necessary to achieve \((\varepsilon, 0)\)-differential privacy.

Each distribution \(D^{(i)}\) is defined with respect to a halfspace \(w^{(i)} \in \{\pm 1/\sqrt{d}\}^d\), and has margin \(\gamma\) with respect to this halfspace. That is

\[
\Pr_{(x, y) \sim D^{(i)}}[y \cdot \langle w^{(i)}, x \rangle \geq \gamma] = 1.
\]

In addition, \(x\) is distributed uniformly at random on the remaining surface of \(\mathbb{B}_2^d\) so that it does not violate the margin and \(y = \text{sign}(\langle w^{(i)}, x \rangle)\). Formally, if \(U\) denotes the uniform distribution on \(\mathbb{B}_2^d\) and \(f_U\) is its density function, then the probability density function of \(X\) where \((X, y) \sim D^{(i)}\), is

\[
f_X(x') = \begin{cases} 
  f_U(x')/\Pr_{x \sim U}[|\langle w^{(i)}, x \rangle| \geq \gamma], & \text{if } |\langle w^{(i)}, x' \rangle| \geq \gamma \\
  0, & \text{otherwise}.
\end{cases}
\]

Using standard constructions of error correcting codes, there exists a set \(w^{(1)}, \ldots, w^{(K)}\) such that the Hamming distance of any pair \(i \neq j\), is \(\text{Ham}(w^{(i)}, w^{(j)}) \geq d/10\). This implies that \(\langle w^{(i)}, w^{(j)} \rangle \leq 4/5\).

Let \(\{w^{(1)}, \ldots, w^{(K)}\}\) be such a set and let \(D^{(1)}, \ldots, D^{(K)}\) be the resulting distributions. The crux of the proof is in establishing the following claim about this set of distributions. For each distribution \(D^{(i)}\), we define the set

\[
G^{(i)} = \left\{ \hat{w} \in \mathbb{B}_2^d : \text{err}_{D^{(i)}}(\hat{w}) \leq \frac{1}{10} \right\}
\]

of all classifiers that have error at most \(1/10\) on the distribution \(D^{(i)}\).

Claim 6.1. For every \(i \neq j\), \(G^{(i)}\) and \(G^{(j)}\) are disjoint.

Using this claim, we can complete the proof as follows. Let \(S^{(1)} \sim (D^{(i)})^n\) denote a random iid sample of \(n\) examples from \(D^{(i)}\). Let \(A\) be an \((\varepsilon, 0)\)-differentially private \((\frac{1}{10}, \frac{1}{10}, \gamma)\) learner. By privacy and accuracy, we have for every \(i \in \{2, 3, \ldots, K\}\)

\[
\Pr[A(S^{(1)}) \in G^{(i)}] \geq \exp(-n\varepsilon) \Pr[A(S^{(1)}) \in G^{(1)}] \geq \frac{9}{10} \exp(-n\varepsilon).
\]

Since the sets \(G^{(i)}\) are disjoint,

\[
\Pr[A(S^{(1)}) \notin G^{(1)}] \geq \sum_{i=2}^{K} \Pr[A(S^{(1)}) \in G^{(i)}] \geq \sum_{i=2}^{K} \frac{9}{10} \exp(-n\varepsilon) = \frac{9}{10} (K - 1) \exp(-n\varepsilon).
\]

Since, by accuracy, \(\Pr[A(S^{(1)}) \notin G^{(1)}] \leq \frac{1}{10}\), it follows that

\[
\frac{9}{10} (K - 1) \exp(-n\varepsilon) \leq \frac{1}{10}.
\]

Rearranging, and substituting our choice of \(K\), we conclude \(n = \Omega(1/\varepsilon \gamma^2)\).

Let us now prove Claim 6.1 which will complete the proof.
Lemma 5. If $B$ of a uniformly distributed point on $w$ remains unchanged if we replace $x$ each coordinate dimensional gaussian vectors, we know that the projection of $w$ is uniform over the unit sphere in $\mathbb{R}^d$ and $y = \text{sign}(\langle w^{(i)}, x \rangle)$. Define the probability

$$p_\gamma = \Pr_{x \sim U} [||w, x|| < \gamma]$$

of a uniformly distributed point on $B^d_2$ lying within margin $\gamma$ of a unit vector $w$. Probability $p_\gamma$ remains unchanged if we replace $w$ with any other unit vector and, more specifically,

$$p_\gamma = \Pr_{(x,y) \sim U_i} [||w^{(i)}, x|| < \gamma]$$

holds for all $U_i, i \in [K]$.

The next lemma will allow us to show that $U_i$ is not too far from $D^{(i)}$.

Lemma 5. If $d = \frac{1}{1000\gamma^2}$ then $p_\gamma \leq 0.2$.

Proof. Consider the following sampling process from the uniform distribution on the sphere: choose each coordinate $x_i \sim \mathcal{N}(0,1)$ and normalize with $||x||_2$. By the symmetric property of multi-dimensional gaussian vectors, we know that the projection of $x$ on a unit vector $w$ is distributed as $x_1/||x||_2$, where $x_1 \sim \mathcal{N}(0,1)$ is the first coordinate of $x$ and $||x||_2^2 \sim \chi^2(d)$ is the square of the normalization factor. The probability of a point having margin more than $\gamma$ from $w$ is:

$$1 - p_\gamma = \Pr_{x \sim U} \left[ \frac{|x_1|}{||x||_2} \geq \gamma \right]$$

$$\geq \Pr_{x \sim U} \left[ (|x_1| \geq \frac{1}{10}) \land (||x||_2 \leq \frac{1}{10\gamma}) \right]$$

$$= 1 - \Pr_{x \sim U} \left[ |x_1| < \frac{1}{10} \lor (||x||_2 > \sqrt{10d}) \right]$$

$$\geq 1 - \Pr_{x_1 \sim \mathcal{N}(0,1)} \left[ |x_1| < \frac{1}{10} \right] - \Pr_{||x||_2^2 \sim \chi^2(d)} \left[ ||x||_2^2 > 10d \right]$$

By the tables of the standard normal distribution we have that $\Pr_{x_1 \sim \mathcal{N}(0,1)} \left[ |x_1| < \frac{1}{10} \right] \leq 0.08$. Also, the mean of a $\chi^2(d)$ distributed variable is $d$. By Markov’s inequality, it follows that

$$\Pr_{||x||_2^2 \sim \chi^2(d)} \left[ ||x||_2^2 > 10d \right] \leq d/10d = 1/10.$$

Thus, $p_\gamma \leq 0.18$. \qed

We can apply the preceding lemma to relate $\text{err}_{U_i}(\tilde{w})$ to $\text{err}_{D^{(i)}}(\tilde{w})$. Specifically, for any $\tilde{w}$ with $\text{err}_{D^{(i)}}(\tilde{w}) \leq 0.10$, it holds that:

$$\text{err}_{U_i}(\tilde{w}) = \Pr_{(x,y) \sim U_i} [\text{sign}(\langle \tilde{w}, x \rangle) \neq \text{sign}(\langle w^{(i)}, x \rangle)]$$

$$\leq \Pr_{(x,y) \sim U_i} [\text{sign}(\langle \tilde{w}, x \rangle) \neq \text{sign}(\langle w^{(i)}, x \rangle)] \cdot \Pr_{(x,y) \sim U_i} [\langle w^{(i)}, x \rangle \geq \gamma]$$

$$+ \Pr_{(x,y) \sim U_i} [\langle w^{(i)}, x \rangle < \gamma]$$

$$\leq 0.1 + 0.2 = 0.3$$
Therefore, \[ \text{err}_U(\hat{w}) \leq 0.3. \] (12)

Next we will argue that the same vector \( \hat{w} \) cannot have low error with respect to some other distribution \( U_j \). Fix any two vectors \( w^{(i)}, w^{(j)} \) as in our construction. Consider the plane defined by these vectors and let \( \theta \) be their angle. It holds that

\[
\Pr_{x \sim U} [\text{sign}(\langle w^{(i)}, x \rangle) = \text{sign}(\langle w^{(j)}, x \rangle)] = \frac{2\theta}{2\pi} = \frac{\theta}{\pi} = \frac{\cos^{-1}(\langle w^{(i)}, w^{(j)} \rangle)}{\pi}.
\]

Since \( \text{Ham}(w^{(i)}, w^{(j)}) \geq d/10 \), \( \langle w^{(i)}, w^{(j)} \rangle \leq \frac{1}{\pi}(9d/10 - d/10) = \frac{8}{10} \). Thus,

\[
\Pr_{x \sim U} [\text{sign}(\langle w^{(i)}, x \rangle) = \text{sign}(\langle w^{(j)}, x \rangle)] \leq \frac{\cos^{-1}(8/10)}{\pi} = 0.21
\]

For the error of \( \hat{w} \) on distribution \( U_j \) it holds that:

\[
\Pr_{(x,y) \sim U_j} [\text{sign}(\langle \hat{w}, x \rangle) = \text{sign}(\langle w^{(j)}, x \rangle)] \\
\leq \Pr_{(x,y) \sim U_j} [\text{sign}(\langle \hat{w}, x \rangle) \neq \text{sign}(\langle w^{(i)}, x \rangle)] + \Pr_{(x,y) \sim U_j} [\text{sign}(\langle \hat{w}, x \rangle) = \text{sign}(\langle w^{(i)}, x \rangle)] \\
\leq 0.3 + 0.21 = 0.51 \quad (\text{by } (12))
\]

Therefore,

\[
\text{err}_{U_j}(\hat{w}) \geq 0.49. \quad (13)
\]

Once again, we can relate this to the error on the distribution \( D^{(j)} \) as follows.

\[
\Pr_{(x,y) \sim D^{(j)}} [\text{sign}(\langle \hat{w}, x \rangle) \neq \text{sign}(\langle w^{(j)}, x \rangle)] \\
= \Pr_{(x,y) \sim U_j} [\text{sign}(\langle \hat{w}, x \rangle) \neq \text{sign}(\langle w^{(j)}, x \rangle)] \cdot \Pr_{(x,y) \sim U_j} [\langle w^{(j)}, x \rangle \geq \gamma] \cdot \Pr_{(x,y) \sim U_j} [\langle w^{(j)}, x \rangle \geq \gamma] \\
\geq \Pr_{(x,y) \sim U_j} [\text{sign}(\langle \hat{w}, x \rangle) \neq \text{sign}(\langle w^{(j)}, x \rangle)] - \Pr_{(x,y) \sim U_j} [\langle w^{(j)}, x \rangle < \gamma] \\
\geq 0.49 - p_\gamma \geq 0.29 \quad (\text{by } (13))
\]

Therefore, \( \text{err}_{D^{(j)}}(\hat{w}) \geq 0.29 \). Thus, for any \( \hat{w} \), if \( \text{err}_{D^{(j)}}(\hat{w}) \leq 0.1 \) then \( \text{err}_{D^{(j)}}(\hat{w}) \geq 0.29 \). \( \square \)

This completes the proof of the lower bound.

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A Algorithm and proofs of Section 3

A.1 Differentially Private Empirical Risk Minimization Algorithm \( \mathcal{F} \)

A complete algorithm, deploying the differentially private stochastic gradient descent algorithm by Bassily et al. [2014], is presented below in Algorithm 3. We denote by \( \Pi_\mathcal{C}(\cdot) \) the euclidean projection on \( \mathcal{C} \) and by \( \|\mathcal{C}\|_2 \) the diameter of \( \mathcal{C} \).

**Algorithm 3 \( \mathcal{A}_{\alpha,\beta,\epsilon,\delta,\gamma}(S) \)**

1: Choose a random matrix \( A \in \mathbb{R}^{m \times d} \), where \( m = O\left( \frac{\log(1/\beta JL)}{\epsilon^2} \right) \), \( \beta JL = \alpha \beta^2 / 64n \), and

\[
A_{ij} = \begin{cases} +1/\sqrt{m} & \text{w.p. 1/2} \\ -1/\sqrt{m} & \text{w.p. 1/2}. \end{cases}
\]

2: Define \( S_A \leftarrow \{(Ax/\|Ax\|_2, y) \mid (x, y) \in S\} \).
3: Define the hypothesis set \( \mathcal{C} \leftarrow \mathcal{B}_2^m \).
4: Define the \( \frac{100}{86}\)-Lipschitz loss function \( \ell : \mathcal{C} \times (\mathcal{B}_2^m \times \{\pm 1\}) \rightarrow \mathbb{R} \) as

\[
\ell(w; (x, y)) = \mathbb{1}\left\{ y \cdot \langle w, x \rangle < \frac{96\gamma}{100} \right\} \cdot \left( \frac{96}{86} - \frac{y \cdot \langle w, x \rangle}{86\gamma/100} \right).
\]

5: Let \( \hat{w} \leftarrow \mathcal{F}(S_A, \ell, (\epsilon, \delta), \mathcal{C}) \).
6: return \( \hat{w}^\top A \).

7: **procedure** \( \mathcal{F}(D, \ell, (\epsilon, \delta), \mathcal{C}) \)

8: \hspace{1em} for \( i = 1 \) to \( \lceil \log(8/\beta) \rceil \) do

9: \hspace{2em} \( \hat{w}^{(i)} \leftarrow \mathcal{A}_{\text{Noise-GD}}(D, \ell, (\epsilon / \lceil \log(8/\beta) \rceil, \delta / \lceil \log(8/\beta) \rceil), \mathcal{C}) \)

10: \( W \leftarrow \{\hat{w}^{(1)}, \ldots, \hat{w}^{(\lceil \log(8/\beta) \rceil)}\} \)

11: return \( \hat{w} \leftarrow \mathcal{M}_E(D, -\ell, W) \)

12: **procedure** \( \mathcal{A}_{\text{Noise-GD}}(D, \ell, (\epsilon', \delta'), \mathcal{C}) \)

13: Noise variance \( \sigma^2 \leftarrow \frac{32L^2n^2\log(n/\delta')\log(1/\delta')}{\epsilon'^2} \), where \( L \) is the Lipschitz constant of \( \ell \).

14: Learning rate function \( \eta : [n^2] \rightarrow \mathbb{R} \): \( \eta(t) = \frac{\|\mathcal{C}\|_2}{\sqrt{t(n^2L^2 + m\sigma^2)}} \).

15: Choose a point from \( \mathcal{C}, w_1, \).

16: \hspace{1em} for \( t = 1 \) to \( n^2 - 1 \) do

17: \hspace{2em} Pick \( (x, y) \sim_u D \) with replacement.

18: \hspace{2em} \( w_{t+1} \leftarrow \Pi_\mathcal{C}(w_t - \eta(t)[n\nabla \ell(w_t; (x, y)) + b_t]), \) where \( b_t \sim \mathcal{N}(0, \mathbb{I}_m\sigma^2) \).

19: return \( w_{n^2} \).

To achieve a high-probability guarantee, algorithm \( \mathcal{F} \) runs \( \mathcal{A}_{\text{Noise-GD}} \lceil \log(8/\beta) \rceil \) times, with privacy parameters \( \epsilon / \lceil \log(8/\beta) \rceil \) and \( \delta / \lceil \log(8/\beta) \rceil \), and uses the Exponential Mechanism to pick the best hypothesis \( \hat{w} \), as described in Appendix D of Bassily et al. [2014].

A.2 Proof of Lemma \(^3\)

We state Lemma \(^3\) again for convenience.
Lemma 6 (Lemma 3). For every given matrix $A$, let $G_A \subseteq \mathcal{X} \times \{\pm 1\}$ be the set of data points $(x, y)$ that satisfy the following two statements:

(i) $\|Ax\|^2_2 - \|x\|^2_2 \leq \frac{\gamma}{100}\|x\|^2_2$ and

(ii) $w_A^* = \frac{A^*}{\|A^*\|_2}$ has margin at least $96\gamma/100$ on $(x_A, y)$, i.e. $y \cdot \langle w_A^*, x_A \rangle \geq 96\gamma/100$.

It holds that $\Pr_{(x, y) \sim D}[(x, y) \in G_A] \geq 1 - 4\beta_{JL}$.

Proof of Lemma. By Lemma 2,

$$\|Au\|^2_2 - \|u\|^2_2 \leq \frac{\gamma}{100}\|u\|^2_2$$

holds for a point $u \in \mathbb{R}^d$ with probability at least $1 - 3\beta_{JL}$. By union bound, it holds simultaneously for all points $x + w^*$, $x - w^*$, $x$, and $w^*$, with probability at least $1 - 4\beta_{JL}$. Under this condition, statement (i) is true and for $y = 1$ we have:

$$\langle w^*, x \rangle = \frac{1}{4}\|x + w^*\|^2_2 - \frac{1}{4}\|x - w^*\|^2_2$$

$$\leq \frac{1}{4(1 - \frac{\gamma}{100})}\|A(x + w^*)\|^2_2 - \frac{1}{4(1 + \frac{\gamma}{100})}\|A(x - w^*)\|^2_2$$

$$= \frac{1}{4(1 - \frac{\gamma}{100})}\left((1 + \frac{\gamma}{100})\|A(x + w^*)\|^2_2 - (1 - \frac{\gamma}{100})\|A(x - w^*)\|^2_2\right)$$

$$= \frac{1}{1 - \frac{\gamma}{100}}\left(\frac{1}{4}\|Ax + Aw^*\|^2_2 - \frac{1}{4}\|Ax - Aw^*\|^2_2\right)$$

$$+ \frac{\frac{\gamma}{100}}{4(1 - \frac{\gamma}{100})}(\|Ax + Aw^*\|^2_2 + \|Ax - Aw^*\|^2_2)$$

$$= \frac{1}{1 - \frac{\gamma}{100}}\langle Aw^*, Ax \rangle + \frac{\frac{\gamma}{100}}{2(1 - \frac{\gamma}{100})}(\|Ax\|^2_2 + \|Aw^*\|^2_2)$$

$$\leq \frac{1}{1 - \frac{\gamma}{100}}\langle Aw^*, Ax \rangle + \frac{\frac{\gamma}{100}}{1 - \frac{\gamma}{100}}$$

Equivalently $\langle Aw^*, Ax \rangle \geq \left(1 - \frac{\gamma}{100}\right)\langle w^*, x \rangle - \frac{\gamma}{100}\left(1 + \frac{\gamma}{100}\right)$. Since $y = 1$ and $\langle w^*, x \rangle = y \cdot \langle w^*, x \rangle \geq \gamma$, it follows that:

$$y \cdot \langle Aw^*, Ax \rangle \geq \left(1 - \frac{\gamma^2}{100}\right)\gamma - \frac{\gamma}{100}\left(1 + \frac{\gamma}{100}\right) \geq \frac{98\gamma}{100}$$

Therefore, for $y = 1$,

$$y \cdot \langle w_A^*, x_A \rangle = y \cdot \left(\frac{\langle Aw^*, Ax \rangle}{\|Aw^*\|_2 \|Ax\|_2}\right) \geq \frac{98\gamma}{100} \geq \frac{96\gamma}{100}.$$

The proof for $y = -1$ is similar. We conclude that with probability at least $1 - 4\beta_{JL}$, statements (i) and (ii) are true. \hfill $\Box$
B Proof of Sample Complexity: $(\varepsilon, 0)$-DP

**Theorem 7** (Sample Complexity, Theorem 4). Algorithm $A_{\alpha, \beta, \varepsilon, \gamma}$ is an $(\alpha, \beta, \gamma)$-learner with sample complexity
\[
n = \frac{1}{\alpha \varepsilon^2} \cdot \text{polylog} \left( \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\varepsilon}, \frac{1}{\gamma} \right).
\]

**Proof of Theorem 4.** As in the previous section, the first step of the algorithm is to sample matrix $A$ uniformly at random from $U = \{ \pm \frac{1}{\sqrt{m}} \}^{m \times d}$. From Lemma 3 it follows that:
\[
\mathbb{E}_{A} \left[ \Pr_{(x, y) \sim D} [(x, y) \notin G_A] \right] \leq 4 \beta J L
\]
And, by Markov’s inequality,
\[
\Pr_{A} \left[ \Pr_{(x, y) \sim D} [(x, y) \notin G_A] \geq \beta' \right] \leq \frac{\mathbb{E}_{A} \left[ \Pr_{(x, y) \sim D} [(x, y) \notin G_A] \right]}{\beta'} \leq \frac{4 \beta J L}{\beta'}.
\]
We set $\beta' = \alpha \beta / 4n$. Then, substituting $\beta J L = \frac{\alpha \beta^2}{6n}$, we get that with probability at least $1 - \beta/4$,
\[
\Pr_{(x, y) \sim D} [(x, y) \in G_A] \geq 1 - \beta'.
\]
Therefore, with probability $1 - \beta/4$, the sampled matrix $A$ satisfies the above inequality, that is, a point $(x, y) \sim D$ is in $G_A$ with probability at least $1 - \beta'$. Furthermore, by union bound, $\forall (x, y) \in S$ it holds that $(x, y) \in G_A$, with probability at least $1 - n \beta' \geq 1 - \beta/4$.

For the remainder of the proof, we condition on the event that

1. $\Pr_{(x, y) \sim D} [(x, y) \in G_A] \geq 1 - \beta'$ holds for $A$ and

2. $S \subseteq G_A$, that is, $w_A^*$ has margin at least $96 \gamma / 100$ on $S_A$.

This event occurs with probability at least $1 - \beta/4 - \beta/4 = 1 - \beta/2$.

**Claim 7.1.** If $n = \frac{1}{\alpha \varepsilon^2} \cdot \text{polylog} \left( \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\varepsilon}, \frac{1}{\gamma} \right)$, then with probability $1 - \beta/4$, for hypothesis $\hat{w}$ returned by the Exponential Mechanism it holds that
\[
\frac{1}{n} \sum_{(x, y) \in S_A} \mathbb{1}\{y \cdot \langle \hat{w}, x_A \rangle < \frac{\gamma}{10}\} \leq \frac{\alpha}{4}.
\]

**Proof of Claim 7.1.** Every point in $B_m^2$ is within $\gamma/10$ from a center of $W$. Let $w_c^*$ be the center within $\gamma/10$ from $w_A^*$, that is,
\[
\|w_A^* - w_c^*\|_2 \leq \gamma / 10.
\]
Recall that in our conditioned probability space,
\[
y \cdot \langle w_A^*, x_A \rangle \geq 96 \gamma / 100
\]
holds for all $(x_A, y) \in S_A$. Therefore, for all $(x_A, y) \in S_A$,
\[
y \cdot \langle w_c^*, x_A \rangle = y \cdot \langle w_A^*, x_A \rangle - y \cdot \langle w_A^* - w_c^*, x_A \rangle \\
\geq y \cdot \langle w_A^*, x_A \rangle - \|w_A^* - w_c^*\|_2 \cdot \|x_A\|_2 \\
\geq 96 \gamma / 100 - \gamma / 10 = 86 \gamma / 10 > \gamma / 10.
\]
(by inequalities (15), (16))
It follows that
\[
\max_{\mathcal{W}} u(S_A, \mathbf{w}) \geq u(S_A, \mathbf{w}_c^*) = -\frac{1}{n} \sum_{(x_A, y) \in S_A} 1\{y \cdot \langle \mathbf{w}, x_A \rangle < \frac{\gamma}{10}\} = 0.
\] (17)

By Lemma 4 and inequality (17), with probability at least \(1 - \beta/4\), it holds that:
\[
\frac{1}{n} \sum_{(x_A, y) \in S_A} 1\{y \cdot \langle \hat{\mathbf{w}}, x_A \rangle < \frac{\gamma}{10}\} \leq \frac{2}{n\varepsilon} \left(\ln(|\mathcal{W}|) + \ln(4/\beta)\right)
\] (18)

It is a well-known result that the covering number of an \(m\)-dimensional unit ball by balls of radius \(\gamma/10\) is at most \(O\left(\left(\frac{1}{\gamma^2/10}\right)^m\right)\). Therefore, substituting \(m = O\left(\frac{\log(n\beta)}{\gamma^2}\right)\), it follows that
\[
\ln |\mathcal{W}| = \frac{1}{\gamma^2} \cdot \text{polylog} \left(n, \frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}\right).
\]
Thus, by inequality (18), if \(n = \frac{1}{\alpha\gamma^2} \cdot \text{polylog} \left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}, \varepsilon\right)\) then with probability at least \(1 - \beta/4\),
\[
\frac{1}{n} \sum_{(x_A, y) \in S_A} 1\{y \cdot \langle \hat{\mathbf{w}}, x_A \rangle < \frac{\gamma}{10}\} \leq \alpha/4.
\]
This concludes the proof of the claim.

Claim 7.2. If \(n = \frac{1}{\alpha \gamma^2} \cdot \text{polylog} \left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}, \varepsilon\right)\), then with probability \(1 - \beta/2\), the error of the returned classifier \(\hat{\mathbf{w}}^\top A\) on distribution \(D\) is
\[
\Pr_{(x, y) \sim D, (x_A, y) \sim D_A} [y \cdot \langle \hat{\mathbf{w}}^\top A, x \rangle < 0] \leq \alpha.
\] (19)

Proof of Claim 7.2. Let \(D_A\) denote the probability distribution with domain \(B^m_2 \times \{\pm 1\}\), from which a sample \((x_A, y) \in S_A\) is drawn. Let us also denote by \(D_{G_A}\) distribution \(D\) restricted on \(G_A\). In our conditioned probability space, \(S_A \sim D_A^m\), where the probability density function of \(D_A\) would be defined as
\[
\Pr_{(x_A, y) \sim D_A} [x_A = x' \land y = y'] = \Pr_{(x, y) \sim D_{G_A}} \left[\frac{Ax}{\|Ax\|_2} = x' \land y = y'\right].
\]
Let \(\mathcal{H} = \{h : \{x_A \mid (x, y) \in G_A\} \rightarrow \{\pm 1\}\text{ s.t. } h(x) = \text{sign}(\langle \mathbf{w}, x \rangle)\text{ for some } \mathbf{w} \in B^m_2\}\) be a concept class of threshold functions in \(B^m_2\). By Theorem 3.4 of Anthony and Bartlett [2009], \(\text{VCdim}(\mathcal{H}) = m + 1\).

By the generalization bound of Theorem 5.7 of Anthony and Bartlett [2009], it holds that:
\[
\Pr_{S_A \sim D_A} \left[\exists h \in \mathcal{H} : \text{err}_{D_A}(h) > 2 \cdot \frac{1}{n} \sum_{(x_A, y) \in S_A} 1\{h(x_A) \neq y\} + \frac{\alpha}{4}\right] \leq 4 \Pi_{\mathcal{H}}(2n) \exp(-\alpha n/32)
\]
where the growth function \(\Pi_{\mathcal{H}}(2n) \leq (2n)^{m+1} + 1\), by Theorem 3.7 of Anthony and Bartlett [2009].

Using \(m = O\left(\frac{\log(1/\alpha \beta)}{\gamma^2}\right)\), it holds that if \(n = \frac{1}{\alpha \gamma^2} \cdot \text{polylog} \left(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\gamma}\right)\) then \(4 \Pi_{\mathcal{H}}(2n) \exp(-\alpha n/32) \leq \beta/4\). Therefore, with probability at least \(1 - \beta/4\),
\[
\text{err}_{D_A}(f_{\hat{\mathbf{w}}}) \leq 2 \cdot \frac{1}{n} \sum_{(x_A, y) \in S_A} 1\{y \cdot \langle \hat{\mathbf{w}}, x_A \rangle < 0\} + \frac{\alpha}{4}
\] (20)
By Claim 7.1, \[
\frac{1}{n} \sum_{(\mathbf{x}, y) \in S_A} 1\{y \cdot \langle \hat{\mathbf{w}}, \mathbf{A} \rangle < 0\} \leq \frac{1}{n} \sum_{(\mathbf{x}, y) \in S_A} 1\{y \cdot \langle \hat{\mathbf{w}}, \mathbf{x} \rangle < \frac{7}{10}\} \leq \frac{\beta}{4}
\] holds with probability \(1 - \beta/4\), if \(n = \frac{1}{\alpha^2 \varepsilon^2} \cdot \text{polylog}(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\varepsilon}, \frac{1}{\gamma})\).

Therefore, by inequality (20), if \(n = \frac{1}{\alpha^2 \varepsilon^2} \cdot \text{polylog}(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\varepsilon}, \frac{1}{\gamma})\), then with probability at least \(1 - \beta/4 - \beta/4 = 1 - \beta/2\),

\[
\text{err}_{D_A}(f_{\hat{w}}) \leq 2 \cdot \alpha + \alpha = 3\alpha.
\]

Equivalently, with probability at least \(1 - \beta/2\),

\[
\Pr_{(\mathbf{x}, y) \sim D_A} [y \cdot \langle \hat{\mathbf{w}}^\top \mathbf{A}, \mathbf{x} \rangle < 0] = \Pr_{(\mathbf{x}, y) \sim D_A} [y \cdot \langle \hat{\mathbf{w}}, \mathbf{x} \rangle < 0] = \text{err}_{D_A}(f_{\hat{w}}) \leq \frac{3\alpha}{4}.
\]

Since, by Condition 1., \(\Pr_{(\mathbf{x}, y) \sim D} [(\mathbf{x}, y) \notin G_A] \leq \beta' \leq \frac{\beta}{4}\), it follows that with probability at least \(1 - \beta/2\),

\[
\Pr_{(\mathbf{x}, y) \sim D} [y \cdot \langle \hat{\mathbf{w}}^\top \mathbf{A}, \mathbf{x} \rangle < 0] \leq \Pr_{(\mathbf{x}, y) \sim D_{G_A}} [y \cdot \langle \hat{\mathbf{w}}^\top \mathbf{A}, \mathbf{x} \rangle < 0] \cdot (1 - \beta') + 1 \cdot \beta'
\]

\[
\leq \frac{3\alpha}{4} \cdot (1 - \beta') + \beta'
\]

\[
\leq \frac{3\alpha}{4} + \frac{\alpha}{4} \leq \alpha.
\]

This completes the proof of the claim. \(\square\)

Accounting for the probability that we are not in the conditioned space, we conclude that if \(n = \frac{1}{\alpha^2 \varepsilon^2} \cdot \text{polylog}(\frac{1}{\alpha}, \frac{1}{\beta}, \frac{1}{\varepsilon}, \frac{1}{\gamma})\), then with probability at least \(1 - \beta/2 - \beta/2 = 1 - \beta\), \(\text{err}_{D}(f_{\hat{w}^\top \mathbf{A}}) \leq \alpha\). This completes the proof of the theorem. \(\square\)