

Non-Linear Learning in the Huber ϵ -Contamination Model

Arvind Rathnashyam
RPI Math and CS, rathna@rpi.edu

Alex Gittens
RPI CS, gittea@rpi.edu

Abstract

In this paper we study Subquantile Minimization for learning the Adversarial Huber- ϵ Contamination Problem for Learning Single Neurons. We first reduce the Subquantile Minimization Algorithm to Iterative Thresholding using ideas from convex optimization. Let the target data be distributed as $y = \sigma(\mathbf{x}^T \mathbf{w}^*) + \xi_i$ for a non-linear function, σ for noise $\xi_i \sim \mathcal{N}(0, \sigma^2)$ and \mathbf{x}_i be sampled from a sub-Gaussian Distribution with second-moment matrix $\mathbf{\Sigma}$. Our main result is for sufficiently large N , there exists an algorithm that returns $\mathbf{w}^{(T)}$ with high probability such that $\|\mathbf{w}^* - \mathbf{w}^{(T)}\|_2 \leq \epsilon$ in time,

$$O(\text{polylog}(N, d, \sigma, \epsilon, \kappa(\mathbf{\Sigma}), \|\mathbf{w}^*\|_2, (1/\epsilon)))$$

for ϵ sufficiently small. The iterative thresholding algorithm has been used in large neural network models in prior research [SS19a]. Our work provides the first steps for a theoretical understanding for learning neural networks with iterative thresholding algorithms in the Huber- ϵ contamination model.

1 Introduction

There has been extensive study of algorithms to learn the target distribution from a Huber ϵ -Contaminated Model for a Generalized Linear Model (GLM), [DKK⁺19, ADKS22, LBSS21, OZS20, FB81] as well as for linear regression [BJKK17, MGJK19]. Robust Statistics has been studied extensively [DK23] for problems such as high-dimensional mean estimation [PBR19, CDGS20] and Robust Covariance Estimation [CDGW19, FWZ18]. Recently, there has been an interest in solving robust machine learning problems by gradient descent [PSBR18, DKK⁺19]. Subquantile minimization aims to address the shortcomings of standard ERM in applications of noisy/corrupted data [KLA18, JZL⁺18]. In many real-world applications, the covariates have a non-linear dependence on labels [AMMIL12, Section 3.4]. In which case it is suitable to transform the covariates to a different space utilizing kernels [HSS08]. Therefore, in this paper we consider the problem of Robust Learning for Kernel Learning.

Definition 1 (Huber ϵ -Contamination Model [HR09]). *Given a corruption parameter $0 < \epsilon < 0.5$, a data matrix, \mathbf{X} and labels \mathbf{y} . An adversary is allowed to inspect all samples and modify ϵn samples arbitrarily. The algorithm is then given the ϵ -corrupted data matrix \mathbf{X} and ϵ -corrupted labels vector \mathbf{y} as training data.*

Current approaches for robust learning across various machine learning tasks often use gradient descent over a robust objective, [LBSS21]. These robust objectives tend to not be convex and therefore do not have a strong analysis on the error bounds for general classes of models.

We similarly propose a robust objective which has a nonconvex-concave objective. This objective function has also been proposed recently in [HYwL20] where there has been an analysis in the Binary Classification Task. We show Subquantile Minimization reduces to the same objective function given in [HYwL20].

The study of Kernel Learning in the Gaussian Design is quite popular, [CLKZ21, Dic16]. In [CLKZ21], the feature space, $\phi(\mathbf{x}_i) \sim \mathcal{N}(0, \Sigma)$ where Σ is a diagonal matrix of dimension p , where p can be infinite. We will now give our formal definition of the dataset.

Definition 2 (Corruption Model). *Let \mathcal{P} be a distribution over \mathbb{R}^d such that $\mathcal{P}_\# \phi$ is a centered distribution in the Hilbert Space \mathcal{H} with trace-class covariance operator Σ and trace-class sub-Gaussian proxy Γ such that $\Sigma \preceq c\Gamma$. The original dataset is denoted as \hat{P} , the adversary is able to observe \hat{P} and arbitrarily corrupts ϵn samples denoted as Q such that $|Q| = \epsilon n$. The remaining uncorrupted samples are denoted as P such that $|P| = n(1 - \epsilon)$. Together $X \triangleq P \cup Q$ represents the given dataset.*

We will now give one of the first results proving the effectiveness of Iterative Thresholding in Learning Problems.

Theorem 3 (Theorem 5 in [BJK15]). *Let \mathbf{X} be a sub-Gaussian data matrix, and $\mathbf{y} = \mathbf{X}^T \mathbf{w}^* + \mathbf{e}$ where \mathbf{e} is the corruption. Then there exists an algorithm such that $\|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2 \leq \epsilon$ after $t = O\left(\left(\log\left(\frac{\|\mathbf{b}\|_2}{\sqrt{n}}\right)\right)\frac{1}{\epsilon}\right)$ iterations.*

More recently, Awasthi et al. [ADKS22] studied the iterative trimmed maximum likelihood estimator. We will give their formal theorem result.

Theorem 4 (Theorem 4.2 in [ADKS22]). *Let $P = \{(\mathbf{x}_i, y_i)\}_{i=1}^n$ be the data generated by a Gaussian regression model defined as $y_i = \mathbf{x}_i^T \mathbf{w}^* + \eta_i$ where $\eta_i \sim \mathcal{N}(0, \sigma^2)$ and \mathbf{x}_i are sampled from a sub-Gaussian Distribution with second-moment matrix \mathbf{I} . Suppose the dataset has ϵ -fraction of label corruption and $n = \Omega\left(\frac{d + \log(1/\delta)}{\epsilon^2}\right)$. Then there exists an algorithm that returns $\hat{\mathbf{w}}$ such that with probability $1 - \delta$,*

$$\|\hat{\mathbf{w}} - \mathbf{w}^*\|_2 = O(\sigma \epsilon \log(1/\epsilon))$$

Our first result recovers this result for vectorized-regression. We will now give our results for the Kernelized GLM problem.

1.1 Contributions

Our main contribution is the approximation bounds for Subquantile Minimization for various non-linear learning problems from the iterative thresholding algorithm given in Algorithm 1. Our proof techniques

extend [BJK15, SS19b, ADKS22] as we suppose the adversary also corrupts the covariates. To our knowledge, we are also the first to theoretically study iterative thresholding for non-linear learning algorithms beyond the generalized linear model.

Reference	Approximation	Runtime	Model
[ADKS22]	$O(\sigma\epsilon \log \epsilon^{-1})$	$O((Nd^2 + d^3)\frac{1}{\epsilon^2})$	Regression; Label
[BJK15]	$O(\sigma\epsilon \log \epsilon^{-1})$	$O((Nd^2 + d^3) \log(\frac{1}{\sqrt{n}} \frac{\ \mathbf{b}\ }{\epsilon^2}))$	Regression; Label
Corollary 15	$O(\sigma\epsilon \log \epsilon^{-1})$	$O(Nd \log(\frac{\ \mathbf{w}^*\ }{\epsilon^2}))$	Regression; Label
Theorem 14	$O(\sigma\epsilon \sqrt{C_Q K} \log \epsilon^{-1})$	$O(NKd \log(\frac{\ \mathbf{W}^*\ _F}{\epsilon^2}))$	K -variate Regression
Theorem 16	$O(L^2(\sigma + \epsilon \sqrt{C_Q} \log \epsilon^{-1}))$	$O(Nd \log(\frac{\ f^*\ _{\mathcal{H}}}{\epsilon^2}))$	GLM (<i>In progress</i>)
Theorem 18	$O(\sigma\kappa^2(\Sigma)C_\psi^{-1}C_K \sqrt{\epsilon \log \epsilon^{-1}})$	$O(Nd \log(\frac{\ \mathbf{w}^*\ _{2+(d/\delta)}}{\epsilon}))$	Leaky ReLU Neuron
Theorem 19	$O(\sigma\kappa^2(\Sigma)C_\psi^{-1}C_K d\epsilon \log \epsilon^{-1})$	$O(Nd \log(\frac{\ \mathbf{w}^*\ _{2+(d/\delta)}}{\epsilon}))$	ReLU Neuron

Table 1: Summary of related work on Iterative Thresholding Algorithms for Learning in the Huber- ϵ Contamination Model and our contributions. We assume the good data is sampled from a sub-Gaussian distribution with second-moment matrix, Σ , and sub-Gaussian norm C_K and dimension d . We assume the variance of the optimal estimator is σ . The Leaky-ReLU function is given as $\max\{C_\psi x, x\}$.

We are able to remove the super-linear dependence on d by leveraging Gradient Descent. Comparing to [BJK15], our bound does not depend on the norm of the noise.

2 Preliminaries

Notation. We denote $[T]$ as the set $\{1, 2, \dots, T\}$. We define $(x)^+ \triangleq \max(0, x)$ as the Rectified Linear Unit (ReLU) function. We say $y = O(x)$ if there exists x_0 s.t. for all $x \geq x_0$ there exists C s.t. $y \leq Cx$. We say $y = \Omega(x)$ if there exists x_0 s.t. for all $x \geq x_0$ there exists C s.t. $y \geq Cx$. We denote $a \vee b \triangleq \max(a, b)$ and $a \wedge b \triangleq \min(a, b)$. We define \mathbb{S}^{d-1} as the sphere $\{\mathbf{x} \in \mathbb{R}^d : \|\mathbf{x}\| = 1\}$. We will typically denote capital roman letters A, B, C as fixed constants, lower-case roman letters f, g, h as functions, bold-face lower-case letters $\mathbf{x}, \mathbf{y}, \mathbf{z}$ as vectors, and bold-face, upper-case letters $\mathbf{P}, \mathbf{Q}, \mathbf{R}$ as matrices. Throughout the paper, we will use the following matrix norms for a matrix $\mathbf{A} \in \mathbb{R}^{m \times n}$ and vector $\mathbf{x} \in \mathbb{R}^n$,

$$\text{Spectral Norm: } \|\mathbf{A}\| = \max_{\mathbf{x} \in \mathbb{S}^{m-1}} \|\mathbf{A}\mathbf{x}\| = \sigma_1(\mathbf{A})$$

$$\text{Trace Norm: } \text{Tr}(\mathbf{A}) = \sum_{i \in [m \wedge n]} \sigma_i(\mathbf{A})$$

$$\text{Frobenius Norm: } \|\mathbf{A}\|_F^2 = \text{Tr}(\mathbf{A}^T \mathbf{A}) = \sum_{i \in [m \wedge n]} \sigma_i^2(\mathbf{A})$$

$$\ell_2 \text{ Norm: } \|\mathbf{x}\|_2^2 = \mathbf{x}^T \mathbf{x} = \sum_{i \in [n]} x_i^2$$

2.1 Assumptions

We will first give our assumptions for robust kernelized regression.

Assumption 5 (Sub-Gaussian Design). *We assume for $\mathbf{x}_i \sim \mathcal{X}$, then it follows for the function to the Hilbert Space, $\phi(\cdot) : \mathcal{X} \rightarrow \mathcal{H}$,*

$$\phi(\mathbf{x}) \triangleq X \sim \mathcal{P}_\# \phi \triangleq \mathcal{SG}(\mathbf{\Gamma}, 1/2)$$

where $\mathbf{\Gamma}$ is a possibly infinite dimensional covariance operator.

Assumption 6 (Bounded Functions). We assume for $\mathbf{x}_i \sim \mathcal{P} \in \mathcal{X}$, then it follows for the feature map, $\phi(\cdot) : \mathcal{X} \rightarrow \mathcal{H}$,

$$\sup_{\mathbf{x} \in \mathcal{X}} \|\phi(\mathbf{x})\|_{\mathcal{H}}^2 \leq P_k < \infty$$

where \mathcal{H} is a Reproducing Kernel Hilbert Space.

Assumption 7 (Normal Residuals). Let $\inf_{f \in \mathcal{H}} \mathbb{E}_{(\mathbf{x}, y) \sim \mathcal{D}} [\mathcal{R}(f; \mathbf{x}, y)]$. The residual is defined as $\xi_i \triangleq f^*(\mathbf{x}_i) - y_i$. Then we assume for some $\sigma > 0$, it follows

$$\xi_i \sim \mathcal{N}(0, \sigma^2)$$

2.2 Related Work

The idea of iterative thresholding algorithms for robust learning tasks dates back to 1806 by Legendre [Leg06]. Iterative thresholding have been studied theoretically and tested empirically in various machine learning domains [HYW⁺23, MGJK19]. Therefore, we will dedicate this subsection to reviewing such works and to make clear our contributions to the iterative thresholding literature.

[BJK15] study iterative thresholding for least squares regression / sparse recovery. In particular, one part of their study is of a gradient descent algorithm when the data $\mathcal{P} = \mathcal{Q} = \mathcal{N}(\mathbf{0}, \mathbf{I})$ or multivariate sub-Gaussian with proxy \mathbf{I} . Their approximation bounds relies on the fact that $\lambda_{\min}(\mathbf{\Sigma}) = \lambda_{\max}(\mathbf{\Sigma})$ and with sufficiently large data and sufficiently small ϵ , $\kappa(\mathbf{X}) \searrow 1$. This is similar to the study by [ADKS22], where the iterative trimmed maximum likelihood estimator is studied for General Linear Models. The algorithm studied by [ADKS22] utilizes a filtering algorithm with the sketching matrix $\mathbf{\Sigma}^{-1/2}$ so the columns of \mathbf{X} are sampled from a multivariate sub-Gaussian Distribution with proxy \mathbf{I} before running the iterative thresholding procedure. This ‘whitening’ procedure to decrease the conditioning number of the covariates is also done in recent work, [SBRJ19, BJKK17].

Conditioning covariates does not generalize to kernel learning where we are given a matrix \mathbf{K} which is equivalent to inner product of the quasimatrix¹, Φ , with itself. In the infinite dimensional case, it is not possible to sketch the kernel matrix [W⁺14] in order to have the original covariates be well-conditioned. In the finite dimensional case, the feature maps can be quite large and it is very difficult to obtain in practice. Thus, we are left with Φ where the columns are sampled from a sub-Gaussian Distribution with proxy $\mathbf{\Gamma}$ is a trace-class operator, which implies the eigenvalues tend to zero, i.e. $\lambda_{\inf}(\mathbf{\Gamma}) = 0$, and there is no longer a notion of $\lambda_{\min}(\mathbf{\Gamma})$.

3 Subquantile Minimization

We propose to optimize over the subquantile of the risk. The p -quantile of a random variable, U , is given as $\mathcal{Q}_p(U)$, this is the largest number, t , such that the probability of $U \leq t$ is at least p .

$$\mathcal{Q}_p(U) \leq t \iff \mathbb{P}\{U \leq t\} \geq p$$

The p -subquantile of the risk is then given by

$$\mathbf{L}_p(U) = \frac{1}{p} \int_0^p \mathcal{Q}_p(U) dq = \mathbb{E}[U | U \leq \mathcal{Q}_p(U)] = \max_{t \in \mathbb{R}} \left\{ t - \frac{1}{p} \mathbb{E}[(t - U)^+] \right\}$$

Given a function to minimize, \mathcal{L} , the variational problem is given as:

$$\min_{f \in \mathcal{K}} \max_{t \in \mathbb{R}} \left\{ g(t, \mathbf{w}) \triangleq t - \frac{1}{(1 - \epsilon)N} \cdot \sum_{i=1}^n (t - \mathcal{L}(\mathbf{w}; \mathbf{x}_i, y_i))^+ \right\}$$

where t is the p -quantile of the empirical risk. Note that for a fixed t therefore the objective is not concave with respect to \mathbf{w} . Thus, to solve this problem we use the iterations from Equation 11 in [RHL⁺20]. Our update steps are,

$$t^{(k+1)} = \arg \max_{t \in \mathbb{R}} g(\mathbf{w}^{(k)}, t) \quad (3.1)$$

¹ A quasimatrix is an infinite-dimensional analogue of a tall-skinny matrix that represents an ordered set of functions in ℓ_2 (see e.g. [TT15]).

$$\mathbf{w}^{(k+1)} = \mathbf{w}^{(k)} - \eta \nabla_f g(\mathbf{w}^{(k)}, t^{(k+1)}) \quad (3.2)$$

3.1 Reduction to Iterative Thresholding

To consider theoretical guarantees of Subquantile Minimization, we first analyze the inner and outer optimization problems. We first analyze kernel learning in the presence of corrupted data. Next, we provide error bounds for the two most important kernel learning problems, kernel ridge regression, and kernel classification. Now we will give our first result regarding kernel learning in the Huber ϵ -contamination model. Now we will analyze the two-step minimax optimization steps described in Equations (3.1) and (3.2).

Lemma 8. *Let $\mathcal{R} : \mathcal{H} \times \mathbb{R} \rightarrow \mathbb{R}$ be a loss function (not necessarily convex). Let $\mathbf{x}_{[i]}$ represent the point with the i -th smallest loss w.r.t \mathcal{R} . If we denote $\hat{\nu}_i \triangleq \mathcal{R}(\mathbf{w}; \mathbf{x}_{[i]}, y_{[i]})$, it then follows $\hat{\nu}_{(1-\epsilon)N} \in \arg \max_{t \in \mathbb{R}} g(\mathbf{w}, t)$.*

Proof. First we can note, the max value of t for g is equivalent to the min value of t for the convex w.r.t t function $-g$. We can now find the Fermat Optimality Conditions for g .

$$\partial(-g(t, f)) = \partial \left(-t + \frac{1}{(1-\epsilon)N} \sum_{i=1}^N (t - \hat{\nu}_i)^+ \right) = -1 + \frac{1}{(1-\epsilon)N} \sum_{i=1}^{(1-\epsilon)N} \begin{cases} 1 & \text{if } t > \hat{\nu}_i \\ 0 & \text{if } t < \hat{\nu}_i \\ [0, 1] & \text{if } t = \hat{\nu}_i \end{cases}$$

We observe when setting $t = \hat{\nu}_{(1-\epsilon)N}$, it follows that $0 \in \partial(-g(t, f))$. This is equivalent to the $(1-\epsilon)$ -quantile of the Empirical Risk. ■

From Lemma 8, we see that t will be greater than or equal to the errors of exactly $(1-\epsilon)N$ points. Thus, we are continuously updating over the $(1-\epsilon)N$ minimum errors.

Lemma 9. *Let $\hat{\nu}_i \triangleq \mathcal{R}(\mathbf{w}; \mathbf{x}_{[i]}, y_{[i]})$, if we choose $t^{(k+1)} = \hat{\nu}_{(1-\epsilon)N}$ as by Lemma 8, it then follows $\nabla_f g(t^{(k)}, \mathbf{w}^{(k)}) = \frac{1}{(1-\epsilon)N} \sum_{i=1}^{(1-\epsilon)N} \nabla_{\mathbf{w}} \mathcal{R}(\mathbf{w}^{(k)}; \mathbf{x}_{[i]}, y_{[i]})$.*

Proof. By our choice of $t^{(k+1)}$, it follows,

$$\begin{aligned} \partial_f g(t^{(k+1)}, \mathbf{w}^{(k)}) &= \partial_f \left(t^{(k+1)} - \frac{1}{(1-\epsilon)N} \sum_{i=1}^N (t^{(k+1)} - \mathcal{R}(\mathbf{w}^{(k)}; \mathbf{x}_{[i]}, y_{[i]}))^+ \right) \\ &= -\frac{1}{(1-\epsilon)N} \sum_{i=1}^{(1-\epsilon)N} \partial_f (t^{(k+1)} - \mathcal{R}(\mathbf{w}^{(k)}; \mathbf{x}_{[i]}, y_{[i]}))^+ \\ &= \frac{1}{(1-\epsilon)N} \sum_{i=1}^n \nabla_f \mathcal{R}(\mathbf{w}^{(k)}; \mathbf{x}_{[i]}, y_{[i]}) \begin{cases} 1 & \text{if } t > \hat{\nu}_i \\ 0 & \text{if } t < \hat{\nu}_i \\ [0, 1] & \text{if } t = \hat{\nu}_i \end{cases} \end{aligned}$$

Now we note $\hat{\nu}_{(1-\epsilon)N} \leq t^{(k+1)} \leq \hat{\nu}_{(1-\epsilon)N+1}$. Then, we have

$$\partial_f g(t^{(k+1)}, \mathbf{w}^{(k)}) \ni \frac{1}{(1-\epsilon)N} \sum_{i=1}^{(1-\epsilon)N} \nabla_f \mathcal{R}(\mathbf{w}^{(k)}; \mathbf{x}_{[i]}, y_{[i]})$$

This concludes the proof. ■

Theorem 10. *Suppose there exists constants such that the Hessian of any $(1-\epsilon)$ -subset of the data w.r.t to \mathcal{L} is μ -strongly convex and L -smooth. Then there exists an algorithm that returns a stationary point of $g(t, \mathbf{w})$ in $O(\text{poly}(\mu, L))$.*

Proof. The proof is by construction, consider the algorithm described in Equations (3.1) and (3.2). From the proof of Lemma 8, $t = \hat{\nu}_{(1-\epsilon)N}$ is a maximizer of Equation (3.2). We can then see that $g(t^{(k+1)}, \mathbf{w}^{(k+1)}) \leq g(t^{(k)}, \mathbf{w}^{(k)})$. ■

4 Convergence

In this section we give the algorithm for subquantile minimization. We will start with the simple case of vectorized regression as a warm-up to our general proof technique. We then move to the GLM with kernel learning. Finally, we give our results for one-hidden layer neural networks. We will now give the algorithm for Subquantile Minimization with Gradient Descent. We first give the non-linear functions we will be learning.

Property 11. *The non-linear function, $\psi : \mathbb{R} \rightarrow \mathbb{R}$ is $C_{\lceil \psi \rceil}$ -Lipschitz.*

Property 12. *The second-derivative, $\psi'' : \mathbb{R} \rightarrow \mathbb{R}$ is non-zero at finitely many points.*

Property 13. *The non-linear function, $\psi : \mathbb{R} \rightarrow \mathbb{R}$ has lower bounded derivative, $\psi'(x) \geq C_{\lfloor \psi \rfloor}$ for all $x \in \mathbb{R}$.*

We prove error bounds, for

4.1 Algorithm

Algorithm 1 Subquantile Minimization for One Hidden-Layer Neural Networks

input: Possibly corrupted $\mathbf{X} \in \mathbb{R}^{d \times N}$ with outputs $\mathbf{y} \in \mathbb{R}^N$ and corruption parameter $\epsilon = O(\text{poly}(C_3, \Gamma))$.

output: Approximate solution $\mathbf{W} \in \mathbb{R}^{k \times d}$ to $\min \|\mathbf{W} - \mathbf{W}^*\|_{\text{F}}$.

```

1:  $\mathbf{W}^{(0)} \leftarrow \mathbf{0}$ 
2: for  $t \in [T]$  do
3:    $S^{(t)} \leftarrow \{i \in [n] : \mathcal{L}(\mathbf{W}^{(t)}; \mathbf{x}_i, y_i) \leq \mathcal{L}(\mathbf{W}^{(t)}; \mathbf{x}_{\lfloor (1-\epsilon)N \rfloor}; y_{\lfloor (1-\epsilon)N \rfloor})\}$ 
4:    $\left[ \nabla \mathcal{R}(\mathbf{W}; S^{(t)}) \right]_k \leftarrow \frac{2}{(1-\epsilon)N} \cdot \sum_{i \in S^{(t)}} \left( \sum_{k \in [K]} \sigma(\mathbf{x}_i^T \mathbf{w}_k) - y_i \right) \cdot (\sigma(\mathbf{x}_i^T \mathbf{w}_k^{(t)})) \cdot \mathbf{x}_i^T$ 
5:    $\mathbf{W}^{(t+1)} \leftarrow \mathbf{W}^{(t)} - \eta \nabla \mathcal{R}(\mathbf{W}^{(t)}; S^{(t)})$ 
return:  $\mathbf{W}^{(T)}$ 
```

4.2 Warm-up: Multivariate Linear Regression

We will first present our results for the well-studied problem of linear regression in the Huber- ϵ contamination model. Our results will extend the results in [BJKK17] Theorem 5 and [ADKS22] Lemma A.1 by including covariate corruption, variance in the optimal estimator, and non-identity second-moment matrix of the uncorrupted data. The loss function for the multivariate linear regression problem for $\mathbf{W} \in \mathbb{R}^{k \times d}$, $\mathbf{X} \in \mathbb{R}^{d \times n}$, and $\mathbf{Y} \in \mathbb{R}^{k \times n}$.

$$\mathcal{L}(\mathbf{W}; \mathbf{X}, \mathbf{Y}) = \|\mathbf{W}\mathbf{X} - \mathbf{Y}\|_{\text{F}}^2$$

Theorem 14. *Let $\mathbf{X} = [\mathbf{x}_1, \dots, \mathbf{x}_n]^T \in \mathbb{R}^{d \times N}$ be the data matrix and $\mathbf{Y} = [\mathbf{y}_1, \dots, \mathbf{y}_n] \in \mathbb{R}^{K \times N}$ be the output, such that for $i \in P$, \mathbf{x}_i are sampled from a sub-Gaussian distribution with sub-Gaussian norm L and second-moment matrix Σ . Suppose for $i \in P$ the output is given as $\mathbf{y}_i = \mathbf{W}\mathbf{x}_i + \mathbf{e}_i$ where for $j \in [K]$, $[\mathbf{e}_i]_j \sim \mathcal{N}(0, \sigma^2)$. Then after $O\left(\kappa(\Sigma) \log\left(\frac{\|\mathbf{W}^*\|_{\text{F}}}{\epsilon}\right)\right)$ gradient descent iterations, $N \geq \frac{(1/\delta)K \text{Tr}(\Sigma)}{1600\epsilon^2 \log \epsilon^{-1} \lambda_{\max}(\Sigma)}$, and learning rate $\eta = 0.1\lambda_{\max}^{-2}(\Sigma)$, with probability exceeding $1 - \delta$, Algorithm 1 returns $\mathbf{W}^{(T)}$ such that*

$$\|\mathbf{W}^{(T)} - \mathbf{W}^*\|_{\text{F}} \leq \epsilon + O\left(\sigma \epsilon \sqrt{KC_3 \log \epsilon^{-1}}\right)$$

Proof. The proof is deferred to § A.1. ■

We are able to recover the result of Lemma 4.2 in [ADKS22] when $K = 1$ and the covariates (corrupted and un-corrupted) are sampled from a sub-Gaussian distribution with second-moment matrix \mathbf{I} . The full solve algorithm developed in [ADKS22] returns a $O(\sigma \epsilon \log \epsilon^{-1})$ in time $O\left(\frac{1}{\epsilon^2}(Nd^2 + d^3)\right)$, with the gradient descent based approach, we are able to improve the runtime to $O\left(\log\left(\frac{\|\mathbf{W}^*\|_{\text{F}}}{\sigma \epsilon^2}\right)Nd^2\right)$ for the same approximation bound. We will formalize our results into a corollary to give a more representative comparison in the literature.

Corollary 15. Let $\mathbf{X} = [\mathbf{x}_1, \dots, \mathbf{x}_n]^T \in \mathbb{R}^{d \times N}$ be the data matrix and $\mathbf{y} = [y_1, \dots, y_n] \in \mathbb{R}^N$ be the output, such that for $i \in P$, \mathbf{x}_i are sampled from a sub-Gaussian distribution with sub-Gaussian norm L and second-moment matrix \mathbf{I} . Suppose for $i \in P$ the output is given as $\mathbf{y}_i = \mathbf{x}_i^T \mathbf{w}^* + \xi_i$ where $\xi_i \sim \mathcal{N}(0, \sigma^2)$. Then after $O\left(\log\left(\frac{\|\mathbf{w}^*\|_2}{\epsilon}\right)\right)$ gradient descent iterations, $N \geq \frac{(d/\delta)}{800\epsilon^2}$, and learning rate $\eta = 0.1$, with probability exceeding $1 - \delta$, Algorithm 1 returns $\mathbf{w}^{(T)}$ such that

$$\|\mathbf{w}^{(T)} - \mathbf{w}^*\|_2 \leq \epsilon + O\left(\sigma \epsilon \sqrt{KC_3 \log \epsilon^{-1}}\right)$$

Suppose for $i \in Q$, \mathbf{x}_i are sampled from a sub-Gaussian distribution with sub-Gaussian Norm K and second-moment matrix \mathbf{I} . Then,

$$\|\mathbf{w}^{(T)} - \mathbf{w}^*\|_2 \leq \epsilon + O\left(\sigma \epsilon \log \epsilon^{-1}\right)$$

4.3 Learning Generalized Linear Models

We next study the problem of learning GLMs following the model given in § 5 of [SS19b]. The error function for the Kernelized GLM problem is given by the following equation for a single training pair $(\mathbf{x}_i, y_i) \sim \mathcal{D}$ in the kernelized case.

$$\mathcal{L}(f; \mathbf{x}_i, y_i) = (\omega(f(\mathbf{x}_i)) - y_i)^2$$

Theorem 16. Let $\mathbf{X} = [\mathbf{x}_1, \dots, \mathbf{x}_n]^T \in \mathbb{R}^{d \times N}$ be the data matrix and $\mathbf{y} = [y_1, \dots, y_n]$ be the output, such that for $i \in P$, \mathbf{x}_i are sampled from a sub-Gaussian distribution s.t. $\phi(\mathbf{x}_i) = X_i$ has sub-Gaussian norm L and second-moment matrix Σ , and $y_i = \omega(\mathbf{x}_i^T \mathbf{w}^* + \xi_i)$ for ξ_i sampled from a centered sub-Gaussian distribution with sub-Gaussian norm ν . Suppose the link function $\omega : \mathbb{R} \rightarrow \mathbb{R}$, has bounded gradient s.t. $C_1 \leq \omega'(x) \leq C_2$ for absolute constants $C_1, C_2 > 0$ for all $x \in \mathbb{R}$. Then after $O\left(\kappa(\Sigma) \log\left(\frac{\|f^*\|_{\mathcal{H}}}{\epsilon}\right)\right)$ gradient descent iterations, then with probability exceeding $1 - \delta$,

$$\|f^{(T)} - f^*\|_{\mathcal{H}} \leq \epsilon + O\left(C_1^{-1} C_2^2 \cdot \epsilon \sqrt{\lambda_{\max}(\Sigma) C_3 \log \epsilon^{-1}}\right) + O\left(\lambda_{\max}(\Sigma) \lambda_{\min}^{-2}(\Sigma) \cdot \sigma \cdot (C_1^{-2} C_2^2)\right)$$

when $N \geq \frac{1}{\lambda_{\min}^2(\Sigma)} \cdot \left(8C_K \cdot d + \frac{2}{c_K} \cdot \log(2/\delta)\right)$.

Proof. The proof is deferred to § B.1. ■

Theorem 17. Let $\mathbf{X} = [\mathbf{x}_1, \dots, \mathbf{x}_n]^T \in \mathbb{R}^{d \times N}$ be the data matrix and $\mathbf{y} = [y_1, \dots, y_n]$ be the output, such that for $i \in P$, \mathbf{x}_i are sampled from a sub-Gaussian distribution s.t. $\phi(\mathbf{x}_i) = X_i$ has sub-Gaussian norm L and second-moment matrix Σ , and $y_i = \omega(f^*(\mathbf{x}_i)) + \xi_i$ for ξ_i sampled from a centered sub-Gaussian distribution with sub-Gaussian norm ν . Suppose the link function $\omega : \mathbb{R} \rightarrow \mathbb{R}$, has bounded gradient s.t. $C_1 \leq \omega'(x) \leq C_2$ for absolute constants $C_1, C_2 > 0$ for all $x \in \mathbb{R}$. Then after $O\left(\kappa(\Sigma) \log\left(\frac{\|f^*\|_{\mathcal{H}}}{\epsilon}\right)\right)$ gradient descent iterations, then with probability exceeding $1 - \delta$,

$$\|f^{(T)} - f^*\|_{\mathcal{H}} \leq \epsilon + O\left(C_1^{-1} C_2^2 \cdot \epsilon \sqrt{\lambda_{\max}(\Sigma) C_3 \log \epsilon^{-1}}\right) + O\left(\lambda_{\max}(\Sigma) \lambda_{\min}^{-2}(\Sigma) \cdot \sigma \cdot (C_1^{-2} C_2^2)\right)$$

when $N \geq \frac{1}{\lambda_{\min}^2(\Sigma)} \cdot \left(8C_K \cdot d + \frac{2}{c_K} \cdot \log(2/\delta)\right)$.

Proof. The proof is deferred to § B.1. ■

When considerin the linear regression case

4.4 Learning Leaky-ReLU Neural Networks

In this section we will consider Iterative Thresholding for a linear one-layer neural network and then a general two-layer neural network. We start with the simple case of a linear regression for multi-variate outputs.

Theorem 18. Let $\mathbf{X} = [\mathbf{x}_1, \dots, \mathbf{x}_n]^T \in \mathbb{R}^{N \times d}$ be the data matrix and $\mathbf{y} = [y_1, \dots, y_n]^T$ be the output, such that for $i \in P$, $\mathbf{x}_i \sim \mathcal{P}$ are sampled from a sub-Gaussian distribution with sub-Gaussian norm K and second-moment matrix Σ , and $y_i = \psi(\mathbf{x}_i^T \mathbf{w}^*) + \xi_i$ for $\xi_i \sim \mathcal{N}(0, \sigma^2)$ where $\psi(x) = \max\{C_\psi x, x\}$. Then after $O\left(C_\psi^{-2} \kappa(\Sigma) \log\left(\frac{\|\mathbf{w}^*\|_F}{\epsilon}\right)\right)$ gradient descent iterations and $\epsilon \leq \frac{C_\psi^2 \lambda_{\min}(\Sigma)}{\sqrt{32 C_Q \lambda_{\max}(\Sigma)}}$, with probability exceeding $1 - \delta$, Algorithm 1 with learning rate $\eta = O(\kappa^{-2}(\Sigma))$ returns $\mathbf{w}^{(T)}$ such that

$$\|\mathbf{w}^{(T)} - \mathbf{w}^*\|_2 \leq \epsilon + O\left(\kappa^2(\Sigma) C_\psi^{-1} C_K C_\sigma d \epsilon \log \epsilon^{-1}\right)$$

Proof. The proof is deferred to § C.1.1. ■

4.5 Learning ReLU Neural Networks

We will now consider the problem of learning ReLU neural networks.

4.5.1 Single Neuron

Theorem 19. Let $\mathbf{X} = [\mathbf{x}_1, \dots, \mathbf{x}_n]^T \in \mathbb{R}^{n \times d}$ be the data matrix and $\mathbf{y} = [y_1, \dots, y_n]^T$ be the output, such that for $i \in P$, \mathbf{x}_i are sampled from a sub-Gaussian distribution with sub-Gaussian norm K and second-moment matrix Σ . Suppose for $i \in P$, the output is given as $y_i = \psi(\mathbf{x}_i^T \mathbf{w}^*) + \xi_i$ for $\xi_i \sim \mathcal{N}(0, \sigma^2)$ and $\psi = \max\{0, x\}$ is the ReLU function. Then after $O(\Xi)$ gradient descent iterations and $n = \Omega(\Xi)$, then with probability exceeding $1 - \delta$, Algorithm 1 with learning rate $\eta = O(\Xi)$ returns $\mathbf{w}^{(T)}$ such that $\|\mathbf{w}^{(T)} - \mathbf{w}^*\|_2 \leq \epsilon + O(\Xi)$.

Proof. The proof is deferred to § C.2 ■

5 Discussion

In this paper, we study the theoretical convergence properties of iterative thresholding for non-linear learning problems in the Huber- ϵ contamination model. Our warm-up result for linear regression reduces the runtime while achieving the same approximation bound. Many papers have experimentally studied the iterative thresholding estimator in large scale neural networks. We are the first paper to give statistical learning guarantees in the two-layer case with the ReLU activation function.

References

- [ADKS22] Pranjali Awasthi, Abhimanyu Das, Weihao Kong, and Rajat Sen. Trimmed maximum likelihood estimation for robust generalized linear model. In Alice H. Oh, Alekh Agarwal, Danielle Belgrave, and Kyunghyun Cho, editors, *Advances in Neural Information Processing Systems*, 2022. 1, 1, 4, 1.1, ??, 2.2, 4.2, 4.2
- [AMMIL12] Yaser S Abu-Mostafa, Malik Magdon-Ismael, and Hsuan-Tien Lin. *Learning from data*, volume 4. AMLBook New York, 2012. 1
- [B⁺15] Sébastien Bubeck et al. Convex optimization: Algorithms and complexity. *Foundations and Trends® in Machine Learning*, 8(3-4):231–357, 2015. 29
- [BJK15] Kush Bhatia, Prateek Jain, and Purushottam Kar. Robust regression via hard thresholding. In C. Cortes, N. Lawrence, D. Lee, M. Sugiyama, and R. Garnett, editors, *Advances in Neural Information Processing Systems*, volume 28. Curran Associates, Inc., 2015. 3, 1.1, ??, 1.1, 2.2

- [BJKK17] Kush Bhatia, Prateek Jain, Parameswaran Kamalaruban, and Purushottam Kar. Consistent robust regression. In I. Guyon, U. Von Luxburg, S. Bengio, H. Wallach, R. Fergus, S. Vishwanathan, and R. Garnett, editors, *Advances in Neural Information Processing Systems*, volume 30. Curran Associates, Inc., 2017. 1, 2.2, 4.2
- [CDGS20] Yu Cheng, Ilias Diakonikolas, Rong Ge, and Mahdi Soltanolkotabi. High-dimensional robust mean estimation via gradient descent. In Hal Daumé III and Aarti Singh, editors, *Proceedings of the 37th International Conference on Machine Learning*, volume 119 of *Proceedings of Machine Learning Research*, pages 1768–1778. PMLR, 13–18 Jul 2020. 1
- [CDGW19] Yu Cheng, Ilias Diakonikolas, Rong Ge, and David P. Woodruff. Faster algorithms for high-dimensional robust covariance estimation. In Alina Beygelzimer and Daniel Hsu, editors, *Proceedings of the Thirty-Second Conference on Learning Theory*, volume 99 of *Proceedings of Machine Learning Research*, pages 727–757. PMLR, 25–28 Jun 2019. 1
- [CLKZ21] Hugo Cui, Bruno Loureiro, Florent Krzakala, and Lenka Zdeborová. Generalization error rates in kernel regression: The crossover from the noiseless to noisy regime. *Advances in Neural Information Processing Systems*, 34:10131–10143, 2021. 1
- [CLRS22] Thomas H Cormen, Charles E Leiserson, Ronald L Rivest, and Clifford Stein. *Introduction to algorithms*. MIT press, 2022. 35
- [Dic16] Lee H Dicker. Ridge regression and asymptotic minimax estimation over spheres of growing dimension. 2016. 1
- [DK23] Ilias Diakonikolas and Daniel M Kane. *Algorithmic high-dimensional robust statistics*. Cambridge University Press, 2023. 1
- [DKK⁺19] Ilias Diakonikolas, Gautam Kamath, Daniel M. Kane, Jerry Li, Jacob Steinhardt, and Alistair Stewart. Sever: A robust meta-algorithm for stochastic optimization. In *Proceedings of the 36th International Conference on Machine Learning, ICML ’19*, pages 1596–1606. JMLR, Inc., 2019. 1
- [FB81] Martin A. Fischler and Robert C. Bolles. Random sample consensus: A paradigm for model fitting with applications to image analysis and automated cartography. *Commun. ACM*, 24(6):381–395, jun 1981. 1
- [FWZ18] Jianqing Fan, Weichen Wang, and Yiqiao Zhong. An l_1 eigenvector perturbation bound and its application to robust covariance estimation. *Journal of Machine Learning Research*, 18(207):1–42, 2018. 1
- [HMT11] Nathan Halko, Per-Gunnar Martinsson, and Joel A Tropp. Finding structure with randomness: Probabilistic algorithms for constructing approximate matrix decompositions. *SIAM review*, 53(2):217–288, 2011. 31
- [HR09] Peter J. Huber and Elvezio Ronchetti. *Robust statistics*. Wiley series in probability and statistics. Wiley, Hoboken, N.J., 2nd ed. edition, 2009. 1
- [HSS08] Thomas Hofmann, Bernhard Schölkopf, and Alexander J. Smola. Kernel methods in machine learning. *The Annals of Statistics*, 36(3):1171 – 1220, 2008. 1
- [HYW⁺23] Shu Hu, Zhenhuan Yang, Xin Wang, Yiming Ying, and Siwei Lyu. Outlier robust adversarial training. *arXiv preprint arXiv:2309.05145*, 2023. 2.2
- [HYwL20] Shu Hu, Yiming Ying, xin wang, and Siwei Lyu. Learning by minimizing the sum of ranked range. In H. Larochelle, M. Ranzato, R. Hadsell, M.F. Balcan, and H. Lin, editors, *Advances in Neural Information Processing Systems*, volume 33, pages 21013–21023. Curran Associates, Inc., 2020. 1

- [JZL⁺18] Lu Jiang, Zhengyuan Zhou, Thomas Leung, Li-Jia Li, and Li Fei-Fei. Mentornet: Learning data-driven curriculum for very deep neural networks on corrupted labels. In *ICML*, 2018. [1](#)
- [KLA18] Ashish Khetan, Zachary C. Lipton, and Anima Anandkumar. Learning from noisy singly-labeled data. In *International Conference on Learning Representations*, 2018. [1](#)
- [LBSS21] Tian Li, Ahmad Beirami, Maziar Sanjabi, and Virginia Smith. Tilted empirical risk minimization. In *International Conference on Learning Representations*, 2021. [1](#), [1](#)
- [Leg06] Adrien M Legendre. *Nouvelles methodes pour la determination des orbites des cometes: avec un supplement contenant divers perfectionnemens de ces methodes et leur application aux deux cometes de 1805*. Courcier, 1806. [2.2](#)
- [LM00] Beatrice Laurent and Pascal Massart. Adaptive estimation of a quadratic functional by model selection. *Annals of statistics*, pages 1302–1338, 2000. [20](#)
- [MGJK19] Bhaskar Mukhoty, Govind Gopakumar, Prateek Jain, and Purushottam Kar. Globally-convergent iteratively reweighted least squares for robust regression problems. In Kamalika Chaudhuri and Masashi Sugiyama, editors, *Proceedings of the Twenty-Second International Conference on Artificial Intelligence and Statistics*, volume 89 of *Proceedings of Machine Learning Research*, pages 313–322. PMLR, 16–18 Apr 2019. [1](#), [2.2](#)
- [OZS20] Muhammad Osama, Dave Zachariah, and Petre Stoica. Robust risk minimization for statistical learning from corrupted data. *IEEE Open Journal of Signal Processing*, 1:287–294, 2020. [1](#)
- [PBR19] Adarsh Prasad, Sivaraman Balakrishnan, and Pradeep Ravikumar. A unified approach to robust mean estimation. *arXiv preprint arXiv:1907.00927*, 2019. [1](#)
- [PP⁺08] Kaare Brandt Petersen, Michael Syskind Pedersen, et al. The matrix cookbook. *Technical University of Denmark*, 7(15):510, 2008. [A.1](#)
- [PSBR18] Adarsh Prasad, Arun Sai Suggala, Sivaraman Balakrishnan, and Pradeep Ravikumar. Robust estimation via robust gradient estimation. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, 82, 2018. [1](#)
- [RH23] Philippe Rigollet and Jan-Christian Hütter. High-dimensional statistics. *arXiv preprint arXiv:2310.19244*, 2023. [D.1](#)
- [RHL⁺20] Meisam Razaviyayn, Tianjian Huang, Songtao Lu, Maher Nouiehed, Maziar Sanjabi, and Mingyi Hong. Nonconvex min-max optimization: Applications, challenges, and recent theoretical advances. *IEEE Signal Processing Magazine*, 37(5):55–66, 2020. [3](#)
- [SBRJ19] Arun Sai Suggala, Kush Bhatia, Pradeep Ravikumar, and Prateek Jain. Adaptive hard thresholding for near-optimal consistent robust regression. In Alina Beygelzimer and Daniel Hsu, editors, *Proceedings of the Thirty-Second Conference on Learning Theory*, volume 99 of *Proceedings of Machine Learning Research*, pages 2892–2897. PMLR, 25–28 Jun 2019. [2.2](#)
- [SS19a] Yanyao Shen and Sujay Sanghavi. Learning with bad training data via iterative trimmed loss minimization. In *International Conference on Machine Learning*, pages 5739–5748. PMLR, 2019. [\(document\)](#)
- [SS19b] Yanyao Shen and Sujay Sanghavi. Learning with bad training data via iterative trimmed loss minimization. In Kamalika Chaudhuri and Ruslan Salakhutdinov, editors, *Proceedings of the 36th International Conference on Machine Learning*, volume 97 of *Proceedings of Machine Learning Research*, pages 5739–5748. PMLR, 09–15 Jun 2019. [1.1](#), [4.3](#)
- [TT15] Alex Townsend and Lloyd N Trefethen. Continuous analogues of matrix factorizations. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 471(2173):20140585, 2015. [1](#)

- [Ver10] Roman Vershynin. Introduction to the non-asymptotic analysis of random matrices. *arXiv preprint arXiv:1011.3027*, 2010. [22](#)
- [Ver20] Roman Vershynin. High-dimensional probability. *University of California, Irvine*, 2020. [D.1](#)
- [W⁺14] David P Woodruff et al. Sketching as a tool for numerical linear algebra. *Foundations and Trends® in Theoretical Computer Science*, 10(1–2):1–157, 2014. [1](#)
- [You12] William Henry Young. On classes of summable functions and their fourier series. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 87(594):225–229, 1912. [30](#)
- [ZYWG19] Xiao Zhang, Yaodong Yu, Lingxiao Wang, and Quanquan Gu. Learning one-hidden-layer relu networks via gradient descent. In *The 22nd international conference on artificial intelligence and statistics*, pages 1524–1534. PMLR, 2019. [C.2](#), [D.1](#)

A Proofs for Linear Regression

Notation. We will first give some notational preliminaries. Let $X = P \cup Q$ for $|P| = (1 - \epsilon)N$ and $|Q| = \epsilon N$ represent the sets such that for $i \in P$, (\mathbf{x}_i, y_i) is the good data and for $j \in Q$, (\mathbf{x}_j, y_j) has been given by the adversary. For $t \in [T]$, we denote $S^{(t)}$ as the Subquantile set at iteration t and represents the points. We decompose $S^{(t)} = S^{(t)} \cap P \cup S^{(t)} \cap Q = TP \cup FP$ to represent the *True Positives* and *False Positives*. We also decompose $X \setminus S^{(t)} = (X \setminus S^{(t)}) \cap P \cup (X \setminus S^{(t)}) \cap Q = FN \cup TN$ to represent the *False Negatives* and the *True Negatives*.

A.1 Proof of Theorem 14

Proof. Recall that for any $\mathbf{W} \in \mathbb{R}^{k \times d}$, $\mathbf{X} \in \mathbb{R}^{d \times n}$, and $\mathbf{Y} \in \mathbb{R}^{k \times n}$,

$$\begin{aligned} \mathcal{L}(\mathbf{W}; \mathbf{X}, \mathbf{Y}) &= \|\mathbf{W}\mathbf{X} - \mathbf{Y}\|_F^2 = \text{Tr}(\mathbf{X}^T \mathbf{W}^T \mathbf{W} \mathbf{X} - \mathbf{X}^T \mathbf{W}^T \mathbf{Y} - \mathbf{Y}^T \mathbf{W} \mathbf{X} + \mathbf{Y}^T \mathbf{Y}) \\ &= \text{Tr}(\mathbf{X}^T \mathbf{W}^T \mathbf{W} \mathbf{X}) + \text{Tr}(\mathbf{Y}^T \mathbf{Y}) - 2 \text{Tr}(\mathbf{X}^T \mathbf{W}^T \mathbf{Y}) \end{aligned}$$

Then, from [PP⁺08] Equations (102) and (119) (where we set $\mathbf{B} = \mathbf{I}$ and $\mathbf{C} = \mathbf{0}$). We have,

$$\nabla \mathcal{L}(\mathbf{W}) = 2(\mathbf{W}\mathbf{X} - \mathbf{Y})\mathbf{X}^T$$

Step 1: Linear Convergence. We will first show iterative thresholding has linear convergence to optimal. Let $\widehat{\mathbf{W}} = \arg \min_{\mathbf{W} \in \mathbb{R}^{k \times d}} \mathcal{R}(\mathbf{W}; P)$ be the minimizer over the good data. Then, we have

$$\begin{aligned} \|\mathbf{W}^{(t+1)} - \mathbf{W}^*\|_F &= \|\mathbf{W}^{(t)} - \mathbf{W}^* - \eta \nabla \mathcal{R}(\mathbf{W}^{(t)}; S^{(t)})\|_F \\ &= \|\mathbf{W}^{(t)} - \mathbf{W}^* - \eta \nabla \mathcal{R}(\mathbf{W}^{(t)}; TP) + \eta \nabla \mathcal{R}(\mathbf{W}^*; P) - \eta \nabla \mathcal{R}(\mathbf{W}^*; P) + \eta \nabla \mathcal{R}(\widehat{\mathbf{W}}; P) - \eta \nabla \mathcal{R}(\mathbf{W}^{(t)}; FP)\|_F \\ &\leq \|\mathbf{W}^{(t)} - \mathbf{W}^* + \eta \nabla \mathcal{R}(\mathbf{W}^{(t)}; TP) + \eta \nabla \mathcal{R}(\mathbf{W}^*; TP)\|_F + \|\eta \nabla \mathcal{R}(\mathbf{W}^{(t)}; FP)\|_F + \|\eta \nabla \mathcal{R}(\mathbf{W}^*; FN)\|_F \\ &\quad + \|\eta \nabla \mathcal{R}(\mathbf{W}^*; P) - \eta \nabla \mathcal{R}(\widehat{\mathbf{W}}; P)\|_F \end{aligned} \tag{A.1}$$

We first will upper bound the first term in Equation (A.1) through its square.

$$\begin{aligned} \|\mathbf{W}^{(t)} - \mathbf{W}^* - \eta \nabla \mathcal{R}(\mathbf{W}^{(t)}; TP) + \eta \nabla \mathcal{R}(\mathbf{W}^*; TP)\|_F^2 &= \|\mathbf{W}^{(t)} - \mathbf{W}^*\|_F^2 \\ &\quad - 2\eta \cdot \text{Tr}((\mathbf{W}^{(t)} - \mathbf{W}^*)^T (\nabla \mathcal{R}(\mathbf{W}^{(t)}; TP) - \nabla \mathcal{R}(\mathbf{W}^*; TP))) + \|\eta \nabla \mathcal{R}(\mathbf{W}^{(t)}; TP) - \eta \nabla \mathcal{R}(\mathbf{W}^*; TP)\|_F^2 \end{aligned} \tag{A.2}$$

We then lower bound the second term in Equation (A.2),

$$\begin{aligned} &2\eta \cdot \text{Tr}((\mathbf{W}^{(t)} - \mathbf{W}^*)^T (\nabla \mathcal{R}(\mathbf{W}^{(t)}; TP) - \nabla \mathcal{R}(\mathbf{W}^*; TP))) \\ &\stackrel{\text{def}}{=} \frac{4\eta}{(1 - \epsilon)N} \cdot \text{Tr}((\mathbf{W}^{(t)} - \mathbf{W}^*)^T ((\mathbf{W}^{(t)} \mathbf{X}_{TP} - \mathbf{Y}_{TP}) \mathbf{X}_{TP}^T - \mathbf{E}_{TP} \mathbf{X}_{TP}^T)) \\ &= \frac{4\eta}{(1 - \epsilon)N} \cdot \text{Tr}((\mathbf{W}^{(t)} - \mathbf{W}^*)^T (\mathbf{W}^{(t)} - \mathbf{W}^*) \mathbf{X}_{TP} \mathbf{X}_{TP}^T) \end{aligned} \tag{A.3}$$

In the above, the second equation follows from noting that $\mathbf{Y}_{TP} = \mathbf{W}^* \mathbf{X}_{TP} - \mathbf{E}_{TP}$. We can now lower bound the term in Equation (A.3).

$$\begin{aligned} &\frac{4\eta}{(1 - \epsilon)N} \cdot \text{Tr}((\mathbf{W}^{(t)} - \mathbf{W}^*)^T (\mathbf{W}^{(t)} - \mathbf{W}^*) \mathbf{X}_{TP} \mathbf{X}_{TP}^T) \\ &= \frac{4\eta}{(1 - \epsilon)N} \cdot \text{Tr}((\mathbf{W}^{(t)} - \mathbf{W}^*) \mathbf{X}_{TP} \mathbf{X}_{TP}^T (\mathbf{W}^{(t)} - \mathbf{W}^*)^T) \\ &= \frac{4\eta}{(1 - \epsilon)N} \cdot \langle \text{vec}((\mathbf{W}^{(t)} - \mathbf{W}^*)^T), \text{vec}(\mathbf{X}_{TP} \mathbf{X}_{TP}^T (\mathbf{W}^{(t)} - \mathbf{W}^*)^T) \rangle \\ &= \frac{4\eta}{(1 - \epsilon)N} \cdot \langle \text{vec}((\mathbf{W}^{(t)} - \mathbf{W}^*)^T), (\mathbf{I} \otimes \mathbf{X}_{TP} \mathbf{X}_{TP}^T) \text{vec}((\mathbf{W}^{(t)} - \mathbf{W}^*)^T) \rangle \end{aligned}$$

$$\begin{aligned}
&= \frac{4\eta}{(1-\epsilon)N} \cdot \sum_{k \in [K]} \langle \mathbf{w}_k^{(t)} - \mathbf{w}_k^*, \mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T (\mathbf{w}_k^{(t)} - \mathbf{w}_k^*) \rangle \\
&\geq \frac{2\eta}{(1-\epsilon)N} \cdot \sum_{k \in [K]} (\lambda_{\min}(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \|\mathbf{w}_k^{(t)} - \mathbf{w}_k^*\|_2^2 + \|\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T\|_2^{-1} \|\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T (\mathbf{w}_k^{(t)} - \mathbf{w}_k^*)\|_2^2) \\
&= \frac{2\eta}{(1-\epsilon)N} \cdot \lambda_{\min}(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \|\mathbf{W}^{(t)} - \mathbf{W}^*\|_F^2 + \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T\|_2^{-1} \|(\mathbf{W}^{(t)} - \mathbf{W}^*) \mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T\|_F^2 \quad (\text{A.4})
\end{aligned}$$

In the above, in the first relation we use the cyclic property of the trace, in the second relation we use the relation given in Lemma 33, in the third relation we apply the relation given in Lemma 34, in the fifth relation we apply Lemma 29, and in the fourth relation we apply Lemma 34, which gives the following equality,

$$(\mathbf{I} \otimes \mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \text{vec}((\mathbf{W}^{(t)} - \mathbf{W}^*)^T) = \begin{bmatrix} \mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T & & \\ & \ddots & \\ & & \mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T \end{bmatrix} \begin{bmatrix} \mathbf{w}_1 - \mathbf{w}_1^* \\ \vdots \\ \mathbf{w}_K - \mathbf{w}_K^* \end{bmatrix} = \begin{bmatrix} \mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T (\mathbf{w}_1 - \mathbf{w}_1^*) \\ \vdots \\ \mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T (\mathbf{w}_K - \mathbf{w}_K^*) \end{bmatrix}$$

We now upper bound the second term in Equation (A.1),

$$\begin{aligned}
\|\eta \nabla \mathcal{R}(\mathbf{W}^{(t)}; \text{FP})\|_F &\stackrel{\text{def}}{=} \frac{2\eta}{(1-\epsilon)N} \cdot \|(\mathbf{W}^{(t)} \mathbf{X}_{\text{FP}} - \mathbf{Y}_{\text{FP}}) \mathbf{X}_{\text{FP}}^T\|_F \\
&\leq \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{W}^{(t)} \mathbf{X}_{\text{FP}} - \mathbf{Y}_{\text{FP}}\|_F \\
&\leq \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{W}^{(t)} \mathbf{X}_{\text{FN}} - \mathbf{Y}_{\text{FN}}\|_F \\
&\leq \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 (\|\mathbf{W}^{(t)} \mathbf{X}_{\text{FN}} - \mathbf{W}^* \mathbf{X}_{\text{FN}}\|_F + \|\mathbf{E}_{\text{FN}}\|_F) \\
&\leq \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{X}_{\text{FN}}\|_2 \|\mathbf{W}^{(t)} - \mathbf{W}^*\|_F + \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{E}_{\text{FN}}\|_F
\end{aligned}$$

In the above, the first and fourth inequalities from the fact that for any two size compatible matrices, \mathbf{A}, \mathbf{B} , it holds that $\|\mathbf{AB}\|_F \leq \|\mathbf{A}\|_F \|\mathbf{B}\|_2$, the second inequality follows from the optimality of the Subquantile set, the third inequality follows from the sub-additivity of the Frobenius norm. We will now upper bound the third term in Equation (A.1),

$$\|\eta \nabla \mathcal{R}(\mathbf{W}^*; \text{FN})\|_F \stackrel{\text{def}}{=} \frac{2\eta}{(1-\epsilon)N} \cdot \|(\mathbf{W}^* \mathbf{X}_{\text{FN}} - \mathbf{Y}_{\text{FN}}) \mathbf{X}_{\text{FN}}^T\|_F \leq \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{E}_{\text{FN}} \mathbf{X}_{\text{FN}}^T\|_F \quad (\text{A.5})$$

In the above, we use the fact that for any two size compatible matrices, \mathbf{A}, \mathbf{B} , it holds that $\|\mathbf{AB}\|_F \leq \|\mathbf{A}\|_F \|\mathbf{B}\|_2$.

Step 2: Consistency. We will now upper bound the consistency estimate of the fourth term of Equation (A.1).

$$\|\eta \nabla \mathcal{R}(\mathbf{W}^*; \text{P}) - \eta \nabla \mathcal{R}(\widehat{\mathbf{W}}; \text{P})\|_F \stackrel{\text{def}}{=} \frac{2\eta}{(1-\epsilon)N} \cdot \|(\widehat{\mathbf{W}} - \mathbf{W}^*) \mathbf{X}_{\text{P}} \mathbf{X}_{\text{P}}^T\|_F \leq \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{E}_{\text{P}} \mathbf{X}_{\text{P}}^T\|_F$$

We can then have from Proposition 31,

$$\mathbb{E} \|\mathbf{E}_{\text{P}} \mathbf{X}_{\text{P}}^T\|_F^2 = \sigma^2 \left(K \mathbb{E} \|\mathbf{X}_{\text{P}}\|_F^2 \right) = \sigma^2 (K \mathbb{E} \text{Tr}(\mathbf{X}_{\text{P}} \mathbf{X}_{\text{P}}^T)) = \sigma^2 ((1-\epsilon)NK \text{Tr}(\mathbf{\Sigma}))$$

Then from a simple application of Markov's Inequality, we have with probability exceeding $1 - \delta$,

$$\frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{E}_{\text{P}} \mathbf{X}_{\text{P}}^T\|_F \leq 2\eta\sigma \cdot \sqrt{\frac{(1/\delta)K \text{Tr}(\mathbf{\Sigma})}{(1-\epsilon)N}}$$

We then have from our choice of $\eta = 0.1\lambda_{\max}^{-2}(\mathbf{\Sigma})$, the third term in Equation (A.1) will be less than the second term in Equation (A.4). We thus obtain from noting that $\sqrt{1-2x} \leq 1-x$ for any $x \leq 1/2$,

$$\begin{aligned}\|\mathbf{W}^{(t+1)} - \mathbf{W}^*\|_F &\leq \|\mathbf{W}^{(t)} - \mathbf{W}^*\|_F \left(1 - \frac{2\eta}{(1-\epsilon)N} \cdot \lambda_{\min}(\mathbf{X}_{\text{TP}}\mathbf{X}_{\text{TP}}^T) + \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{X}_{\text{FN}}\|_2\right) \\ &\quad + \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{E}_{\text{FN}}\|_F + \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{E}_{\text{FN}}\mathbf{X}_{\text{FN}}^T\|_F + 2\sigma\eta \cdot \sqrt{\frac{(1/\delta)K \text{Tr}(\mathbf{\Sigma})}{(1-\epsilon)N}}\end{aligned}$$

Step 3: Concentration Bounds. From Proposition 21, we obtain with probability exceeding $1 - \delta$ that $\|\mathbf{E}_{\text{FN}}\|_F \leq \sigma\sqrt{30NK\epsilon \log \epsilon^{-1}}$. From our assumption on bounded covariate corruptions, we have $\|\mathbf{E}_{\text{FN}}\|_F \|\mathbf{X}_{\text{FP}}\|_F \leq \sigma\epsilon\sqrt{30NK C_3 \log \epsilon^{-1}}$. From Lemma 26, we have that $\|\mathbf{E}_{\text{FN}}\mathbf{X}_{\text{FN}}^T\|_F \leq \sqrt{6K \log N} \|\mathbf{X}_{\text{FN}}\|_F$ when $n \geq (1/\delta)$ with probability exceeding $1 - \delta$. From Lemma 23, we have for $\epsilon \leq \frac{1}{240}\kappa^{-1}(\mathbf{\Sigma})$, the minimum eigenvalue satisfies $\lambda_{\min}(\mathbf{X}_{\text{TP}}\mathbf{X}_{\text{TP}}^T) \geq (N/2) \cdot (1 - 2\epsilon) \cdot \lambda_{\min}(\mathbf{\Sigma}) \geq (N/4) \cdot \lambda_{\min}(\mathbf{\Sigma})$. From our assumption of corrupted covariates, we have that $\|\mathbf{X}_{\text{FP}}\|_2 \leq \sqrt{\epsilon N C_3}$. We also have from Lemma 23, we have $\|\mathbf{X}_{\text{FN}}\|_2 \leq \sqrt{\lambda_{\max}(\mathbf{\Sigma}) \cdot (10N\epsilon \log \epsilon^{-1})}$ with high probability. Then when $\epsilon \leq \sqrt{\frac{1}{960C_3} \cdot \kappa^{-1}(\mathbf{\Sigma}) \lambda_{\min}(\mathbf{\Sigma})}$, we have that $\|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{X}_{\text{FN}}\|_2 \leq (N/8)\lambda_{\min}(\mathbf{\Sigma})$. Then, solving for the induction with an infinite sum, we have after $O\left(\kappa(\mathbf{\Sigma}) \cdot \log\left(\frac{\|\mathbf{W}^*\|_F}{\epsilon}\right)\right)$ iterations,

$$\begin{aligned}\|\mathbf{W}^{(t+1)} - \mathbf{W}^*\|_F &\leq \epsilon + \sigma\epsilon\sqrt{4800K C_3 \log \epsilon^{-1}} \cdot \frac{\sqrt{\lambda_{\max}(\mathbf{\Sigma})}}{\lambda_{\min}(\mathbf{\Sigma})} + \frac{\sqrt{60\sigma K \log N \cdot \epsilon \log \epsilon^{-1} \lambda_{\max}(\mathbf{\Sigma})}}{\sqrt{N} \lambda_{\min}(\mathbf{\Sigma})} \\ &\quad + \frac{\sigma}{\lambda_{\min}(\mathbf{\Sigma})} \cdot \sqrt{\frac{(8/\delta)K \text{Tr}(\mathbf{\Sigma})}{N}} \leq \epsilon + \sigma\epsilon\sqrt{43200K C_3 \log \epsilon^{-1}}\end{aligned}$$

In the above, the final equality follows when $N \geq \frac{(1/\delta)K \text{Tr}(\mathbf{\Sigma})}{1600\epsilon^2 \log \epsilon^{-1} \lambda_{\max}(\mathbf{\Sigma})} \vee \frac{1}{6400C_3^2 \epsilon^2}$. Our proof is complete. ■

B Proofs for Learning Property 13 Activation

B.1 Proof of Theorem 16

Proof. From Algorithm 1, we have the gradient update for the generalized linear model.

$$\mathbf{w}^{(t+1)} = \mathbf{w}^{(t)} - \frac{2\eta}{(1-\epsilon)N} \cdot \sum_{i \in S^{(t)}} (\omega(\mathbf{x}_i^T \mathbf{w}^{(t)}) - y_i) \cdot \omega'(f^{(t)}(\mathbf{x}_i)) \cdot \mathbf{x}_i$$

Step 1: Linear Convergence.

$$\begin{aligned}\|\mathbf{w}^{(t+1)} - \mathbf{w}^*\|_2 &= \|\mathbf{w}^{(t)} - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \mathbf{S}^{(t)}) - \mathbf{w}^*\|_2 \\ &= \|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{FP})\|_2 \\ &\leq \|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2 + \|\eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{FP})\|_2\end{aligned}\tag{B.1}$$

We upper bound the first term of Equation (B.1) through its square.

$$\|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2^2 = \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 - 2\eta \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) \rangle + \eta^2 \cdot \|\nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2^2\tag{B.2}$$

We now lower bound the second term of Equation (B.2).

$$\begin{aligned}2\eta \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) \rangle &= \frac{4\eta}{(1-\epsilon)N} \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \sum_{i \in \text{TP}} (\omega(\mathbf{x}_i^T \mathbf{w}^{(t)}) - y_i) \cdot \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \rangle \\ &= \frac{4\eta}{(1-\epsilon)N} \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \sum_{i \in \text{TP}} (\omega(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \omega(\mathbf{x}_i^T \mathbf{w}^* + \xi_i)) \cdot \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \rangle \\ &\geq \frac{4\eta}{(1-\epsilon)N} \cdot C_{[\omega]}^2 \lambda_{\min}(\mathbf{X}_{\text{TP}}\mathbf{X}_{\text{TP}}^T) \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 - \frac{4\eta}{(1-\epsilon)N} \cdot \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2 \left\| \sum_{i \in \text{TP}} \xi_i \omega'(c_i) \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \right\|_2\end{aligned}\tag{B.3}$$

In the above, in the final relation, we apply Cauchy-Schwarz inequality after using the mean-value theorem, which gives us the existence of some $c_i \in \mathbb{R}$ such that $\omega'(c_i)(\mathbf{x}_i^T \mathbf{w}^{(t)} - \mathbf{x}_i^T \mathbf{w}^* - \xi_i) = \omega(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \omega(\mathbf{x}_i^T \mathbf{w}^* + \xi_i)$. Then from an application of Young's Inequality (see Proposition 30), we obtain

$$\begin{aligned} & \frac{4\eta}{(1-\epsilon)N} \cdot \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2 \left\| \sum_{i \in \text{TP}} \xi_i \omega'(c_i) \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \right\|_2 \\ & \leq \frac{\eta}{(1-\epsilon)N} \cdot C_{[\omega]}^2 \lambda_{\min}(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 + \frac{4\eta}{(1-\epsilon)N} \cdot \lambda_{\min}^{-1}(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \left\| \sum_{i \in \text{TP}} \xi_i \omega'(c_i) \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \right\|_2^2 \end{aligned}$$

We next upper bound the third term in Equation (B.2).

$$\begin{aligned} \eta^2 \cdot \|\nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2^2 &= \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \left\| \sum_{i \in \text{TP}} (\omega(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \omega(\mathbf{x}_i^T \mathbf{w}^* + \xi_i)) \cdot \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \right\|_2^2 \\ &= \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \left\| \sum_{i \in \text{TP}} (\mathbf{x}_i^T \mathbf{w}^{(t)} - \mathbf{x}_i^T \mathbf{w}^* + \xi_i) \cdot \omega'(c_i) \cdot \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \right\|_2^2 \\ &\leq \frac{8\eta^2}{[(1-\epsilon)N]^2} \cdot \left(C_{[\omega]}^4 \lambda_{\max}^2(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 + \left\| \sum_{i \in \text{TP}} \xi_i \cdot \omega'(c_i) \cdot \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \right\|_2^2 \right) \quad (\text{B.4}) \end{aligned}$$

Then, from choosing $\eta \leq \frac{C_{[\omega]}^2 (1-\epsilon) N \lambda_{\min}(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T)}{4C_{[\omega]}^4 \lambda_{\max}^2(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T)}$. We see the first term of Equation (B.4) is less than half the first term in Equation (B.3). We now bound the second term in Equation (B.1).

$$\begin{aligned} \eta^2 \cdot \|\nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{FP})\|_2^2 &= \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \left\| \sum_{i \in \text{FP}} (\omega(\mathbf{x}_i^T \mathbf{w}^{(t)}) - y_i) \cdot \omega'(\mathbf{x}_i^T \mathbf{w}) \cdot \mathbf{x}_i \right\|_2^2 \\ &\leq \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot C_{[\omega]}^2 \|\mathbf{X}_{\text{FP}} \mathbf{X}_{\text{FP}}^T\|_2 \sum_{i \in \text{FP}} (\omega(\mathbf{x}_i^T \mathbf{w}^{(t)}) - y_i)^2 \\ &\leq \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot C_{[\omega]}^2 \|\mathbf{X}_{\text{FP}} \mathbf{X}_{\text{FP}}^T\|_2 \sum_{i \in \text{FN}} (\omega(\mathbf{x}_i^T \mathbf{w}^{(t)}) - y_i)^2 \\ &= \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot C_{[\omega]}^2 \|\mathbf{X}_{\text{FP}} \mathbf{X}_{\text{FP}}^T\|_2 \sum_{i \in \text{FN}} (\omega(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \omega(\mathbf{x}_i^T \mathbf{w}^*) + \xi_i)^2 \\ &\leq \frac{8\eta^2}{[(1-\epsilon)N]^2} \cdot C_{[\omega]}^2 \|\mathbf{X}_{\text{FP}} \mathbf{X}_{\text{FP}}^T\|_2 \left(C_{[\omega]}^2 \cdot \|\mathbf{X}_{\text{FN}} \mathbf{X}_{\text{FN}}^T\|_2 \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 + \|\boldsymbol{\xi}_{\text{FN}}\|_2^2 \right) \end{aligned}$$

Concluding the step, we have

$$\begin{aligned} \|\mathbf{w}^{(t+1)} - \mathbf{w}^*\|_2 &\leq \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2 \left(1 - \frac{\eta}{2(1-\epsilon)N} \cdot C_{[\omega]}^2 \lambda_{\min}(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) + \frac{\sqrt{8}\eta}{(1-\epsilon)N} \cdot C_{[\omega]}^2 \|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{X}_{\text{FN}}\|_2 \right) \\ &\quad + \left(\frac{\sqrt{8}\eta}{(1-\epsilon)N} + \frac{2\sqrt{\eta}}{\sqrt{(1-\epsilon)N}} \cdot \sigma_{\min}^{-1}(\mathbf{X}_{\text{TP}}) \right) \left\| \sum_{i \in \text{TP}} \xi_i \omega'(c_i) \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \mathbf{x}_i \right\|_2 + \frac{\sqrt{8}\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 \|\boldsymbol{\xi}_{\text{FN}}\|_2 \end{aligned}$$

Step 2: Concentration Bounds. First we will show that $\xi \omega'(c) \omega'(\mathbf{x}^T \mathbf{w})$ is sub-Gaussian for any $c \in \mathbb{R}$, $\mathbf{w} \in \mathbb{R}^d$ and \mathbf{x} sampled from a sub-Gaussian distribution. Note that ξ is sub-Gaussian s.t. $\|\xi\|_{\psi_2} = C_\sigma$. Then, we have

$$\left(\mathbb{E} |\xi \omega'(c) \omega'(\mathbf{x}^T \mathbf{w})|^p \right)^{1/p} \stackrel{(i)}{\leq} \left(\sup_{x \in \mathbb{R}} [\omega'(x)]^{6p} \mathbb{E} |\xi|^{3p} \right)^{1/3p} \leq C_{[\psi]}^2 C_\sigma$$

In (i) we apply Hölder's Inequality. We thus have $\|\xi \omega'(c) \omega'(\mathbf{x}^T \mathbf{w})\|_{\psi_2} \leq C_{[\psi]}^2 C_\sigma$. Then applying Lemma 24, we have with probability at least $1 - \delta$,

$$\left\| \sum_{i \in \text{TP}} \xi_i \cdot \omega'(c_i) \cdot \omega'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \right\|_2 \leq N C_K C_{[\psi]}^2 C_\sigma \left(\frac{2d}{N} \log(5) + \frac{2}{N} \log(1/\delta) + 6\epsilon \log \epsilon^{-1} \right)^{1/2}$$

Recall that $\|\mathbf{X}_{\text{FP}}\|_2 \leq \sqrt{N\epsilon C_Q}$. Then, with probability at least $1 - \delta$, we have $\|\mathbf{X}_{\text{FN}}\|_2 \|\mathbf{X}_{\text{FP}}\|_2 \leq N\epsilon \cdot \sqrt{10C_3 \log \epsilon^{-1}}$. We also have $\|\boldsymbol{\xi}_{\text{FN}}\|_2 \leq \sqrt{30N\epsilon \log \epsilon^{-1}}$. ■

C Proofs for Neural Networks

C.1 Leaky-ReLU Networks

C.1.1 Proof of Theorem 18

Proof. We will decompose the gradient into the good component and corrupted component. The first part of our proof will show that \mathbf{w} moves in the direction of \mathbf{w}^* , then in the second part of the proof we will show the affect of the corrupted gradient. Finally, we combine step 1 and step 2 to show that there exists sufficiently small ϵ such that we can get linear convergence with a small additive error term.

Step 1: Upper bounding the ℓ_2 norm distance between $\mathbf{w}^{(t+1)}$ and \mathbf{w}^* . Let $\hat{\mathbf{w}} = \arg \min_{\mathbf{w} \in \mathbb{R}^{K \times d}} \mathcal{R}(\mathbf{w}; \mathbf{P})$. We then have,

$$\begin{aligned} \|\mathbf{w}^{(t+1)} - \mathbf{w}^*\|_2 &= \|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \mathbf{S}^{(t)})\|_2 \\ &= \|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) + \eta \nabla \mathcal{R}(\mathbf{w}^*; \mathbf{P}) - \eta \nabla \mathcal{R}(\mathbf{w}^*; \mathbf{P}) - \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{FP})\|_2 \\ &\leq \|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) + \eta \nabla \mathcal{R}(\mathbf{w}^*; \text{TP})\|_2 + \|\eta \nabla \mathcal{R}(\mathbf{w}^*; \text{TP})\|_2 + \|\eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{FP})\|_2 \end{aligned} \quad (\text{C.1})$$

We will first upper bound the first term of Equation (C.1) through its square.

$$\begin{aligned} \|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2^2 &= \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 - 2\eta \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) \rangle + \eta^2 \cdot \|\nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2^2 \end{aligned} \quad (\text{C.2})$$

We will first lower bound the second term of Equation (C.2).

$$\begin{aligned} 2\eta \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) - \nabla \mathcal{R}(\mathbf{w}^*; \text{TP}) \rangle &= \frac{4\eta}{(1-\epsilon)N} \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \int_0^1 \nabla^2 \mathcal{R}(\mathbf{w}^* + \theta(\mathbf{w}^* - \mathbf{w}^{(t)}); \text{TP}) d\theta \cdot (\mathbf{w}^{(t)} - \mathbf{w}^*) \rangle \\ &\geq \frac{4\eta}{(1-\epsilon)N} \cdot C_\psi^2 \lambda_{\min}(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 \end{aligned} \quad (\text{C.3})$$

We now will upper bound the second term of Equation (C.2). We first will quickly give spectral bounds on $\nabla^2 \mathcal{L}(\mathbf{w}; \text{TP})$ where $\mathbf{w} \in \mathbb{R}^d$ is an arbitrary vector.

$$\begin{aligned} \nabla^2 \mathcal{L}(\mathbf{w}; \text{TP}) &= 2 \cdot \sum_{i \in \text{TP}} (\psi(\mathbf{x}_i^T \mathbf{w}) - y_i) \cdot \psi''(\mathbf{x}_i^T \mathbf{w}) \cdot \mathbf{x}_i \mathbf{x}_i^T + 2 \cdot \sum_{i \in \text{TP}} [\psi'(\mathbf{x}_i^T \mathbf{w})]^2 \cdot \mathbf{x}_i \mathbf{x}_i^T \\ &\stackrel{\text{a.s.}}{=} 2 \cdot \sum_{i \in \text{TP}} [\psi'(\mathbf{x}_i^T \mathbf{w})]^2 \cdot \mathbf{x}_i \mathbf{x}_i^T \end{aligned}$$

We then obtain,

$$2 \cdot C_{[\psi]}^2 \lambda_{\min}(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \cdot \mathbf{I} \preceq \nabla^2 \mathcal{L}(\mathbf{w}; \text{TP}) \preceq 2 \cdot C_{[\psi]}^2 \lambda_{\max}(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \cdot \mathbf{I}$$

We canow lower bound the second term of Equation (C.2).

$$\begin{aligned} \eta^2 \cdot \|\nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) - \nabla \mathcal{R}(\mathbf{w}^*; \text{TP})\|_2^2 &= \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \left\| \int_0^1 \nabla^2 \mathcal{R}(\mathbf{w}^* + \theta(\mathbf{w}^* - \mathbf{w}^{(t)}); \text{TP}) d\theta \cdot (\mathbf{w}^{(t)} - \mathbf{w}^*) \right\|_2^2 \\ &\leq \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \lambda_{\max}^2(\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T) \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 \end{aligned} \quad (\text{C.4})$$

We then observe that the first term of Equation (C.3) is greater than half the first term in Equation (C.4) when $\eta \leq \frac{C_\psi^2(1-\epsilon)N\lambda_{\min}(\mathbf{X}_{\text{TP}}\mathbf{X}_{\text{TP}}^T)}{2\lambda_{\max}^2(\mathbf{X}_{\text{TP}}\mathbf{X}_{\text{TP}}^T)}$.

Step 2: Upper bounding the corrupted gradient. We now upper bound the third term in Equation (C.2).

$$\begin{aligned} \eta^2 \cdot \|\nabla \mathcal{R}(\mathbf{W}^{(t)}; \text{FP})\|_{\text{F}}^2 &= \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \left\| \sum_{i \in \text{FP}} (\psi(\mathbf{x}_i^T \mathbf{w}) - \psi(\mathbf{x}_i^T \mathbf{w}^*)) \cdot \psi'(\mathbf{x}_i^T \mathbf{w}_k^{(t)}) \cdot \mathbf{x}_i \right\|_2^2 \\ &\leq \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \|\mathbf{X}_{\text{FP}}\mathbf{X}_{\text{FP}}^T\|_2 \sum_{i \in \text{FP}} (\psi(\mathbf{x}_i^T \mathbf{w}) - \psi(\mathbf{x}_i^T \mathbf{w}^*))^2 \\ &\leq \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \|\mathbf{X}_{\text{FP}}\mathbf{X}_{\text{FP}}^T\|_2 \sum_{i \in \text{FN}} (\psi(\mathbf{x}_i^T \mathbf{w}) - \psi(\mathbf{x}_i^T \mathbf{w}^*))^2 \\ &\leq \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \|\mathbf{X}_{\text{FP}}\mathbf{X}_{\text{FP}}^T\|_2 \|\mathbf{X}_{\text{FN}}\mathbf{X}_{\text{FN}}^T\|_2 \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 \end{aligned}$$

In the above, the first inequality follows from Lemma 27, the second inequality follows from the optimality of the Subquantile set, the third inequality follows from the AM-QM inequality (see Lemma 32), the final inequality follows from the C_2 -Lipschitzness of ψ . We will now show the random variable, $\psi'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i$ is sub-Gaussian. Let $\mathbf{v} \in \mathbb{S}^{d-1}$, then since \mathbf{x}_i is sampled from sub-Gaussian distribution with sub-Gaussian norm K , we then have $\mathbf{v}^T \mathbf{x}_i$ is sub-Gaussian with norm K . Therefore,

$$(\mathbb{E}|\psi'(\mathbf{x}_i^T \mathbf{w}) \mathbf{v}^T \mathbf{x}_i|^p)^{1/p} \leq \sup_{x \in \mathbb{R}} |\psi'(x)| (\mathbb{E}|\mathbf{v}^T \mathbf{x}_i|^{2p})^{1/2p} \leq K$$

In the above, in the first inequality we used Hölder's Inequality. We therefore have, $\|\psi'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i\|_{\psi_2} = K$. Then from Lemma 24, we have with probability at least $1 - \delta$,

$$\left\| \sum_{i \in \text{TP}} \xi_i \cdot \psi'(\mathbf{x}_i^T \mathbf{w}^{(t)}) \cdot \mathbf{x}_i \right\|_2 \leq 9NC_K C_\sigma \left(\frac{2d}{N} \log 5 + \frac{2}{N} \log(1/\delta) + 6\epsilon \log \epsilon^{-1} \right)^{1/2}$$

Step 3: Concentration Bounds First we give the linear convergence result. Noting that $\sqrt{1-2x} \leq 1-x$ when $x \leq 1/2$, we have

$$\begin{aligned} \|\mathbf{w}^{(t+1)} - \mathbf{w}^*\|_2 &\leq \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2 \left(1 - \frac{2C_\psi^2\eta}{(1-\epsilon)N} \cdot \lambda_{\min}(\mathbf{X}_{\text{TP}}\mathbf{X}_{\text{TP}}^T) + \frac{2\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{X}_{\text{FN}}\|_2 \right) \\ &\quad + \frac{15C_K C_\sigma d \log 5}{\sqrt{(1-\epsilon)N}} + \frac{15C_K C_\sigma \log(1/\delta)}{\sqrt{(1-\epsilon)N}} + 16C_K C_\sigma \sqrt{\epsilon \log \epsilon^{-1}} \end{aligned}$$

We will give the relevant probabilistic bounds for the random variables in Steps 1 and 2. From Lemma 23, we have $\|\mathbf{X}_{\text{FN}}\|_2 \|\mathbf{X}_{\text{FP}}\|_2 \leq \epsilon \sqrt{\lambda_{\max}(\Sigma)} \cdot 10C_3 N \log \epsilon^{-1}$ with probability at least $1 - \delta$ when $N \geq \frac{2}{\epsilon} \cdot \left(dC_K^2 + \frac{\log(2/\delta)}{c_K} \right)$ when $\epsilon \leq \frac{1}{60} \cdot \kappa^{-1}(\Sigma)$. From the same Lemma and under the same data conditions we have $\lambda_{\min}(\mathbf{X}_{\text{TP}}\mathbf{X}_{\text{TP}}^T) \geq \frac{1}{4} \cdot \lambda_{\min}(\Sigma)$. Then for $\epsilon \leq \frac{C_\psi^2 \lambda_{\min}(\Sigma)}{\sqrt{32C_3 \lambda_{\max}(\Sigma)}}$, we have $\|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{X}_{\text{FN}}\|_2 \leq \frac{1}{2} \cdot \lambda_{\min}(\Sigma)$.

We then have, after $O\left(\kappa^2(\Sigma) \log\left(\frac{\|\mathbf{w}^*\|_2 + 10d}{\epsilon}\right)\right)$ iterations with high probability,

$$\begin{aligned} \|\mathbf{w}^{(T)} - \mathbf{w}^*\|_2 &\leq \varepsilon + \frac{1}{N} \cdot 144C_\psi^{-2} \kappa^2(\Sigma) K C_\sigma d \log 5 + 432\kappa^2(\Sigma) C_\psi^{-1} K C_\sigma d \epsilon \log \epsilon^{-1} \\ &= O\left(\kappa^2(\Sigma) C_\psi^{-2} K C_\sigma d \epsilon \log \epsilon^{-1}\right) \end{aligned}$$

In the final inequality above, we set $\varepsilon = O\left(\kappa^2(\Sigma) C_\psi^{-1} K C_\sigma d \epsilon \log \epsilon^{-1}\right)$ for $N \geq \epsilon^{-2} C_\psi^{-2} \kappa^2(\Sigma) \log 5$. Our proof is complete. \blacksquare

C.2 Proof of Theorem 19

Proof. We will now begin our standard analysis.

$$\begin{aligned}
\|\mathbf{w}^{(t+1)} - \mathbf{w}^*\|_2 &= \|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}; \mathbf{S}^{(t)})\|_2 \\
&= \|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{FP})\|_2 \\
&\leq \|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2 + \|\eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{FP})\|_2
\end{aligned} \tag{C.5}$$

We will now upper bound the first term of Equation C.5 through its square,

$$\begin{aligned}
\|\mathbf{w}^{(t)} - \mathbf{w}^* - \eta \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2^2 &= \\
&= \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 - 2\eta \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) \rangle + \eta^2 \cdot \|\nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2^2
\end{aligned} \tag{C.6}$$

We will lower bound the second term of Equation C.6. We will first adopt the notation from [ZYWG19], let $\Sigma_{\text{TP}}(\mathbf{w}, \hat{\mathbf{w}}) = \mathbf{X}_{\text{TP}}^T \mathbf{X}_{\text{TP}} \cdot \mathbb{I}\{\mathbf{X}_{\text{TP}}^T \mathbf{w} \geq \mathbf{0}\} \cdot \mathbb{I}\{\mathbf{X}_{\text{TP}}^T \hat{\mathbf{w}} \geq \mathbf{0}\}$, it then follows

$$\begin{aligned}
&2\eta \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP}) \rangle \\
&\stackrel{\text{def}}{=} \frac{4\eta}{(1-\epsilon)N} \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \sum_{i \in \text{TP}} (\psi(\mathbf{x}_i^T \mathbf{w}^{(t)}) - y_i) \cdot \mathbf{x}_i \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \geq 0\} \rangle \\
&= \frac{4\eta}{(1-\epsilon)N} \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \Sigma_{\text{TP}}(\mathbf{w}^{(t)}, \mathbf{w}^{(t)}) \mathbf{w}^{(t)} - \Sigma_{\text{TP}}(\mathbf{w}^{(t)}, \mathbf{w}^*) \mathbf{w}^* \rangle \\
&\quad + \frac{4\eta}{(1-\epsilon)N} \cdot \langle \mathbf{w}^{(t)} - \mathbf{w}^*, \sum_{i \in \text{TP}} \xi_i \mathbf{x}_i \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \geq 0\} \rangle \\
&\geq \frac{4\eta}{(1-\epsilon)N} \cdot \lambda_{\min}(\Sigma_{\text{TP}}(\mathbf{w}^{(t)}, \mathbf{w}^*)) \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2 \\
&\quad - \frac{4\eta}{(1-\epsilon)N} \cdot \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2 \left\| \sum_{i \in \text{TP}} \xi_i \mathbf{x}_i \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \geq 0\} \right\|_2
\end{aligned} \tag{C.7}$$

In the above, the final inequality holds because $\mathbf{x}_i^T \mathbf{w}^{(t)} \geq \mathbf{x}_i^T \mathbf{w}^*$, therefore we have that $(\mathbf{x}_i^T \mathbf{w}^{(t)} - \mathbf{x}_i^T \mathbf{w}^*)(\mathbf{x}_i^T \mathbf{w}^{(t)}) \geq 0$. From Weyl's Inequality, we have

$$\lambda_{\min}(\Sigma_{\text{TP}}(\mathbf{w}^{(t)}, \mathbf{w}^*)) \geq \lambda_{\min}(\Sigma_{\text{TP}}(\mathbf{w}^*, \mathbf{w}^*)) - \|\Sigma_{\text{TP}}(\mathbf{w}^*, \mathbf{w}^{(t)}) - \Sigma_{\text{TP}}(\mathbf{w}^*, \mathbf{w}^*)\|_2$$

We bound the two terms individually. We bound the first term now. Since $\|\mathbf{w}^*\|$ is fixed and non-zero, and \mathcal{P} is isotropic, we have that $\Pr\{\mathbf{x}^T \mathbf{w}^* \geq 0\} = \frac{1}{2}$ for $\mathbf{x} \sim \mathcal{P}$. Let B be the sum of $(1-\epsilon)N$ i.i.d Bernoulli random variables. Then from Hoeffding's Inequality, we have that

$$\Pr\{B - \mathbb{E} B \leq t\} \leq 2e^{-\frac{t^2}{(1-\epsilon)N}}$$

From which by elementary manipulations, we obtain with probability exceeding $1 - \delta$,

$$B \geq \frac{1}{2} \cdot N - \frac{1}{2} \sqrt{N \log(2/\delta)} \geq \frac{1}{4} \cdot N$$

In the above, the final inequality holds when $N \geq 64 \log(2/\delta)$ with probability at least $1 - \delta$. We then obtain with sufficient data that,

$$\lambda_{\min}(\Sigma_{\text{TP}}(\mathbf{w}^*, \mathbf{w}^*)) \geq \frac{n}{8} \cdot \lambda_{\min}(\Sigma)$$

We now upper bound the second term.

$$\begin{aligned}
\|\Sigma_{\text{TP}}(\mathbf{w}^*, \mathbf{w}^*) - \Sigma_{\text{TP}}(\mathbf{w}^*, \mathbf{w}^{(t)})\|_2 &= \left\| \sum_{i \in \text{TP}} \mathbf{x}_i \mathbf{x}_i^T \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^* \geq 0\} \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \leq 0\} \right\|_2 \\
&\leq \left\| \sum_{i \in \text{P}} \mathbf{x}_i \mathbf{x}_i^T \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^* \geq 0\} \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \leq 0\} \right\|_2
\end{aligned}$$

$$\begin{aligned}
&\leq (1/\delta) \cdot \mathbb{E} \left[\sum_{i \in P} \|\mathbf{x}_i \mathbf{x}_i^T\|_2 \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^* \geq 0\} \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \leq 0\} \right] \\
&\leq (1/\delta) \cdot \sum_{i \in P} (\mathbb{E}[\|\mathbf{x}_i \mathbf{x}_i^T\|_2^2])^{1/2} \left(\mathbb{E}[\mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^* \geq 0\} \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \leq 0\}] \right)^{1/2} \\
&\leq \frac{(1/\delta)}{2\pi} \cdot \sqrt{d} N \arcsin^{1/2} \left(\frac{\|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2}{\|\mathbf{w}^*\|_2} \right) \\
&\leq \frac{(1/\delta)}{\pi} \cdot \sqrt{d} N \cdot \left(\frac{\|\mathbf{w}^{(0)} - \mathbf{w}^*\|_2}{\|\mathbf{w}^*\|_2} \right)^{1/2}
\end{aligned}$$

In the above, the first inequality follows from Weyl's Inequality, and the second inequality follows from Markov's inequality to a triangle inequality and finally applying Lemma 25. Then, from our assumption that $\|\mathbf{w}^{(0)} - \mathbf{w}^*\|_2 \leq \frac{\pi^2 \|\mathbf{w}^*\|_2}{(16/\delta)^d}$, we have with probability exceeding $1 - \delta$,

$$\lambda_{\min}(\Sigma_{\text{TP}}(\mathbf{w}^{(t)}; \mathbf{w}^*)) \geq \frac{N}{16} \cdot \lambda_{\min}(\Sigma)$$

Noise Bound: From Lemma 24, we can bound the noise with probability exceeding $1 - \delta$, we have,

$$\|\xi_{\text{TP}}^T \tilde{\mathbf{X}}_{\text{TP}}\|_2 \leq \frac{4}{3} \cdot N K C_\sigma \cdot \left(\frac{2d}{N} \log(5) + \frac{2}{N} \log(1/\delta) + 6\epsilon \log \epsilon^{-1} \right)^{1/2}$$

Step 2: Upper bounding the norm gradient.

$$\begin{aligned}
\eta^2 \cdot \|\nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{TP})\|_2^2 &= \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \left\| \sum_{i \in \text{TP}} (\psi(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \psi(\mathbf{x}_i^T \mathbf{w}^*) - \xi_i) \cdot \mathbf{x}_i \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \geq 0\} \right\|_2^2 \\
&\leq \frac{8\eta^2}{[(1-\epsilon)N]^2} \cdot \left(\left\| \sum_{i \in \text{TP}} (\psi(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \psi(\mathbf{x}_i^T \mathbf{w}^*)) \cdot \mathbf{x}_i \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \geq 0\} \right\|_2^2 + \left\| \sum_{i \in \text{TP}} \xi_i \mathbf{x}_i \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \geq 0\} \right\|_2^2 \right)
\end{aligned} \tag{C.8}$$

Recall we have from Lemma 24, we have an upper bound on the second term of Equation (C.8). We give a bound on the first term of Equation (C.8).

$$\begin{aligned}
&\frac{8\eta^2}{[(1-\epsilon)N]^2} \cdot \left\| \sum_{i \in \text{TP}} (\psi(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \psi(\mathbf{x}_i^T \mathbf{w}^*)) \cdot \mathbf{x}_i \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \geq 0\} \right\|_2^2 \\
&\leq \frac{8\eta^2}{[(1-\epsilon)N]^2} \cdot \|\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T\|_2 \sum_{i \in \text{TP}} (\psi(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \psi(\mathbf{x}_i^T \mathbf{w}^*))^2 \\
&\leq \frac{8\eta^2}{[(1-\epsilon)N]^2} \cdot \|\mathbf{X}_{\text{TP}} \mathbf{X}_{\text{TP}}^T\|_2^2 \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2
\end{aligned} \tag{C.9}$$

Then, by choosing $\eta \leq \frac{\lambda_{\min}(\Sigma)}{80\lambda_{\max}^2(\Sigma)}$, we have that the RHS in Equation C.9 will be less than $\frac{\lambda_{\min}(\Sigma)}{8}$.

Step 3: Upper bounding the corrupted gradient. We now upper bound the third term in Equation (C.6).

$$\begin{aligned}
\eta^2 \cdot \|\nabla \mathcal{R}(\mathbf{w}^{(t)}; \text{FP})\|_{\text{F}}^2 &= \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \left\| \sum_{i \in \text{FP}} (\psi(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \psi(\mathbf{x}_i^T \mathbf{w}^*)) \cdot \mathbf{x}_i \cdot \mathbb{I}\{\mathbf{x}_i^T \mathbf{w}^{(t)} \geq 0\} \right\|_2^2 \\
&\leq \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \|\Sigma_{\text{FP}}(\mathbf{w}^{(t)}, \mathbf{w}^{(t)})\|_2 \sum_{i \in \text{FP}} (\psi(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \psi(\mathbf{x}_i^T \mathbf{w}^*))^2 \\
&\leq \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \|\mathbf{X}_{\text{FP}} \mathbf{X}_{\text{FP}}^T\|_2 \sum_{i \in \text{FN}} (\psi(\mathbf{x}_i^T \mathbf{w}^{(t)}) - \psi(\mathbf{x}_i^T \mathbf{w}^*))^2
\end{aligned}$$

$$\leq \frac{4\eta^2}{[(1-\epsilon)N]^2} \cdot \|\mathbf{X}_{\text{FP}}\mathbf{X}_{\text{FP}}^T\|_2 \|\mathbf{X}_{\text{FN}}\mathbf{X}_{\text{FN}}^T\|_2 \|\mathbf{w}^{(t)} - \mathbf{w}^*\|_2^2$$

In the above, the first inequality follows from the same argument as Lemma 28, the second inequality follows from the optimality of the Subquantile set, and the final inequality follows from noting that ψ is 1-Lipschitz. We now conclude Steps 1-3 with our linear convergence result.

$$\begin{aligned} \|\mathbf{w}^{(t+1)} - \mathbf{w}^*\|_2 \leq \|\mathbf{w}^{(t)} - \mathbf{w}^*\| \left(1 - \frac{\eta}{32} \cdot \lambda_{\min}(\Sigma) + \frac{\sqrt{8}\eta}{(1-\epsilon)N} \cdot \|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{X}_{\text{FN}}\| \right) \\ - \frac{16}{3} K C_\sigma \cdot \left(\frac{2d}{N} \log(5) + \frac{2}{N} \log(1/\delta) + 6\epsilon \log \epsilon^{-1} \right)^{1/2} \end{aligned}$$

Step 4: Concentration Inequalities. From our previous theorems, we have $\|\mathbf{X}_{\text{FP}}\|_2 \|\mathbf{X}_{\text{FN}}\|_2 \leq N\epsilon\sqrt{10C_3 \log \epsilon^{-1}}$ with probability exceeding $1 - \delta$ and sufficiently large N . ■

D Probability Theory

In this section we will give various concentration inequalities on the inlier data for functions in the Reproducing Kernel Hilbert Space.

D.1 Finite Dimensional Concentrations of Measure

Lemma 20 (Upper Bound on Sum of Chi-Squared Variables [LM00]). *Suppose $\xi_i \sim \mathcal{N}(0, \sigma^2)$ for $i \in [n]$, then*

$$\mathbb{P}\{\|\xi\|_2^2 \geq \sigma(n + 2\sqrt{nx} + 2x)\} \leq e^{-x}$$

Proposition 21 (Probabilistic Upper Bound on Sum of Chi-Squared Variables). *Suppose $\xi_i \sim \mathcal{N}(0, \sigma^2)$ for $i \in [n]$. Let $S \subset [n]$ such that $|S| = \epsilon n$ for $\epsilon \in (0, 1]$ and let \mathcal{C} represent all such subsets. Given a failure probability $\delta \in (0, 1)$, when $n \geq \log(1/\delta)$, with probability exceeding $1 - \delta$,*

$$\max_{S \in \mathcal{C}} \|\xi_S\|_2^2 \leq \sigma(30n\epsilon \log \epsilon^{-1})$$

Proof. Directly from Lemma 20, we have with probability exceeding $1 - \delta$.

$$\|\xi\|_2^2 \leq \sigma(n + 2\sqrt{n \log(1/\delta)} + 2 \log(1/\delta))$$

We now can prove the claimed bound using the layer-cake representation,

$$\mathbb{P}\left\{\max_{S \in \mathcal{C}} \|\xi\|_2^2 \geq \sigma(\epsilon n + 2\sqrt{\epsilon n x} + 2x)\right\} \leq \left(\frac{e}{\epsilon}\right)^{\epsilon n} \mathbb{P}\{\|\xi\|_2^2 \geq \sigma(\epsilon n + 2\sqrt{\epsilon n x} + 2x)\} \leq \left(\frac{e}{\epsilon}\right)^{\epsilon n} e^{-x}$$

In the first inequality we apply a union bound over \mathcal{C} with Lemma 35, and in the second inequality we use Lemma 20. We then obtain with probability exceeding $1 - \delta$,

$$\begin{aligned} \max_{S \in \mathcal{C}} \|\xi_S\|_2^2 &\leq \sigma\left(\epsilon n + 2\sqrt{n\epsilon \log(1/\delta)} + 3n^2\epsilon^2 \log \epsilon^{-1} + 2 \log(1/\delta) + 6n\epsilon \log \epsilon^{-1}\right) \\ &\leq \sigma\left(9n\epsilon \log \epsilon^{-1} + 2\sqrt{n\epsilon \log(1/\delta)} + 2\sqrt{3}n\epsilon \sqrt{\log \epsilon^{-1}} + 2 \log(1/\delta)\right) \\ &\leq \sigma\left(15n\epsilon \log \epsilon^{-1} + 2\sqrt{n\epsilon \log(1/\delta)} + 2 \log(1/\delta)\right) \\ &\leq \sigma(30n\epsilon \log \epsilon^{-1}) \end{aligned}$$

In the above, in the first inequality, we note that $\log\left(\frac{n}{\epsilon n}\right) \leq 3n\epsilon \log \epsilon^{-1}$ as $\epsilon < 0.5$, in the second inequality we note that $\sqrt{\log \epsilon^{-1}} \leq (\log(2))^{-1/2} \log \epsilon^{-1} \leq \sqrt{3} \log \epsilon^{-1}$ when $\epsilon < 0.5$, the final inequality holds when $n \geq \log(1/\delta)$ by solving for the quadratic equation. The proof is complete. ■

Lemma 22 (Sub-Gaussian Covariance Matrix Estimation [Ver10] Theorem 5.40). *Let $\mathbf{X} \in \mathbb{R}^{d \times n}$ have columns sampled from a sub-Gaussian distribution with sub-Gaussian norm K and second-moment matrix Σ , then there exists positive constants c_k, C_K , dependent on the sub-Gaussian norm such that with probability at least $1 - 2e^{-c_K t^2}$,*

$$\lambda_{\max}(\mathbf{X}\mathbf{X}^T) \leq n \cdot \lambda_{\max}(\Sigma) + \lambda_{\max}(\Sigma) \cdot \left(C_K \cdot \sqrt{dn} + t \cdot \sqrt{n} \right)$$

Lemma 23. *Let $\mathbf{X} \in \mathbb{R}^{d \times n}$ have columns sampled from a sub-Gaussian distribution with sub-Gaussian norm K and second-moment matrix Σ . Let $S \subset [n]$ such that $|S| = \epsilon n$ for $\epsilon \in (0, 0.5)$ and let \mathcal{C} represent all such subsets. Fix a constant $\zeta \in (0, 1)$, then with probability at least $1 - \delta$,*

$$\begin{aligned} \max_{S \in \mathcal{C}} \lambda_{\max}(\mathbf{X}_S \mathbf{X}_S^T) &\leq \lambda_{\max}(\Sigma) \cdot (10n\epsilon \log \epsilon^{-1}) \\ \min_{S \in \mathcal{C}} \lambda_{\min}(\mathbf{X}_{X \setminus S} \mathbf{X}_{X \setminus S}^T) &\geq \frac{n}{4} \cdot \lambda_{\min}(\Sigma) \end{aligned}$$

when

$$n \geq \frac{2}{\epsilon} \cdot \left(C_K^2 \cdot d + \frac{\log(2/\delta)}{c_K} \right)$$

and $\epsilon \leq \frac{1}{60} \cdot \kappa^{-1}(\Sigma)$.

Proof. We will use the layer-cake representation to obtain our claimed error bound.

$$\begin{aligned} \mathbb{P} \left\{ \max_{S \in \mathcal{C}} \lambda_{\max}(\mathbf{X}_S \mathbf{X}_S^T) \geq n\epsilon \cdot \lambda_{\max}(\Sigma) + \lambda_{\max}(\Sigma) \cdot \left(C_K \cdot \sqrt{dn\epsilon} + t\sqrt{n\epsilon} \right) \right\} \\ \leq \left(\frac{\epsilon}{\epsilon} \right)^{\epsilon n} \mathbb{P} \left\{ \lambda_{\max}(\mathbf{X}_S \mathbf{X}_S^T) \geq n\epsilon \cdot \lambda_{\max}(\Sigma) + \lambda_{\max}(\Sigma) \cdot \left(C_K \cdot \sqrt{dn\epsilon} + t\sqrt{n\epsilon} \right) \right\} \leq 2 \cdot \left(\frac{\epsilon}{\epsilon} \right)^{\epsilon n} e^{-c_K t^2} \end{aligned}$$

In the above, the first inequality follows from a union bound over \mathcal{C} and Lemma 35, the second inequality follows from Lemma 22. Then from elementary inequalities, we obtain with probability $1 - \delta$,

$$\begin{aligned} \max_{S \in \mathcal{C}} \lambda_{\max}(\mathbf{X}_S \mathbf{X}_S^T) &\leq n\epsilon \cdot \lambda_{\max}(\Sigma) + \lambda_{\max}(\Sigma) \cdot \left(C_K \cdot \sqrt{dn\epsilon} + \sqrt{\frac{1}{c_K} (n\epsilon \cdot \log(2/\delta) + 3n^2\epsilon^2 \log \epsilon^{-1})} \right) \\ &\leq n \cdot \lambda_{\max}(\Sigma) \cdot (\epsilon + 3^{3/4}\epsilon \log \epsilon^{-1}) + \lambda_{\max}(\Sigma) \cdot \left(C_K \cdot \sqrt{dn\epsilon} + \sqrt{\frac{1}{c_K} n\epsilon \cdot \log(2/\delta)} \right) \\ &\leq \lambda_{\max}(\Sigma) \cdot (6n\epsilon \log \epsilon^{-1}) + \lambda_{\max}(\Sigma) \cdot \left(C_K \cdot \sqrt{dn\epsilon} + \sqrt{\frac{1}{c_K} n\epsilon \cdot \log(2/\delta)} \right) \\ &\leq \lambda_{\max}(\Sigma) \cdot (10n\epsilon \log \epsilon^{-1}) \end{aligned}$$

In the above, the last inequality holds when

$$n \geq \frac{2}{\epsilon} \cdot \left(C_K^2 \cdot d + \frac{\log(2/\delta)}{c_K} \right)$$

and our proof of the upper bound for the maximal eigenvalue is complete. We have from Weyl's Inequality for any $S \in \mathcal{C}$,

$$\lambda_{\min}(\mathbf{X}_{X \setminus S} \mathbf{X}_{X \setminus S}^T) = \lambda_{\min}(\mathbf{X}\mathbf{X}^T - \mathbf{X}_S \mathbf{X}_S^T) \geq \lambda_{\min}(\mathbf{X}\mathbf{X}^T) - \lambda_{\max}(\mathbf{X}_S \mathbf{X}_S^T)$$

We then have with probability at least $1 - \delta$,

$$\begin{aligned} \lambda_{\min}(\mathbf{X}_{X \setminus S} \mathbf{X}_{X \setminus S}^T) &\geq n \cdot \lambda_{\min}(\Sigma) - C_K \cdot \sqrt{dn} - \sqrt{\frac{1}{c_K} \cdot n \cdot \log(2/\delta)} - \lambda_{\max}(\Sigma) \cdot (10n\epsilon \log \epsilon^{-1}) \\ &\geq \frac{n}{2} \cdot \lambda_{\min}(\Sigma) - \lambda_{\max}(\Sigma) \cdot (10n\epsilon \log \epsilon^{-1}) \geq \frac{n}{4} \cdot \lambda_{\min}(\Sigma) \end{aligned}$$

In the above, the first inequality follows when $n \geq \frac{1}{\lambda_{\min}^2(\Sigma)} \left(8C_K \cdot d + \frac{2}{c_K} \cdot \log(2/\delta) \right)$, and the last inequality follows when $\epsilon \leq \frac{1}{60} \cdot \kappa^{-1}(\Sigma)$. The proof is complete. \blacksquare

Lemma 24 (Noise Bound). *Fix $\mathbf{w} \in \mathbb{R}^d$. Let $\tilde{\mathbf{X}} = [\mathbf{x}_1 \cdot \mathbb{I}\{\mathbf{x}_1^\top \mathbf{w} \geq 0\}, \dots, \mathbf{x}_{(1-\epsilon)N} \cdot \mathbb{I}\{\mathbf{x}_{(1-\epsilon)N}^\top \mathbf{w} \geq 0\}]$ be the data matrix such that for $i \in [(1-\epsilon)N]$, \mathbf{x}_i are sampled from a sub-Gaussian distribution with second-moment matrix Σ with sub-Gaussian norm K . Suppose for $i \in [(1-\epsilon)N]$, ξ_i are sampled from sub-Gaussian distribution with sub-Gaussian norm C_σ . Let \mathcal{S} represent all subset of $[N]$ of size $(1-2\epsilon)N$ to $(1-\epsilon)N$. Then, with probability at least $1-\delta$,*

$$\max_{S \in \mathcal{S}} \|\xi_S^\top \tilde{\mathbf{X}}_S\|_2 \leq \frac{4}{3} \cdot N K C_\sigma \cdot \left(\frac{2d}{N} \log(5) + \frac{2}{N} \log(1/\delta) + 6\epsilon \log \epsilon^{-1} \right)^{1/2}$$

Proof. We will use the following characterization of the spectral norm.

$$\left\| \sum_{i \in \text{TP}} \xi_i \mathbf{x}_i \cdot \mathbb{I}\{\mathbf{x}_i^\top \mathbf{w}^{(t)} \geq 0\} \right\|_2 = \max_{\mathbf{v} \in \mathbb{S}^{d-1}} \sum_{i \in \text{TP}} \xi_i \mathbf{x}_i^\top \mathbf{v} \cdot \mathbb{I}\{\mathbf{x}_i^\top \mathbf{w}^{(t)} \geq 0\}$$

Our proof uses standard ideas in High-Dimensional Probability and will follow similarly to [ZYWG19]. Let $\tilde{\mathbf{x}} = \mathbf{x} \cdot \mathbb{I}\{\mathbf{x}^\top \mathbf{w}\}$, then we can note that $\tilde{\mathbf{x}}$ is also sub-Gaussian with second-moment matrix Σ . It thus follows for any $\mathbf{v} \in \mathbb{S}^{d-1}$, the random variable, $\tilde{\mathbf{x}}_i^\top \mathbf{v}$ is sub-Gaussian by definition s.t. $\|\tilde{\mathbf{x}}_i^\top \mathbf{v}\|_{\psi_2} = K$. Let $C_\sigma \triangleq \|\xi_i\|_{\psi_2}$, then from Lemma 2.7.6 in [Ver20], the random variable $\xi_i \tilde{\mathbf{x}}_i^\top \mathbf{v}$ is sub-exponential s.t. $\|\xi_i \tilde{\mathbf{x}}_i^\top \mathbf{v}\|_{\psi_1} \leq K C_\sigma$. We will now use a ε -covering argument. Let \mathcal{C} be a ε -net of \mathbb{S}^{d-1} such that for any $\mathbf{v} \in \mathbb{S}^{d-1}$, there exists $\mathbf{u} \in \mathcal{C}$ such that $\|\mathbf{u} - \mathbf{v}\|_2 \leq \varepsilon$. Let $\mathbf{u}^* = \arg \max_{\mathbf{u} \in \mathcal{C}} \xi^\top \tilde{\mathbf{X}} \mathbf{u}$ and $\mathbf{v}^* = \arg \max_{\mathbf{v} \in \mathbb{S}^{d-1}} \xi^\top \tilde{\mathbf{X}} \mathbf{v}$. We then have from the reverse triangle inequality,

$$|\xi^\top \tilde{\mathbf{X}} \mathbf{v}^* - \xi^\top \tilde{\mathbf{X}} \mathbf{u}^*| \leq \|\xi^\top \tilde{\mathbf{X}}\|_2 \|\mathbf{u}^* - \mathbf{v}^*\|_2 \leq \varepsilon \cdot \|\xi^\top \tilde{\mathbf{X}}\|_2$$

where in the final inequality we use the definition of a ε -net. We then have,

$$|\xi^\top \tilde{\mathbf{X}} \mathbf{u}^*| \geq |\xi^\top \tilde{\mathbf{X}} \mathbf{v}^*| - |\xi^\top \tilde{\mathbf{X}} \mathbf{u}^* - \xi^\top \tilde{\mathbf{X}} \mathbf{v}^*| \geq (1-\varepsilon) |\xi^\top \tilde{\mathbf{X}} \mathbf{v}^*|$$

From rearranging, we have

$$|\xi^\top \tilde{\mathbf{X}} \mathbf{v}^*| \leq \frac{1}{1-\varepsilon} \cdot |\xi^\top \tilde{\mathbf{X}} \mathbf{u}^*|$$

With this result we are ready to make the probabilistic bounds. Suppose \mathcal{S} represents all subsets of $[N]$ of size $(1-2\epsilon)N$ to $(1-\epsilon)N$. Then,

$$\Pr \left\{ \frac{1}{N} \cdot \max_{S \in \mathcal{S}} \|\xi_S^\top \tilde{\mathbf{X}}_S\| \geq t \right\} \leq \frac{1}{1-\varepsilon} \cdot \Pr \left\{ \frac{1}{N} \cdot \max_{S \in \mathcal{S}} \max_{\mathbf{u} \in \mathcal{C}} |\xi_S^\top \tilde{\mathbf{X}}_S \mathbf{u}| \geq t \right\} \leq \frac{1}{1-\varepsilon} \cdot \sum_{j \in |\mathcal{S}|} \sum_{i \in |\mathcal{C}|} \Pr \left\{ \frac{1}{N} \cdot |\xi^\top \tilde{\mathbf{X}} \mathbf{u}_i| \geq t \right\}$$

Suppose \mathcal{C} is a $1/4$ -net. We can now apply Bernstein's Inequality from [RH23] Lemma 1.13.

$$\begin{aligned} \frac{1}{1-\varepsilon} \cdot \sum_{j \in |\mathcal{S}|} \sum_{i \in |\mathcal{C}|} \Pr \left\{ \frac{1}{N} \cdot |\xi^\top \tilde{\mathbf{X}} \mathbf{u}_i| \geq t \right\} &\leq 5^d \cdot \binom{N}{N\epsilon} \cdot \Pr \left\{ \frac{1}{N} \cdot |\xi^\top \tilde{\mathbf{X}} \mathbf{u}| \geq \frac{3}{4} \cdot t \right\} \\ &\leq 5^d \cdot \left(\frac{e}{\epsilon} \right)^{N\epsilon} \exp \left[-\frac{3N}{4} \left(\frac{t^2}{\frac{4}{3} \cdot K^2 C_\sigma^2} \wedge \frac{t}{\frac{4}{3} \cdot K C_\sigma} \right) \right] \leq \delta \end{aligned}$$

We can now note that $\log \binom{N}{(1-\epsilon)N} = \log \binom{N}{\epsilon N}$. Then, when $N \geq 2d \log 5 + 2 \log(1/\delta)$, to satisfy the above probabilistic condition, it must hold that

$$t \geq \frac{4}{3} \cdot N K C_\sigma \cdot \left(\frac{2d}{N} \log(5) + \frac{2}{N} \log(1/\delta) + 6\epsilon \log \epsilon^{-1} \right)^{1/2}$$

We then have with probability exceeding $1-\delta$,

$$\max_{S \in \mathcal{S}} \|\xi_S^\top \tilde{\mathbf{X}}_S\|_2 \leq \frac{4}{3} \cdot N K C_\sigma \cdot \left(\frac{2d}{N} \log(5) + \frac{2}{N} \log(1/\delta) + 6\epsilon \log \epsilon^{-1} \right)^{1/2}$$

where in the above we use the fact that $\log \binom{N}{(1-\epsilon)N} = \log \binom{N}{\epsilon N}$. Our proof is complete. \blacksquare

Lemma 25. Fix $\mathbf{w}_1, \mathbf{w}_2 \in \mathbb{S}^d$. Let \mathbf{x} be sampled from $\mathcal{N}(\mathbf{0}, \mathbf{I})$. Then,

$$\Pr\{\mathbf{x}^T \mathbf{w}_1 \geq 0, \mathbf{x}^T \mathbf{w}_2 \geq 0\} = \frac{\Theta(\mathbf{w}_1, \mathbf{w}_2)}{2\pi}$$

Proof. We can note that $\mathbf{x}^T \mathbf{w}_1$ and $\mathbf{x}^T \mathbf{w}_2$ are Gaussian variables with distribution $\mathcal{N}(0, 1)$. The covariance of the variables can be calculated simply,

$$\text{Var}(\mathbf{x}^T \mathbf{w}_1, \mathbf{x}^T \mathbf{w}_2) = \mathbb{E}[\mathbf{w}_1^T \mathbf{x} \mathbf{x}^T \mathbf{w}_2] = \text{Tr}(\mathbb{E}[\mathbf{w}_1^T \mathbf{x} \mathbf{x}^T \mathbf{w}_2]) = \mathbf{w}_1^T \mathbf{w}_2$$

Define $\mathbf{\Gamma} \triangleq \begin{bmatrix} 1 & \cos \Theta(\mathbf{w}_1, \mathbf{w}_2) \\ \cos \Theta(\mathbf{w}_1, \mathbf{w}_2) & 1 \end{bmatrix}$. Let $\mathbf{x} \sim \mathcal{N}(\mathbf{0}, \mathbf{\Gamma})$, then we have

$$\begin{aligned} \Pr\{x_1 \geq 0, x_2 \geq 0\} &= \int_0^\infty \int_0^\infty \frac{1}{2\pi} \csc \Theta(\mathbf{w}_1, \mathbf{w}_2) \exp\left[-\frac{1}{2} \cdot \mathbf{x}^T \mathbf{\Gamma}^{-1} \mathbf{x}\right] dx_1 dx_2 \\ &= \frac{1}{2\pi} \cdot \arccos(\cos \Theta(\mathbf{w}_1, \mathbf{w}_2)) = \frac{\Theta(\mathbf{w}_1, \mathbf{w}_2)}{2\pi} \end{aligned}$$

The proof is complete. ■

Lemma 26. Fix $\mathbf{S} \in \mathbb{R}^{K \times N\epsilon}$, $\mathbf{T} \in \mathbb{R}^{N\epsilon \times L}$, then sample a matrix $\mathbf{G} \in \mathbb{R}^{N\epsilon \times N\epsilon}$ such that each column of \mathbf{G} represents a ϵ -subset of a n -dimensional vector sampled from $\mathcal{N}(\mathbf{0}, \mathbf{I})$, then with probability exceeding $1 - \delta$,

$$\|\mathbf{S}\mathbf{G}\mathbf{T}\|_F^2 \leq \|\mathbf{S}\|_F^2 \|\mathbf{T}\|_F^2 \cdot (4 \log N + 2 \log(1/\delta))$$

Proof. The proof will be a calculation.

$$\|\mathbf{S}\mathbf{G}\mathbf{T}\|_F^2 = \sum_{i \in [K]} \sum_{j \in [L]} \sum_{k_1, k_2 \in [N\epsilon] \times [N\epsilon]} (\mathbf{S}_{i, k_1} \mathbf{G}_{k_1, k_2} \mathbf{T}_{k_2, j})^2 \leq \|\mathbf{S}\|_F^2 \|\mathbf{T}\|_F^2 \max_{i, j \in [N\epsilon] \times [N\epsilon]} (\mathbf{G}_{i, j})^2$$

It then suffices to bound the maximum value of a Gaussian squared over N^2 samples.

$$\begin{aligned} \mathbb{P}\left\{\max_{i, j} G_{i, j}^2 \geq t\right\} &\leq N^2 \mathbb{P}\{G_{i, j}^2 \geq t\} \leq 2N^2 \mathbb{P}\{G_{i, j} \geq \sqrt{t}\} = 2N^2 \int_{\sqrt{t}}^\infty \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx \\ &\leq N^2 \sqrt{\frac{2}{\pi}} \int_{\sqrt{t}}^\infty \frac{x}{\sqrt{t}} \cdot e^{-x^2/2} dx = \frac{1}{\sqrt{t}} \cdot N^2 \sqrt{\frac{2}{\pi}} \cdot e^{-t/2} \leq N^2 \sqrt{\frac{2}{\pi}} \cdot e^{-t/2} \end{aligned}$$

where the last inequality follows $t \geq 1$. We thus obtain from elementary inequalities,

$$\max_{i, j} G_{i, j}^2 \leq 2 \log \left(N^2 \sqrt{\frac{2}{\pi}} \cdot \frac{1}{\delta} \right)$$

for $N \geq (2/\pi)^{1/4}$. Our proof is complete. ■

E Additional Lemmas

In this section, we state additional lemmas referenced throughout the text for completeness.

Lemma 27. Let $\mathbf{a}, \mathbf{b} \in \mathbb{R}^n$ and $\mathbf{X} \in \mathbb{R}^{p \times n}$, then

$$\left\| \sum_{i=1}^n a_i b_i \mathbf{x}_i \right\|^2 \leq \|\mathbf{a}\|_\infty^2 \|\mathbf{b}\|_2^2 \|\mathbf{X}\mathbf{X}^T\|_2$$

Proof. The proof is a simple calculation. Expanding out the LHS, we have

$$\left\| \sum_{i=1}^n a_i b_i \mathbf{x}_i \right\|_2^2 = \sum_{i=1}^n \sum_{j=1}^n a_i a_j b_i b_j \mathbf{x}_i^T \mathbf{x}_j = (\mathbf{a} \circ \mathbf{b})^T \mathbf{X}^T \mathbf{X} (\mathbf{a} \circ \mathbf{b}) \leq \|\mathbf{a} \circ \mathbf{b}\|_2^2 \|\mathbf{X}^T \mathbf{X}\|_2 \leq \|\mathbf{a}\|_\infty^2 \|\mathbf{b}\|_2^2 \|\mathbf{X}^T \mathbf{X}\|_2$$

where the final inequality comes from noting

$$\|\mathbf{a} \circ \mathbf{b}\|^2 = \sum_{i=1}^n a_i^2 b_i^2 \leq \max_{i \in [n]} a_i^2 \cdot \sum_{i=1}^n b_i^2$$

Our proof is complete. ■

Lemma 28. Consider a determinate set of numbers $(a_i)_{i=1}^n$, and determinate set of functions in the Hilbert Space, $(X_i)_{i=1}^n$, then

$$\left\| \sum_{i=1}^n a_i X_i \right\|_{\mathcal{H}}^2 \leq \|\mathbf{a}\|_2^2 \|\mathbf{K}\|$$

Proof. The proof is a calculation.

$$\left\| \sum_{i=1}^n a_i X_i \right\|_{\mathcal{H}}^2 = \left\langle \sum_{i=1}^n a_i X_i, \sum_{j=1}^n a_j X_j \right\rangle_{\mathcal{H}} = \sum_{i=1}^n \sum_{j=1}^n a_i a_j k(x_i, x_j) = \mathbf{a}^T \mathbf{K} \mathbf{a} \leq \|\mathbf{a}\|_2^2 \|\mathbf{K}\|$$

where $[\mathbf{K}]_{i,j} = k(x_i, x_j)$ is the kernel Gram matrix. ■

Lemma 29 (Lemma 3.11 [B⁺15]). Let f be β -smooth and α -strongly convex over \mathbb{R}^n , then for all $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$,

$$\langle \nabla f(\mathbf{x}) - \nabla f(\mathbf{y}), \mathbf{x} - \mathbf{y} \rangle \geq \frac{\alpha\beta}{\alpha + \beta} \|\mathbf{x} - \mathbf{y}\|^2 + \frac{1}{\alpha + \beta} \|\nabla f(\mathbf{x}) - \nabla f(\mathbf{y})\|^2$$

Proposition 30 (Young's Inequality [You12]). Suppose $a, b \in \mathbb{R}_+$, then for $p, q > 1$ such that $\frac{1}{p} + \frac{1}{q} = 1$, then

$$ab \leq \frac{a^p}{p} + \frac{b^q}{q}$$

Proposition 31 (Proposition 10.1 [HMT11]). Fix matrices \mathbf{S}, \mathbf{T} , then sample matrix \mathbf{G} such that the elements of \mathbf{G} are sampled from $\mathcal{N}(0, 1)$, then

$$\mathbb{E} \|\mathbf{S} \mathbf{G} \mathbf{T}\|_{\text{F}}^2 = \|\mathbf{S}\|_{\text{F}}^2 \|\mathbf{T}\|_{\text{F}}^2$$

Lemma 32 (AM-QM Inequality). Let x_1, \dots, x_n be scalars in \mathbb{R} , then

$$\left(\sum_{i \in [n]} x_i \right)^2 \leq n \sum_{i \in [n]} x_i^2$$

Lemma 33. Suppose $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{m \times n}$, then

$$\langle \mathbf{A}, \mathbf{B} \rangle_{\text{Tr}} = \langle \text{vec}(\mathbf{A}), \text{vec}(\mathbf{B}) \rangle$$

Lemma 34. Suppose $\mathbf{A}, \mathbf{B}, \mathbf{C}$ are size compatible matrices, then

$$\text{vec}(\mathbf{A} \mathbf{B} \mathbf{C}) = (\mathbf{C}^T \otimes \mathbf{A}) \text{vec}(\mathbf{B})$$

Lemma 35 (Sum of Binomial Coefficients [CLRS22]). Let $k, n \in \mathbb{N}$ such that $k \leq n$, then

$$\sum_{i=0}^k \binom{n}{i} \leq \left(\frac{en}{k} \right)^k$$