GRADIENT FLOW PROVABLY LEARNS ROBUST CLASSIFIERS FOR DATA FROM ORTHONORMAL CLUSTERS

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ABSTRACT

Deep learning-based classifiers are known to be vulnerable to adversarial attacks. Existing methods for defending against such attacks require adding a defense mechanism or modifying the learning procedure (e.g., by adding adversarial examples). This paper shows that for certain data distribution one can learn a provably robust classifier using standard learning methods and without adding a defense mechanism. More specifically, this paper addresses the problem of finding a robust classifier for a binary classification problem in which the data comes from a mixture of Gaussian clusters with orthonormal cluster centers. First, we characterize the largest ℓ_2-attack any classifier can defend against while maintaining high accuracy, and show the existence of optimal robust classifiers achieving this maximum ℓ_2-robustness. Next, we show that given data sampled from the orthonormal cluster model, gradient flow on a two-layer network with a polynomial ReLU activation and without adversarial examples provably finds an optimal robust classifier.

1 INTRODUCTION

The vulnerability of deep neural networks to *adversarial attacks* (Szegedy et al., 2014), which are typically human-imperceptible perturbations to the input data, has led to numerous efforts in building defenses against these attacks (Shafahi et al., 2019; Papernot et al., 2016; Wong et al., 2019; Guo et al., 2018; Cohen et al., 2019; Levine & Feizi, 2020; Yang et al., 2020; Sulam et al., 2020; Kinfu & Vidal, 2022). These defenses have been counteracted by new adaptive attacks (Athalye et al., 2018; Carlini et al., 2019; Croce & Hein, 2020), leading to new defenses and so on. Even in the era of Large Language Models, adversarial attacks exist (Chao et al., 2023; Shah et al., 2023), leading to undesired or harmful model outputs, and the competition between adversaries and defenders continues (Robey et al., 2023; Ji et al., 2024). While such a competition allows us to design more robust networks, it will not end unless many fundamental questions about adversarial robustness are answered.

One question is *what is the maximum adversarial perturbation a neural network can tolerate*? Many works on certified robustness (Cohen et al., 2019; Fazlyab et al., 2020; Zhang et al., 2018) aim to find a certified radius such that a neural network can provably maintain a high prediction accuracy for adversarial attacks within that radius. However, their reported certified radii are often too small compared to what can be achieved by practical defenses (Tramèr et al., 2018; Guo et al., 2018; Gowal et al., 2020; Wu et al., 2020). Yet, practical defenses come at the cost of computing adversarial examples, or sophisticated model designs, mostly without theoretical guarantees, except for the case of linear classifiers (Zou et al., 2021). This also motivates an intriguing question: *Is it possible to (provably) find a robust network by standard training methods, without adversarial examples*?

We argue that these questions can be answered by exploiting properties of the data distribution, which most aforementioned works fail to do. Indeed, recent works show that the existence of a robust classifier is closely related to data geometry. For instance, Pal et al. (2023; 2024) show that if the *data is localized*, i.e., if the distribution of the data given the class concentrates in a set of small volume, then a robust classifier is guaranteed to exist. Moreover, they show that a $2r$ separation (w.r.t. to some distance metric) between the sets that contain each class-conditioned probability mass is sufficient for the existence of a robust classifier against attacks of radius r in the same distance metric.

This paper shows that such a relationship between data geometry and adversarial robustness has deeper implications: For certain data distributions, one can characterize the maximum robustness any classifier can achieve, based on how class-conditional probability masses are separated. Moreover,

one can make suitable architectural designs that exploit the data geometry, such that a nearly optimal robust classifier is provably learned by standard training methods, such as gradient descent. Specifically, we consider a balanced mixture of K-Gaussian clusters in $\mathbb{R}^D$, split into two classes:

$$\underbrace{\mathcal{N}\left(\boldsymbol{\mu}_1, \alpha^2\boldsymbol{I}/D\right), \cdots, \mathcal{N}\left(\boldsymbol{\mu}_{K_1}, \alpha^2\boldsymbol{I}/D\right)}_{\text{positive } (+1) \text{ class}}, \underbrace{\mathcal{N}\left(\boldsymbol{\mu}_{K_1+1}, \alpha^2\boldsymbol{I}/D\right), \cdots, \mathcal{N}\left(\boldsymbol{\mu}_K, \alpha^2\boldsymbol{I}/D\right)}_{\text{negative } (-1) \text{ class}}, \quad (1)$$

where the *cluster centers* $\boldsymbol{\mu}_1, \cdots, \boldsymbol{\mu}_K \in \mathbb{R}^D$ are othonormal, α^2 denotes the *intra-cluster variance*, and the ambient dimension D is sufficiently large. We explain our contributions as follows:

Maximum ℓ_2-robustness This mixture of Gaussian distribution satisfies data localization and separation properties similar to those studied in Pal et al. (2023). As illustrated in Figure 1 for the case of two clusters (one from the positive class and one from the negative class), the class-conditioned probability masses concentrate around two $(D-1)$-dimensional affine subspaces separated by a Euclidean distance of almost $\sqrt{2}$. Based on such observation, our first set of results are:

Theorem (Theorem 1 & 2, informal)**.** *No classifier can defend against an adversarial attack of ℓ_2 radius $\frac{\sqrt{2}}{2}$. However, one can construct a nearly optimal robust classifier that can defend against attacks of radius arbitrarily close to $\frac{\sqrt{2}}{2}$ when D is sufficiently large.*

Our results show that data localization and separation are important properties in understanding the maximum achievable robustness for a classifier. Moreover, we will show that the classifier we construct is the Bayes optimal classifier w.r.t. the 0-1 loss, which operates as a nearest-cluster rule: classifiers that exploit the multi-cluster data structure are naturally and optimally robust.

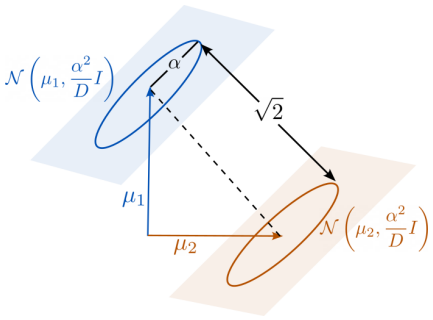

Figure 1: Illustration of two clusters in high-dimensions, each concentrated on a $(D-1)$-dimensional affine subspace such that the subspaces are separated by a Euclidean distance of $\sqrt{2}$.

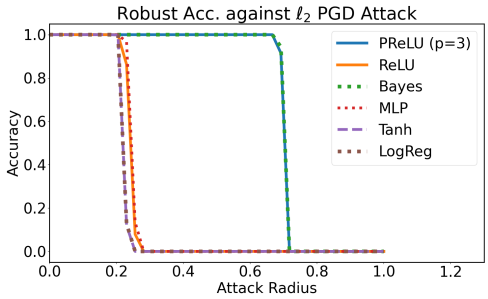

Figure 2: Given sampled data from (1) with 12 positive clusters and 8 negative clusters ($D = 2000$), gradient descent (SGD, small initialization) on (bias-free, width-200) two-layer ReLU network (ReLU) fails to find a robust classifier. This issue persists after 1) increasing depth to 4 (MLP); 2) (blindly) switching to another activation (Tanh); or 3) using a linear classifier (LogReg). However, by choosing a suitable activation (pReLU, $p = 3$), GD can find a nearly optimal robust classifier.

Learning optimal robust networks So far everything seems to be intuitive and straightforward given the fairly simple distributional assumption. However, issues arise when one does not know the data distribution a priori and seeks a classifier by training a neural network on sampled data via gradient descent. As Figure 2 suggests, a trained multi-layer ReLU network fails to find a classifier with the same level of robustness as the Bayes classifier (which indeed can defend against attack of radius $\sim \frac{\sqrt{2}}{2}$, as our results suggest). This matter is first discussed by Frei et al. (2023), where they show that any two-layer ReLU network trained by gradient descent under data samples from (1) is non-robust against adversarial attacks of ℓ_2-radius $\Theta\left(\frac{1}{\sqrt{K}}\right)$, where K is the total number of clusters. Later, Min & Vidal (2024) show that this issue is caused by the fact that a ReLU network fails to learn, internally with its weight parameters, the multi-cluster structure of the data distribution, despite that the sampled data points are revealing such a structure. Therefore, while the structural property of the data distribution allows one to construct an optimal robust classifier, gradient descent algorithms on neural networks may struggle to learn these key properties, leading to non-robust classifiers.

To address this issue, Min & Vidal (2024) propose to change the activation. More specifically, replacing the ReLU activation with a polynomial ReLU activation (pReLU) with polynomial degree p as a hyperparameter. They empirically show that when $p = 3$, the pReLU network can internally learn the data structure, leading to a more robust classifier, and they conjecture that this improvement in robustness happens when $p \geq 3$. However, a rigorous analysis of convergence is not provided. Our second set of results is to develop a full convergence analysis for gradient flow, a continuous time limit of gradient descent by taking the stepsize to zero, on a two-layer pReLU network and show that:

Theorem (Theorem 3 & Corollary 1, informal)**.** *When $p > 2$ and the intra-cluster variance α^2 is sufficiently small, gradient flow on pReLU networks converges to a nearly optimal robust classifier.*

Our analysis is based on prior works on gradient descent/flow with small initialization on two-layer ReLU networks Maennel et al. (2018); Phuong & Lampert (2021); Boursier et al. (2022); Kumar & Haupt (2024); Chistikov et al. (2023); Wang & Ma (2023); Min et al. (2024) and extends to pReLU networks. We show how the implicit bias of the gradient flow dynamics critically depends on a careful choice of activation function, allowing the network to learn accurately the underlying data structure, which, as we have discussed, is essential for finding a robust classifier.

Notation We denote the inner product between vectors $\boldsymbol{x}$ and $\boldsymbol{y}$ by $\langle \boldsymbol{x}, \boldsymbol{y} \rangle = \boldsymbol{x}^\top \boldsymbol{y}$, and the cosine of the angle between them as $\cos(\boldsymbol{x}, \boldsymbol{y}) = \langle \frac{\boldsymbol{x}}{\|\boldsymbol{x}\|}, \frac{\boldsymbol{y}}{\|\boldsymbol{y}\|} \rangle$. For an $n \times m$ matrix $\boldsymbol{A}$, we let $\|\boldsymbol{A}\|$ and $\|\boldsymbol{A}\|_F$ denote the spectral and Frobenius norm of $\boldsymbol{A}$, respectively. We also define $\mathbb{1}_A$ as the indicator for a statement A: $\mathbb{1}_A = 1$ if A is true and $\mathbb{1}_A = 0$ otherwise. We also let $\mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma}^2)$ denote the normal distribution with mean $\boldsymbol{\mu}$ and covariance matrix $\boldsymbol{\Sigma}^2$, and $\mathrm{Unif}(S)$ denote the uniform distribution over a set S. Lastly, we let $[N]$ denote the integer set $\{1, \cdots, N\}$.

2 Optimal Robust Classifiers for Orthonormal Clusters

Orthonormal cluster model We study a balanced mixture of K Gaussian clusters, and K_1 of them belong to the positive $(+1)$ class and $K_2 := K - K_1$ of them the negative (-1) class. Formally, consider a tuple of random variables (X, Y, Z) on $\mathbb{R}^D \times \{+1, -1\} \times [K]$ representing *observed data*, *observed class label*, and *latent cluster membership*, respectively, defined as follow:

$$Z \sim \mathrm{Unif}(\{1, \cdots, K\}),\ X|Z \sim \mathcal{N}\left(\boldsymbol{\mu}_Z, \alpha^2 \boldsymbol{I}/D\right),\ Y|Z = \mathbb{1}_{Z \leq K_1} - \mathbb{1}_{Z > K_1}, \tag{2}$$

where the $\boldsymbol{\mu}_1, \cdots, \boldsymbol{\mu}_K$, called *cluster centers*, are a set of orthonormal vectors in $\mathbb{R}^D$, i.e. $\langle \boldsymbol{\mu}_k, \boldsymbol{\mu}_l \rangle = \mathbb{1}_{l=k}$. We denote the marginal distribution of (X, Y)-pair as $\mathcal{D}_{X,Y}$.

ℓ_2-robust classifier for $\mathcal{D}_{X,Y}$ Our interest is to find a classifier that not only accurately predicts the label y given an observed data $\boldsymbol{x}$, but do so in a way that is robust to some adversarial attacks on observation $\boldsymbol{x}$. Specifically, we search for a classifier $f : \mathbb{R}^D \to \mathbb{R}$ such that with high probability $\min_{\|\boldsymbol{d}\|=1} f(\boldsymbol{x} + r\boldsymbol{d})y > 0$ for some $r \geq 0$ given a new sample $(\boldsymbol{x}, y)$ from $\mathcal{D}_{X,Y}$. When $r = 0$, $f(\boldsymbol{x})y > 0$ suggest that $\mathrm{sign}\left(f(\boldsymbol{x})\right)$ correctly predicts the label y; When $r > 0$, $\min_{\|\boldsymbol{d}\|=1} f(\boldsymbol{x} + r\boldsymbol{d})y > 0$ suggest that $\mathrm{sign}\left(f(\boldsymbol{x} + r\boldsymbol{d})\right)$ still makes correct prediction on y even though observation $\boldsymbol{x}$ has been corrupted by some adversarial attack $r\boldsymbol{d}$, thus *robust to adversarial attacks of ℓ_2-norm radius r*. Ideally, we want a classifier that is robust to attack of radius r, with as large r as possible.

Maximum achievable ℓ_2-robustness Inevitably, any classifier fails to be robust if the adversary has too much power, i.e., the attack radius r exceeds some value. Indeed, for the data distribution $\mathcal{D}_{X,Y}$ of our interest, no classifier can defend against attacks of radius $\frac{\sqrt{2}}{2}$, as formally shown below:

Theorem 1. *Let $f : \mathbb{R}^D \to \mathbb{R}$ be any Lebesgue measurable function such that the random variable $\min_{\|\boldsymbol{d}\| \leq 1} \left[f\left(\boldsymbol{x} + \frac{\sqrt{2}}{2}\boldsymbol{d}\right) y \right]$ is also measurable. Given a sample $(\boldsymbol{x}, y) \sim \mathcal{D}_{X,Y}$, we have*

$$\mathbb{P}_{(\boldsymbol{x},y)\sim\mathcal{D}_{X,Y}} \left(\min_{\|\boldsymbol{d}\| \leq 1} \left[f\left(\boldsymbol{x} + \frac{\sqrt{2}}{2}\boldsymbol{d}\right) y \right] \leq 0 \right) \geq \frac{\min\{K_1, K_2\}}{K}. \tag{3}$$

We refer the readers to Appendix B.1 for the proof. We explain Theorem 1 from a geometric perspective (we have discussed some in the introduction): Consider the case of two clusters $\mathcal{N}\left(\boldsymbol{\mu}_1, \frac{\alpha^2}{D}\boldsymbol{I}\right)$

and $\mathcal{N}\big(\boldsymbol{\mu}_2, \frac{\alpha^2}{D}\boldsymbol{I}\big)$ of different classes. As shown in Figure 1, when ambient dimension D is large, we expect that each cluster concentrates around a $D-1$ affine subspace that is orthogonal to the vector $\boldsymbol{\mu}_1 - \boldsymbol{\mu}_2$. Most importantly, the distance between these two affine subspaces is $\sqrt{2}$, suggesting that given any decision boundary that separates two affine subspaces, an adversary can perturb a substantial portion of the probability mass of these clusters to cross the boundary with an attack radius $\frac{\sqrt{2}}{2}$. The same argument holds for the K-clusters cases, where every two clusters are separated by a Euclidean distance $\sqrt{2}$. We also note that extending Theorem 1 to attacks in another metric amounts to measuring this separation in that metric. Our second result shows the Bayes optimal classifier w.r.t. 0-1 loss is also nearly optimally robust:

Theorem 2. *The Bayes optimal classifier for label Y given observation $\boldsymbol{x}$ w.r.t. 0-1 loss is* $\operatorname{sign}\left(f^*(\boldsymbol{x})\right)$, *where* $f^*(\boldsymbol{x}) = \sum_{k=1}^{K_1} \exp\left(\frac{D\langle \boldsymbol{x}, \boldsymbol{\mu}_k\rangle}{\alpha^2}\right) - \sum_{k=K_1+1}^{K} \exp\left(\frac{D\langle \boldsymbol{x}, \boldsymbol{\mu}_k\rangle}{\alpha^2}\right)$ *. Moreover, given a sample $(\boldsymbol{x}, y) \sim \mathcal{D}_{X,Y}$, we have, for any* $\frac{2\sqrt{2}\alpha^2 \log K}{D} \le \nu \le \sqrt{2}$,

$$\mathbb{P}_{(\boldsymbol{x},y)\sim\mathcal{D}_{X,Y}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[f^*\left(\boldsymbol{x} + \frac{\sqrt{2}-\nu}{2}\boldsymbol{d}\right) y\right] > 0\right) \ge 1 - 2K\exp\left(-\frac{D\nu^2}{64\alpha^2}\right). \tag{4}$$

We refer the readers to Appendix B.2 for the proof. If we pick $\nu = \Theta\big(\big(\frac{\alpha^2}{D}\big)^{\frac{1}{4}}\big)$ in Theorem 2, then the result shows that f^* is robust against attacks of radius $\frac{\sqrt{2}}{2} - \Theta\big(\big(\frac{\alpha^2}{D}\big)^{\frac{1}{4}}\big)$ with probability at least $1 - \mathcal{O}\big(K\exp\big(-\big(\frac{D}{\alpha^2}\big)^{\frac{1}{2}}\big)\big)$ over new sample from $\mathcal{D}_{X,Y}$. Therefore, f^* is nearly optimal robust when $\frac{\alpha^2}{D} = o(1)$, i.e. the ambient dimension is large or the intra-class variance is small.

Interpreting f^* as a nearest-cluster rule We explain why this Bayes classifier is of interest. We have the following derivation:

$$\begin{aligned}
\operatorname{sign}\left(f^*(\boldsymbol{x})\right) &= \operatorname{sign}\left(\sum_{k=1}^{K_1}\exp\left(\frac{D\langle \boldsymbol{x}, \boldsymbol{\mu}_k\rangle}{\alpha^2}\right) - \sum_{k=K_1+1}^{K}\exp\left(\frac{D\langle \boldsymbol{x}, \boldsymbol{\mu}_k\rangle}{\alpha^2}\right)\right) \\
&= \operatorname{sign}\left(\frac{\alpha^2}{D}\log\left(\sum_{k=1}^{K_1}\exp\left(\frac{D\langle \boldsymbol{x}, \boldsymbol{\mu}_k\rangle}{\alpha^2}\right)\right) - \frac{\alpha^2}{D}\log\left(\sum_{k=K_1+1}^{K}\exp\left(\frac{D\langle \boldsymbol{x}, \boldsymbol{\mu}_k\rangle}{\alpha^2}\right)\right)\right) \\
&= \operatorname{sign}\Big(\max_{1\le k\le K_1}\langle \boldsymbol{x}, \mu_k\rangle - \max_{K_1+1\le k\le K}\langle \boldsymbol{x}, \mu_k\rangle + \mathcal{O}\big(\log K\frac{\alpha^2}{D}\big)\Big),
\end{aligned}$$

where the second inequality is due to the fact that $\frac{\alpha^2}{D}\log(\cdot)$ function is a non-decreasing function, and the third inequality is because LogSumExp$(\{z_1, \cdots, z_K\})$ function with a temperature $\frac{D}{\alpha^2}$ uniformly approximate $\max_k z_k$ with an error $\mathcal{O}\big(\log K\frac{\alpha^2}{D}\big)$. When the error is small, the Bayes classifier $f^*(\boldsymbol{x})$ finds the closest cluster center to $\boldsymbol{x}$ and outputs the label to that cluster, which is a nearest-cluster rule. Therefore, by exploiting the multi-cluster structure of $\mathcal{D}_{X,Y}$, f^* achieves the maximum ℓ_2-robustness.

So far we have shown that a nearly optimal robust classifier for $\mathcal{D}_{X,Y}$ can be easily constructed as a nearest-cluster rule. However, as we discussed in the introduction, gradient descent algorithms with sampled data often fail to find a classifier with the same level of robustness. Next, we address the problem of finding a nearly optimal robust classifier by gradient flow dynamics.

3 Optimal Robust Classifiers Obtained via Gradient Flow

In this section, we aim to find a nearly optimal ℓ_2-robust classifier for $\mathcal{D}_{X,Y}$ by vanilla gradient descent without adversarial training. We start by stating the problem of training two-layer networks with gradient flow (gradient descent with infinitesimal step size). Then we show that with a pReLU activation, gradient flow provably finds a classifier that is nearly optimal ℓ_2-robust.

3.1 Preliminaries: Gradient Flow on Two-Layer Networks

pReLU network We consider a two-layer pReLU network (Min & Vidal, 2024) defined as follow:

$$f^{(p)}\left(\boldsymbol{x}; \boldsymbol{\theta}\right) = \sum_{i=1}^{h} v_j \frac{\sigma^p\big(\langle \boldsymbol{x}, \boldsymbol{w}_j\rangle\big)}{\|\boldsymbol{w}_j\|^{p-1}} \qquad \left(\boldsymbol{\theta} := \{\boldsymbol{w}_j, v_j\}_{j=1}^{h}\right), \tag{5}$$

$f^{(p)}$ can be viewed as a generalized version of the ReLU network. When $p = 1$, $f^{(1)}$ is exactly a two-layer ReLU network. When $p > 1$, the output of the hidden activation is equal to the one of the ReLU network multiplying $\cos^{p-1}(\boldsymbol{x}, \boldsymbol{w}_j)$ (Min & Vidal, 2024), which discourages large angle separation between data $\boldsymbol{x}$ and *neuron* $\boldsymbol{w}_j$.

ℓ_2-loss function and balanced dataset Given a dataset $\{\boldsymbol{x}_i, y_i\}_{i=1}^n$, one define the loss function as $\mathcal{L}(\boldsymbol{\theta}; \{\boldsymbol{x}_i, y_i\}_{i=1}^n) = \sum_{i=1}^n \ell(y_i, \hat{y}_i)$, where $\hat{y}_i = f^{(p)}(\boldsymbol{x}_i; \boldsymbol{\theta})$. For classification problem, the typical choice of ℓ can be exponential $\exp(-y\hat{y})$, or logistic loss $\log(1+\exp(-y\hat{y}))$. Most of our theoretical analysis works for these choices for ℓ. However, using classification losses poses additional challenges in analyzing the late phase of the training (details explained in later sections). Therefore, our theorem considers a ℓ_2-loss: $\ell(y, \hat{y}) = \frac{1}{2}\|y - \hat{y}\|^2$, and the extension to classification losses is discussed in Section 3.2.4.

As for the dataset, since $\mathcal{D}_{X,Y}$ samples data with equal probability from each cluster, there are approximately equal number of samples from each cluster when we sample a large number of data. Therefore, instead of considering a dataset directly sampled from $\mathcal{D}_{X,Y}$, we consider the following *balanced dataset* $\hat{\mathcal{D}} = \{\boldsymbol{x}_i, y_i\}_{i=1}^{KN}$, where

$$\boldsymbol{x}_i \sim \mathcal{N}\left(\boldsymbol{\mu}_k, \alpha^2 \boldsymbol{I}/D\right), y_i = \mathbb{1}_{k \le K_1} - \mathbb{1}_{k > K_1}, \quad (k-1)N + 1 \le i \le kN,\ 1 \le k \le K\,. \tag{6}$$

We call this dataset balanced because $\hat{\mathcal{D}}$ has exactly N samples from each cluster $\mathcal{N}(\boldsymbol{\mu}_k, \alpha^2\boldsymbol{I}/D)$. This assumption allows us to omit the additive perturbations in our analysis introduced by unbalanced per-cluster sample size.

Gradient flow with small and balanced initialization Given the network parametrization $\boldsymbol{\theta}$ and the loss function $\mathcal{L}$ constructed from a balanced dataset $\hat{\mathcal{D}}$, we consider training the network by the following *gradient flow* (GF) dynamics[1]:

$$\dot{\boldsymbol{\theta}} = -\nabla_{\boldsymbol{\theta}} \mathcal{L}\left(\boldsymbol{\theta}; \hat{\mathcal{D}}\right), \qquad \boldsymbol{\theta}(0) = \boldsymbol{\theta}_0\,, \tag{7}$$

We assume the initialization $\boldsymbol{\theta}(0)$ is ϵ-*small* and *balanced*, formally defined as the following.

Assumption 1 (ϵ-small and balanced initialization)**.** *The initialization $\boldsymbol{\theta}(0) = \{\boldsymbol{w}_j(0), v_j(0)\}_{j=1}^h$ satisfies the following: there exists an **initialization shape** $\{\boldsymbol{w}_{j0}, v_{j0}\}_{j=1}^h$ with $W_{\min} \le \|\boldsymbol{w}_{j0}\| \le W_{\max}, \forall j$, for some $W_{\min}, W_{\max} > 0$ and an **initialization scale** $\epsilon > 0$ such that*

$$\boldsymbol{w}_j(0) = \epsilon \boldsymbol{w}_{j0},\ v_j(0) = \epsilon v_{j0},\ \|\boldsymbol{w}_{j0}\| = |\boldsymbol{v}_{j0}|, \forall j\,. \tag{8}$$

Under a balanced initialization, we have $\|\boldsymbol{w}_j(0)\| = |v_j(0)|, \forall j$, and this balancedness holds throughout GF trajectory (See Appendix D.1): $\|\boldsymbol{w}_j(t)\| = |v_j(t)|, \forall j$. The balancedness between w_j and v_j allows us to focus on the dynamics of w_j, which has been a common assumption in prior work of this type (Maennel et al., 2018; Boursier et al., 2022; Chistikov et al., 2023; Min et al., 2024). Readers may view this assumption as made out of convenience, but it is essential for a tractable analysis (also allowing an elegant interpretation of dynamics of w_j (Maennel et al., 2018; Boursier & Flammarion, 2024)), and the theoretical results out of this assumption match the empirical results when no balancedness is enforced (Min et al., 2024).

Given a balanced initialization, one can show that $\operatorname{sign}(v_j(t)) = \operatorname{sign}(v_j(0)), \forall j, \forall t \ge 0$ (Boursier et al., 2022). Roughly speaking, $\operatorname{sign}(v_j(0))$ determines the dynamical behavior of neuron $\boldsymbol{w}_j$ under gradient flow: neurons with $\operatorname{sign}(v_j(0)) = +1$ tend to align its direction with one of the positive cluster centers, $\boldsymbol{\mu}_k,\ k = 1, \cdots, K_1$, and those with $\operatorname{sign}(v_j(0)) = -1$ tend to align with one of the negative cluster centers. For this reason, we define the following neuron index sets: $\mathcal{N}_+ := \{j \in [h] : \operatorname{sign}(v_j(0)) = +1\}$ and $\mathcal{N}_- := \{j \in [h] : \operatorname{sign}(v_j(0)) = -1\}$.

[1]Readers may find it more appropriate to study gradient flow as differential inclusion, instead of differential equation, since ReLU is non-differentiable at 0. However, our focus is on pReLU network with $p > 2$, which renders the network $f^{(p)}$ differentiable everywhere.

3.2 MAIN RESULTS: PRELU ($p > 2$) PROVABLY FINDS (NEAR)-OPTIMAL ROBUST CLASSIFIERS

pReLU classifier and the conjecture Min & Vidal (2024) study the adversarial robustness of the following pReLU classifier (that can be expressed by $f^{(p)}(\boldsymbol{x};\boldsymbol{\theta})$ with some choice of $\boldsymbol{\theta}$):

$$F^{(p)}(\boldsymbol{x}) = \sum\nolimits_{k=1}^{K_1} \sigma^p(\langle \boldsymbol{x}, \boldsymbol{\mu}_k\rangle) - \sum\nolimits_{k=K_1+1}^{K} \sigma^p(\langle \boldsymbol{x}, \boldsymbol{\mu}_k\rangle)\,, \tag{9}$$

and show that $F^{(p)}(\boldsymbol{x})$ is robust to adversarial attacks of ℓ_2 radius arbitrarily close to $\frac{\sqrt{2}}{2}$ when $\frac{D}{\alpha^2}$ is large (Now based on our Section 2, we know that $F^{(p)}(\boldsymbol{x})$ is nearly optimally robust). They conjecture that when $p > 3$ and the intra-cluster variance α^2 is small, the gradient flow on pReLU network $f^{(p)}(\cdot;\boldsymbol{\theta})$ with small initialization finds a classifier that is close to $F^{(p)}(\boldsymbol{x})$ up to a constant scaling factor. Then they argue that such proximity to $F^{(p)}(\boldsymbol{x})$ implies that the trained network has the same level of robustness as $F^{(p)}(\boldsymbol{x})$. Our main results fully prove this conjecture with $p > 2$.

Closeness to $F^{(p)}$ implies robustness We first show that given any classifier $f(\boldsymbol{x})$ that is positively homogeneous of degree 1 w.r.t. $\boldsymbol{x}$ and is close to $F^p(\boldsymbol{x})$ in terms of some distance measure, it is nearly optimal robust when the intra-class variance is small (We refer to Appendix C for the proof.).

Proposition 1. *Given a classifier f that satisfies $f(\gamma\boldsymbol{x}) = \gamma f(\boldsymbol{x}), \forall \boldsymbol{x} \in \mathbb{R}^D$, $\forall \gamma > 0$ and $\mathrm{dist}(f, F^{(p)}) = \inf_{c>0} \sup_{\boldsymbol{x}\in\mathbb{S}^{D-1}} |cf(\boldsymbol{x}) - F^{(p)}(\boldsymbol{x})| \le \nu$ for some $p > 2$ and $0 < \nu \le \left(\frac{\sqrt{2}}{8}\right)^p$. Then for a sample $(\boldsymbol{x}, y) \sim \mathcal{D}_{X,Y}$, we have*

$$\mathbb{P}_{(\boldsymbol{x},y)\sim\mathcal{D}_{X,Y}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[f\left(\boldsymbol{x} + \frac{\sqrt{2} - 8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right) y\right] > 0\right) \ge 1 - 2K\exp\left(-\frac{D\nu^{\frac{2}{p}}}{2K^2\alpha^2}\right) - 4\exp\left(-\frac{3}{8\alpha^2}\right). \tag{10}$$

Given this result, it remains to show that gradient flow finds a network $f^{(p)}(\cdot;\boldsymbol{\theta})$ (which is positively homogeneous of degree 1) that is close to $F^{(p)}$ in the distance measure defined above. We will first discuss an additional assumption required on the initialization, then state our main result.

3.2.1 NON-DEGENERATE INITIALIZATION SHAPE

To properly define a non-degenerate initialization shape, we need to define a *radial Voronoi tessellation* of $\mathbb{R}^{D-1}/\{0\}$ given a tuple of unit-norm vectors $\{\boldsymbol{\mu}_k\}_{k\in\mathcal{K}}$.

Definition 1. *Given a tuple of unit-norm vectors $\{\boldsymbol{\mu}_k\}_{k\in\mathcal{K}}$, define the following ($[\cdot]_+ := \max\{\cdot, 0\}$):*

$$\mathcal{R}_k := \left\{\boldsymbol{w}\in\mathbb{R}^{D-1}/\{0\} \;\middle|\; [\cos(\boldsymbol{\mu}_k, \boldsymbol{w})]_+ > [\cos(\boldsymbol{\mu}_l, \boldsymbol{w})]_+, \forall l \ne k\right\}, k \in \mathcal{K}, \quad \textbf{(Voronoi regions)}$$

$$\mathcal{R}^\circ := \left\{\boldsymbol{w}\in\mathbb{R}^{D-1}/\{0\} \;\middle|\; [\cos(\boldsymbol{\mu}_k, \boldsymbol{w})]_+ = 0, \forall k \in \mathcal{K}\right\}. \quad \textbf{(Void region)}$$

From this definition, it is clear that $\{\mathcal{R}_k\}_{k\in\mathcal{K}}, \mathcal{R}^\circ$ are disjoint subsets of $\mathbb{R}^{D-1}/\{0\}$. We are ready to define a non-degenerate initialization shape, whose formal definition is stated below:

Definition 2 (Non-degenerate initialization shape)**.** *A set of initialization shape $\{\boldsymbol{w}_{j0}\}_{j\in\mathcal{N}}$ is **non-degenerate** w.r.t. a set of unit-norm vectors $\{\boldsymbol{\mu}_k\}_{k\in\mathcal{K}}$ if it satisfies that*

- *(Neurons must be within one of the regions) $\forall j \in \mathcal{N}$, $\boldsymbol{w}_{j0} \in \left(\bigcup_{k\in\mathcal{K}} \mathcal{R}_k\right) \bigcup \mathcal{R}^\circ$;*
- *(Non-void regions must contain at least one neuron) $\forall k \in \mathcal{K}$, $\exists j \in \mathcal{N}$ such that $\boldsymbol{w}_{j0} \in \mathcal{R}_k$,*

*where $\{\mathcal{R}_k\}_{k\in\mathcal{K}}$ and $\mathcal{R}^\circ$ are the Voronoi regions and void region defined in Definition 1 w.r.t. $\{\boldsymbol{\mu}_k\}_{k\in\mathcal{K}}$. Moreover, we let $d(\boldsymbol{w}, S) = 1 - \sup_{\boldsymbol{s}\in S, \boldsymbol{s}\ne 0} \cos(\boldsymbol{w}, \boldsymbol{s})$ and define **non-degeneracy gap**:*

$$\Delta := \min\left\{\min_{\{\boldsymbol{w}_{j0}\in(\bigcup_{k\in\mathcal{K}}\mathcal{R}_k)\}} d\Big(\boldsymbol{w}_{j0}, \partial\big(\bigcup_{k\in\mathcal{K}}\mathcal{R}_k\big)\Big), \min_{\{\boldsymbol{w}_{j0}\in\mathcal{R}^\circ\}} d\Big(\boldsymbol{w}_{j0}, \partial\mathcal{R}^\circ\Big)\right\}. \tag{11}$$

Whenever a vector $\boldsymbol{w}$ falls into one of the $\mathcal{R}_k$, it means that: 1) the angle between $\boldsymbol{w}$ and the corresponding $\boldsymbol{\mu}_k$ is less than $\frac{\pi}{2}$; and 2) compared to all other $\boldsymbol{\mu}$s, $\boldsymbol{\mu}_k$ is the closest (in angle) to $\boldsymbol{w}$. We hope that neurons initialized within some $\mathcal{R}_k$ converge to the corresponding $\boldsymbol{\mu}_k$ under GF, and those initialized within $\mathcal{R}^\circ$ stay in $\mathcal{R}^\circ$ (This is indeed the case, see Section 3.2.3).

The special case when a neuron is exactly initialized on the boundary of these Voronoi regions $\partial\big(\bigcup_{k\in\mathcal{K}}\mathcal{R}_k\big)$ cannot be analyzed since if a neuron has equal angular distance to two $\boldsymbol{\mu}$ vectors, there is no way to determine which $\boldsymbol{\mu}$ vector it converges to under GF with sampled data around these $\boldsymbol{\mu}$ vectors. Similarly, if a neuron is initialized at the boundary between some $\mathcal{R}_k$ and $\mathcal{R}^\circ$, then we can not determine whether it converges to $\boldsymbol{\mu}_k$, or it falls into the interior of $\mathcal{R}^\circ$ and stays after that. Therefore we require an initialization shape with a positive non-degeneracy gap. Moreover, every $\mathcal{R}_k$ must contain one neuron, ensuring the corresponding $\boldsymbol{\mu}_k$ gets learned. This leads to our assumption of non-degenerate initialization.

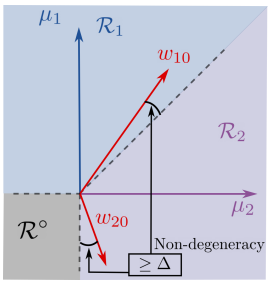

Figure 3: Illustration of a non-degenerate initialization shape $\{\boldsymbol{w}_{10}, \boldsymbol{w}_{20}\}$ w.r.t. two orthonormal vectors $\{\boldsymbol{\mu}_1, \boldsymbol{\mu}_2\}$.

Assumption 2. *(Initialization has at least Δ non-degeneracy gap) $\exists\Delta > 0$ such that $\{\boldsymbol{w}_{j0}\}_{j\in\mathcal{N}_+}$ is non-degenerate w.r.t. $\{\boldsymbol{\mu}_k\}_{1\leq k\leq K_1}$ with at least Δ non-degeneracy gap, and $\{\boldsymbol{w}_{j0}\}_{j\in\mathcal{N}_-}$ is non-degenerate w.r.t. $\{\boldsymbol{\mu}_k\}_{K_1\leq k\leq K}$ with at least Δ non-degeneracy gap.*

As one can see, this condition is stated per class: Positive (Negative) neurons must be initialized to be non-degenerate w.r.t. cluster centers from the positive (negative) class. We let $\{\mathcal{R}_k\}_{1\leq k\leq K_1}$ and $\{\mathcal{R}_k\}_{K_1\leq k\leq K}$ be the Voronoi regions defined by $\{\boldsymbol{\mu}_k\}_{1\leq k\leq K_1}$ and $\{\boldsymbol{\mu}_k\}_{K_1\leq k\leq K}$ respectively and define the neuron index sets $\mathcal{N}_k := \begin{cases} j\in\mathcal{N}_+ : \boldsymbol{w}_{j0}\in\mathcal{R}_k, & 1\leq k\leq K_1 \\ j\in\mathcal{N}_- : \boldsymbol{w}_{j0}\in\mathcal{R}_k, & K_1+1\leq k\leq K \end{cases}$ and $\mathcal{N}_c := [h] - \cup_{1\leq k\leq K}\mathcal{N}_k$. As suggested in our previous discussion, we show that (See Section 3.2.3) under GF, all neurons in $\mathcal{N}_k$ converge in angle to $\boldsymbol{\mu}_k$, which is an essential part of our theoretical results.

3.2.2 Convergence of pReLU ($p > 2$) on orthonormal clusters

Now we are ready to state our main theorem:

Theorem 3 (pReLU converges to optimal robust classifier for orthonormal clusters)**.** *Let $p > 2$. Given $0 \leq \delta \leq 1$ and a sufficiently small α_0^2, consider data dimension $D \geq \tilde{\Omega}(\alpha_0^{-2})$ and per-cluster sample size $\tilde{\Omega}(\alpha_0^{-2}) \leq N \leq \tilde{o}(\exp(\alpha_0^{-2}))$. With probability at least $1-\delta$, the GF dynamics with a balanced dataset $\hat{\mathcal{D}} = \{\boldsymbol{x}_i, y_i\}_{i=1}^{KN}$ sampled with intra-cluster variance $\alpha^2 \leq \alpha_0^2$, starting from some ϵ-small and balanced (Assumption 1) initialization $\boldsymbol{\theta}(0)$ that satisfies Assumption 2 with a non-degeneracy gap $\Delta = \Theta(1)$ and has a sufficiently small initialization scale $\epsilon = \tilde{\Theta}\left(\alpha_0^{8K}\right)$, leads to a solution $\boldsymbol{\theta}(t), t \geq 0$ such that: for some $t^* = \tilde{\mathcal{O}}\left(\log\frac{1}{\alpha_0}\right)$ and $T^* = \tilde{\Theta}\left(\log\frac{1}{\alpha_0}\right) + \tilde{\Omega}\left(\frac{1}{\alpha_0^{\min\{p-2,2\}}}\right)$ with $[t^*, T^*] \neq \emptyset$, we have $\mathcal{L}(\boldsymbol{\theta}(t)) = \tilde{\mathcal{O}}(\alpha_0^4), \forall t \in [t^*, T^*]$ and*

$$\sup_{t\in[t^*,T^*]}\sup_{\boldsymbol{x}\in\mathbb{S}^{D-1}}\left|f^{(p)}(\boldsymbol{x};\boldsymbol{\theta}(t)) - F^{(p)}(\boldsymbol{x})\right| \leq \tilde{\mathcal{O}}\left(\alpha_0^2\right). \tag{12}$$

$\tilde{\Omega}, \tilde{o}, \tilde{\mathcal{O}}$ hide logarithmic factor $\log\frac{K}{\delta}$ and constant factors that depend on p (in the worst case, 2^p). We organize the subsequent discussions as follows: First, we state several remarks on understanding our main result and comparing it with prior work; Then we move to a more technical discussion on its proof sketch in Section 3.2.3; Lastly, we state in Section 3.2.4 several technical limitations of our results and suggesting improvement in future research.

Nearly optimal robust classifier via GF The major implication of Theorem 3 is that one can find a nearly optimal ℓ_2-robust classifier by GF without adversarial examples. When the intra-cluster variance α^2 is small, along the GF trajectory there exists a $f^{(p)}(\cdot;\boldsymbol{\theta}(t))$ that is $\tilde{\mathcal{O}}(\alpha_0^2)$ close to a nearly optimal ℓ_2-robust classifier $F^{(p)}$, and such proximity to $F^{(p)}$ implies the same level of ℓ_2-robustness, as shown in Proposition 1. We can immediately conclude that $f^{(p)}$ is also nearly optimal ℓ_2-robust:

Corollary 1 (Nearly optimal ℓ_2-robustness). *Given any $f^{(p)}(\cdot;\boldsymbol{\theta}(t))$ obtained at $t \in [t^*, T^*]$ from Theorem 3, it can defend against adversarial attacks of radius $\frac{\sqrt{2}}{2} - \tilde{\mathcal{O}}\big(\alpha_0^{\frac{2}{p}}\big)$ with probability $1 - \tilde{\mathcal{O}}\big(\alpha_0^{-2\left(1-\frac{2}{p}\right)}\big)$ over a new sample $(\boldsymbol{x}, y) \sim \mathcal{D}_{X,Y}$, thus nearly optimal ℓ_2-robust for $\mathcal{D}_{X,Y}$.*

Comparison with prior work: robust classifier for orthonormal clusters The study of finding a robust classifier for clusters with orthogonal cluster centers is initiated by Frei et al. (2023), where they theoretically show that any classifier obtained by gradient descent on a two-layer ReLU network is susceptible to an adversarial attack of ℓ_2-radius $\mathcal{O}\big(\frac{1}{\sqrt{K}}\big)$, despite that one can easily construct a ReLU network that is robust to attacks of radius $\Theta(1)$ [2]. Then Min & Vidal (2024) explain this non-robustness issue of ReLU from a neural alignment perspective (Maennel et al., 2018; Boursier & Flammarion, 2024), and propose pReLU to replace ReLU activation. They state as a conjecture that training pReLU network $f^{(p)}(\cdot;\boldsymbol{\theta})$ under samples from $\mathcal{D}_{X,Y}$ leads to a classifier that is close to $F^{(p)}$ when intra-cluster variance α^2 is small, and provide empirical validation to their conjecture. Our work takes one step further to theoretically prove the convergence of pReLU towards $F^{(p)}$ under GF, and also show that the achieved ℓ_2-robustness is nearly optimal. Also, we believe a small initialization is critical for finding a robust classifier as our data is approximately low-dimension thus adversarial examples exist if the initialization scale is large Melamed et al. (2024).

Comparison with prior work: GF on the two-layer network with small initialization Over the past year, gradient descent/flow with small initialization has been studied for both linear networks Gidel et al. (2019); Stöger & Soltanolkotabi (2021) and nonlinear networks Maennel et al. (2018); Phuong & Lampert (2021); Boursier et al. (2022); Kumar & Haupt (2024); Chistikov et al. (2023); Wang & Ma (2023); Min et al. (2024); Tsoy & Konstantinov (2024), to understand the implicit bias of gradient descent algorithms towards structurally simple networks. Our analysis follows this line of work, as we will explain in Section 3.2.3 in detail, and also advances by considering a more complicated dataset. Specifically, the GF on two-layer ReLU networks has been studied for orthogonally separable data Phuong & Lampert (2021); Min et al. (2024); Chistikov et al. (2023), that is, data with the same (different) label has positive (negative) correlation, for mutually orthogonal data Boursier et al. (2022), and for positively correlated data (but only with two data points) Wang & Ma (2023). Our data assumption is closest to mutually orthogonal data Boursier et al. (2022) (if we set $\alpha = 0$), but considers a non-zero intra-cluster variance, which has not been studied in any of the aforementioned work.

3.2.3 Proof Sketch

For simplicity, we consider the case $\alpha^2 = \alpha_0^2$ and use α^2 throughout this section. The discussion is conditioned on a good event (happens with probability at least $1 - \delta$) when samples are well concentrated around their respective cluster centers.

Overall proof Our proof in spirit is close to that of Boursier et al. (2022), with a two-phase analysis of GF dynamics focusing on different quantities. Specifically, at the initial phase, called *alignment phase*, one studied the dynamics of the neuron direction $\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}$ through cosine angles between $\boldsymbol{w}_j$ and cluster center $\boldsymbol{\mu}_k$, where one show, for all k and $j \in \mathcal{N}_k$, that $c_{kj} := \cos(\boldsymbol{\mu}_k, \boldsymbol{w}_j)$ monotonically increases until it reaches $1 - \tilde{\mathcal{O}}(\alpha^2)$, that is, as we mentioned earlier, neurons initialized within $\mathcal{R}_k$ converge in angle to the corresponding $\boldsymbol{\mu}_k$. Then in the second *convergence phase*, we show that all c_{kj} can probably stay above $1 - \tilde{\mathcal{O}}(\alpha^2)$ until T^*, and in the meantime, the norm of the neurons (measured by $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2$ for each k) monotonically grow until reaches $1 \pm \tilde{\mathcal{O}}(\alpha^2)$ before t^*. Moreover, the norm of the neurons initialized in the void region stays small: $\sum_{j\in\mathcal{N}_c} \|\boldsymbol{w}_j(t)\| = \tilde{o}(\alpha^2)$. These three conditions $c_{kj} \geq 1 - \tilde{\mathcal{O}}(\alpha^2)$, $\big|1 - \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2\big| \leq \tilde{\mathcal{O}}(\alpha^2)$ and $\sum_{j\in\mathcal{N}_c} \|\boldsymbol{w}_j\| = \tilde{o}(\alpha^2)$ together imply the desired bound between $f^{(p)}$ and $F^{(p)}$. We refer the readers to Figure 4 for an illustration of these phases.

[2] Frei et al. (2023) considers data sampled from $\mathcal{N}(\sqrt{D}\boldsymbol{\mu}_k, \alpha^2\boldsymbol{I}), 1 \leq k \leq K$, thus their results should be rescaled by $\frac{1}{\sqrt{D}}$ when applied to $\mathcal{D}_{X,Y}$.

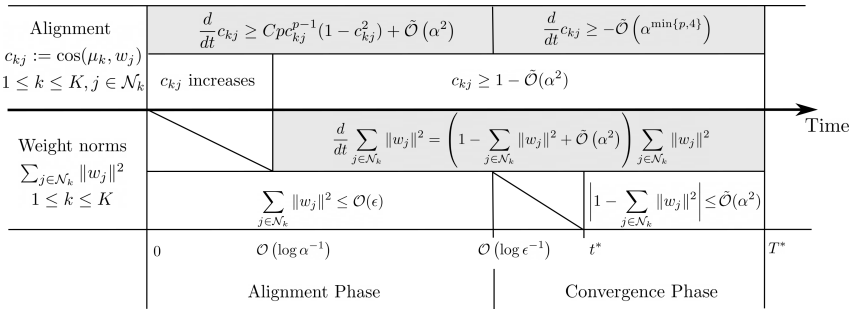

Figure 4: Important quantities (alignment and weight norms) and their dynamics long GF trajectory

Alignment phase (See Appendix E) During the alignment phase (the time interval between 0 and some $\tilde{\mathcal{O}}\left(\log \frac{1}{\epsilon}\right)$ time, where ϵ is the initialization scale). The norms of the weights stays $\tilde{\mathcal{O}}(\epsilon)$ small, which follows a similar proof in Boursier et al. (2022); Min et al. (2024). The small norm bound on weights, together with the positive non-degeneracy gap assumption, allows the following characterization of the alignment for $1 \le k \le K, j \in \mathcal{N}_k$:

$$\frac{d}{dt} c_{kj} \ge Cpc_{kj}^{p-1}(1-c_{kj}^2) + \tilde{\mathcal{O}}\left(\frac{\alpha}{\sqrt{N}} + \frac{\alpha}{\sqrt{D}}\right) + \tilde{\mathcal{O}}\left(\alpha^2 + \frac{\alpha}{\sqrt{D}}\right) + \tilde{\mathcal{O}}\left(\epsilon\right), \tag{13}$$

for some constant $C > 0$. Consider the case when $\alpha = 0$, and $\epsilon \to 0$, for $j \in \mathcal{N}_k$, the dynamics $\frac{d}{dt} c_{kj} \ge Cpc_{kj}^{p-1}(1-c_{kj}^2)$ characterize the nominal effect of cluster centers $\boldsymbol{\mu}_k, 1 \le k \le K$ on neuron direction $\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}$: each cluster centers is either attracting or repelling $\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}$, depending on whether their label matches the sign of v_j, and the aggregate effect is pushing $\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}$ towards $\boldsymbol{\mu}_k$, the closest cluster center to $\boldsymbol{w}_j$ in angle at initialization. We call k-th cluster the target cluster for $\boldsymbol{w}_j$.

The rest of the terms are considered perturbations due to noisy samples around cluster centers and a non-zero initialization scale: The first $\tilde{\mathcal{O}}\left(\frac{\alpha}{\sqrt{N}} + \frac{\alpha}{\sqrt{D}}\right)$ term is due to the noisy samples from (the target) k-th cluster. Since we have a $\Delta = \Theta(1)$ non-degeneracy gap, $\boldsymbol{w}_j$ has a positive inner product with every sampled data within the k-th cluster, then one can utilize concentration results to bound the effect of noise. The second $\tilde{\mathcal{O}}\left(\alpha^2 + \frac{\alpha}{\sqrt{D}}\right)$ term is due to the noisy samples from other non-target clusters. Unfortunately, we have no control over how many of them have positive inner products with $\boldsymbol{w}_j$, thus a worse bound $\tilde{\mathcal{O}}\left(\alpha^2\right)$ is derived. Lastly $\tilde{\mathcal{O}}\left(\epsilon\right)$ is due to an ϵ-small weight norm because the nominal effect is derived when weight norms are all zero. With $N = \tilde{\Omega}(\alpha^{-2})$ samples, $D = \tilde{\Omega}(\alpha^{-2})$ dimension, and small ϵ, the dominant terms become $\tilde{\mathcal{O}}\left(\alpha^2\right)$, allowing us to prove the following:

Proposition 2 (Alignment in pReLU network)**.** *Given the same assumptions as in Theorem 3 and consider the same GF solution $\boldsymbol{\theta}(t), t \ge 0$. There exist some $t_1 = \mathcal{O}\left(\log \frac{1}{\alpha}\right)$ and $t_2 = \mathcal{O}\left(\log \frac{1}{\epsilon}\right)$ such that $\forall k$ and $\forall j \in \mathcal{N}_k$, $\cos\left(\boldsymbol{\mu}_k, w_j(t)\right) \ge 1 - \tilde{\mathcal{O}}(\alpha^2),\ \forall t \in [t_1, t_2]$.*

We explicitly state the result during the alignment phase in Proposition 2 to highlight the difference between its described alignment for pReLU network ($p > 2$) to that of Boursier et al. (2022) for ReLU networks, where neurons are aligned with class average $\boldsymbol{\mu}_+ = \sum_{1\le k\le K_1} \boldsymbol{\mu}_k$ and $\boldsymbol{\mu}_- = \sum_{K_1+1\le k\le K} \boldsymbol{\mu}_k$ instead of cluster centers.

Convergence phase (See Appendix F) During the convergence phase, the weight norm grows and exceeds ϵ-level, as suggested by the following dynamics:

$$\frac{d}{dt} \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 = \left(1 - \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 + \tilde{\mathcal{O}}\left(\frac{\alpha}{\sqrt{N}}\right) + \tilde{\mathcal{O}}\left(\alpha^2\right) + \tilde{\mathcal{O}}\left(\alpha^p\right)\right) \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2, \tag{14}$$

which holds whenever $c_{kj} \ge 1 - \tilde{\mathcal{O}}\left(\alpha^2\right), \forall k, j \in \mathcal{N}_k$. The nominal dynamics $\frac{d}{dt} \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 = \left(1 - \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2\right) \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2$ describes the weight growth if $c_{kj} = 1, \forall k, j \in \mathcal{N}_k$ and $\alpha = 0$. Following nominal dynamics, $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2$ converges to 1 for every k, minimizes the ℓ_2-loss.

The rest of the terms are considered perturbations due to noisy samples around cluster centers and the fact that alignment c_{kj} are only close to 1. The first $\tilde{\mathcal{O}}\left(\frac{\alpha}{\sqrt{N}}\right)$ is due to the noisy sample from the target k-th cluster, the second $\tilde{\mathcal{O}}\left(\alpha^2\right)$ term is from imperfect alignment $c_{kj} \geq 1 - \tilde{\mathcal{O}}\left(\alpha^2\right)$, and the last $\tilde{\mathcal{O}}\left(\alpha^p\right)$ term is from the noisy sample from the non-target clusters (Notice that now $\boldsymbol{w}_j$s are almost orthogonal to non-target clusters, thus the effect of non-target clusters is smaller than during alignment phase). With $N = \tilde{\Omega}(\alpha^{-2})$ samples, the dominant terms become $\tilde{\mathcal{O}}(\alpha^2)$, allowing us to show that $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2$ converges to $1 \pm \tilde{\mathcal{O}}(\alpha^2)$ within t^* time.

The only missing piece is that this argument requires $c_{kj} \geq 1 - \tilde{\mathcal{O}}\left(\alpha^2\right), \forall k, j \in \mathcal{N}_k$ but one no longer has (13) after $\tilde{\Theta}\left(\log \frac{1}{\epsilon}\right)$ when weight norm starts to grow to $\tilde{\Theta}(1)$-level. Nonetheless, once the alignment c_{kj} is $1 - \tilde{\mathcal{O}}\left(\alpha^2\right)$, it is hard to drop below this level as it relies on the attraction from non-target clusters but they are now near orthogonal to the neurons. Indeed, during the convergence phase, we can show that $\frac{d}{dt}c_{kj} \geq -\tilde{\mathcal{O}}\left(\alpha^{\min\{p,4\}}\right)$, by which we show c_{kj} can stay at $1 - \tilde{\mathcal{O}}\left(\alpha^2\right)$ level until T^* time. Since $T^* \geq t^*$ for small α, our analysis of the weight norm growth is valid.

3.2.4 Technical limitations of current results

We conclude by discussing several technical limitations of our current results and potential avenues to address them. These limitations are listed in an order that the most challenging ones are stated first.

Requirement on the initialization The initialization requires a non-degeneracy gap $\Delta = \Theta(1)$, which generally cannot be achieved by random initialization: the cosines between neurons and cluster centers are $\mathcal{O}\big(\frac{1}{\sqrt{D}}\big)$ with high probability. Given that $D = \tilde{\Omega}(\alpha^{-2})$, the actually non-degeneracy gap of a random initialization is $\tilde{\mathcal{O}}(\alpha)$. We have discussed this issue when we define non-degenerate initialization in Section 3.2.1: When neurons are initialized close to the boundary between a Voronoi region $\mathcal{R}_k$ and another region $\mathcal{R}_l$ (or the void region $\mathcal{R}^\circ$), whether they align with $\boldsymbol{\mu}_k$ or with $\boldsymbol{\mu}_l$ (or get further into void region) depends on the actually sampled points in the dataset. In this regard, when weights are randomly initialized, there is a "burn-in" phase during which neurons "choose" their target clusters depending on the samples, then once they get away from the boundary of these Voronoi regions with $\Delta = \Theta(1)$ gap, we can characterize the GF dynamics afterward by Theorem 3.

Upper bound on N Regarding our requirement $\tilde{\Omega}(\alpha_0^{-2}) \leq N \leq \tilde{o}(\exp(\alpha_0^{-2}))$, we have discussed the lower bound $N \geq \tilde{\Omega}(\alpha_0^{-2})$ in Section 3.2.3. In fact, one can remove this lower bound and get a final bound $\tilde{\mathcal{O}}\big(\frac{\alpha_0}{\sqrt{N}}\big)$ in Theorem 3. The upper bound $N \leq \tilde{o}(\exp(\alpha_0^{-2}))$ may seem puzzling. This issue originates from ReLU nonlinearity: a data point must activate a neuron by having a positive inner product. Our analysis requires that a neuron $\boldsymbol{w}_j$ is activated by every data point from its target cluster, which is translated into two conditions: 1) $\Theta(1)$ non-degeneracy gap; and 2) $\sqrt{\log N}\alpha_0 = \tilde{o}(1)$. Here $\sqrt{\log N}\alpha_0$ is essentially the radius of a ℓ_2-ball centered at a cluster center that can contain all the sampled points from that cluster with high probability. Without these conditions, there will be outliers in sampled points, which must be handled with extra analysis. We believe this is possible because those outliers will be rare and thus may have a negligible effect on the dynamics.

Extension to classification losses Our results for the alignment phase directly apply to classification losses: The choice of the loss $\ell(y, \hat{y})$ only affects the alignment dynamics through $\nabla_{\hat{y}}\ell(y, \hat{y})|_{\hat{y}=0}$, and this quantity is same (may up to a constant scaling) regardless of whether ℓ is exponential, logistic, or ℓ_2. However, the analysis of convergence phase critically depends on ℓ: Recall that in Section 3.2.3 we show that the nominal weight norm dynamics are $\dot{z} = (1-z)z, z = \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2$ for ℓ_2 loss. For exponential loss, the nominal dynamics become $\dot{z} = \exp(-z)z$, whose closed-form solution is not available. A better characterization of the solution to the nominal dynamics of the type $\dot{z} = \exp(-z)z$ in future research naturally leads to an extension of Theorem 3 to classification losses.

Analysis until finite time T^* Our focus is on the distance between $f^{(p)}(\cdot; \boldsymbol{\theta}(t))$ and $F^{(p)}$, thus we restrict to the time interval $[0, T^*]$ when we have explicit control of all relevant quantities (alignment, weight norms, etc.). To show convergence towards a minimizer of the loss after T^*, we believe applying the results in Chatterjee (2022) suffices, following the approach in Boursier et al. (2022).

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A Numerical Experiments

A.1 Additional Experiments on Learning Robust Classifier for Data From Orthonormal Clusters

In this section, we provide additional experiments to that in Figure 2, highlighting the importance of parametrization of function space, and the hyperparameters of training algorithm in determining whether one can succeed in obtaining robust classifier for data from orthonormal clusters.

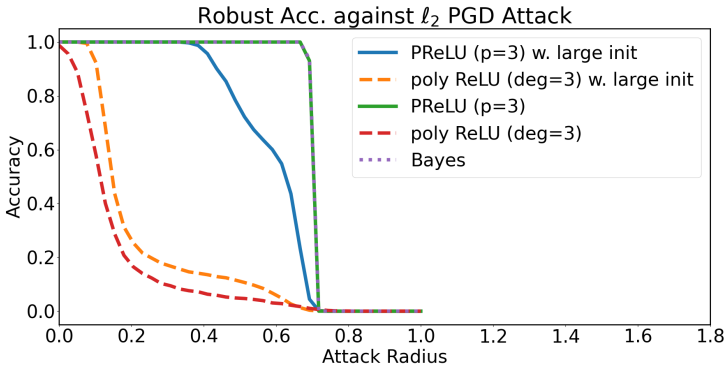

Figure 5: Given sampled data from (1) with 12 positive clusters and 8 negative clusters ($D = 2000$), gradient descent (SGD, small initialization) on (bias-free, width-200) two-layer network with regular polynomial ReLU activation of degree 3 fails to find a robust classifier. Moreover, if one increases the variance of the random initialization, both regular polynomial ReLU network and pReLU network can not find a robust classifier. All networks here are trained for a sufficient amount of epochs until they achieve perfect training accuracy on a synthesis dataset of our orthonormal cluster model of size 20000.

Regular polynomial ReLU networks In this experiment, we consider both the regular polynomial ReLU networks to pReLU networks. In particular, recall that the regular polynomial ReLU networks are defined as:

$$g(\boldsymbol{x};\tilde{\boldsymbol{\theta}}) = \sum_{j=1}^{h} v_j \sigma^p(\langle \boldsymbol{x}, \boldsymbol{w}_j \rangle)\,, \qquad (\tilde{\boldsymbol{\theta}} := \{\boldsymbol{w}_j, v_j\}_{j=1}^h)\,.$$

(Two-layer Networks with Polynomial ReLU activation with degree p)

We note its difference with pReLU networks: regular polynomial ReLU networks do not have a weight normalization at the first layer. Nonetheless, when p is fixed, it is easy to verify that the function/hypothesis spaces induced by pReLU networks and regular polynomial ReLU networks are the same: any function $f^{(p)}(\boldsymbol{x};\boldsymbol{\theta})$ for some $\boldsymbol{\theta} = \{\boldsymbol{w}_j, v_j\}_{j=1}^h$ is equivalent to $g(\boldsymbol{x};\tilde{\boldsymbol{\theta}})$ with $\tilde{\boldsymbol{\theta}} = \{\boldsymbol{w}_j, \frac{v_j}{\|\boldsymbol{w}_j\|^{p-1}}\}_{j=1}^h$[3].

Regular polynomial ReLU networks v.s. pReLU Although the induced function/hypothesis spaces are the same, GD on regular polynomial ReLU networks and pReLU finds classifiers with different levels of robustness. As one can see in Figure 5, with a small initialization (all weight entries are randomly initialized as $\mathcal{N}(0, 1 \times 10^{-4})$), SGD on a pReLU network successfully finds a classifier that is as robust as the Bayes classifier. However, SGD on a regular polynomial ReLU network fails to find a robust classifier. This suggests that the way the function/hypothesis spaces are parametrized is also important in determining the robustness of the networks trained by GD, as different parametrization induces different implicit biases of GD in selecting the loss minimizer in the function space.

Effect of initialization scale Finally, when one uses a large initialization scale, where all weight entries are randomly initialized as $\mathcal{N}(0, 0.25)$, even the GD on a pReLU network fails to find a robust classifier. This is not surprising as the initialization scale also controls the implicit bias of GD Moroshko et al. (2020), and many works Maennel et al. (2018); Stöger & Soltanolkotabi (2021); Li et al. (2018; 2021) have theoretically shown the advantage of using a small initialization scale in GD.

[3]The neurons with $\|\boldsymbol{w}_j\| = 0$ should be eliminated from the parameters for this argument to hold.

A.2 CAT V.S. DOG CLASSIFICATION VIA TRANSFER LEARNING

In this section, we solve the tasks of classifying cats and dogs (Cukierski, 2013) via transfer learning using extracted features from a ResNet152 (He et al., 2016) trained on ImageNet (Deng et al., 2009). We conjecture that the extracted features of the dog (or cat) class may naturally have many clusters: when the feature extractor is trained on ImageNet, dogs are further labeled by their breeds. Thus the extracted features of dogs of the same breed should be sufficiently close, and features of dogs of different breeds should be sufficiently far apart, based on the well-known neural collapse phenomenon (Papyan et al., 2020; Galanti et al., 2021). If such a multi-cluster structure exists in the extracted feature, then we expect training pReLU as a classification head can achieve better robust accuracy compared to its ReLU counterpart.

The rest of the section is organized as follows: First, we show that the extracted features of cats v.s. dogs dataset exhibits a multi-cluster structure; Then we train pReLU networks with different choices of p as a classification head and compute the robust accuracy of these train networks with AutoAttack (Croce & Hein, 2020) on the extracted feature space.

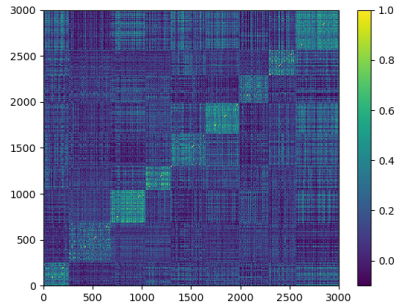

Figure 6: Pairwise inner product of the features of 3000 images of **dogs** from cat v.s. dog dataset Cukierski (2013). The features are clustered into 9 clusters via spectral clustering.

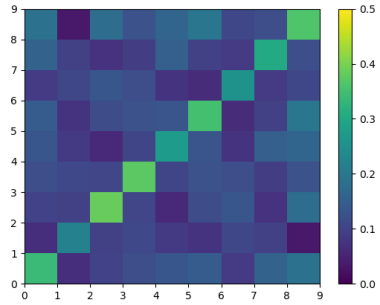

Figure 7: Average pairwise inner product between features from two clusters of **dogs** features. The features are clustered into 9 clusters; Each pixel $(i, j), 1 \leq i, j \leq 9$ represents the average inner product between features from cluster i and cluster j.

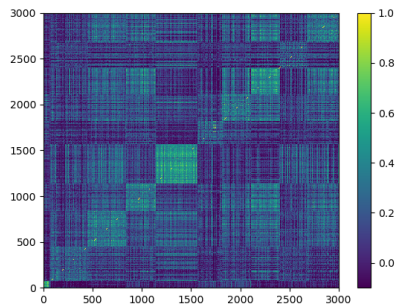

Figure 8: Pairwise inner product of the features of 3000 images of **cats** from cat v.s. dog dataset Cukierski (2013). The features are clustered into 10 clusters via spectral clustering.

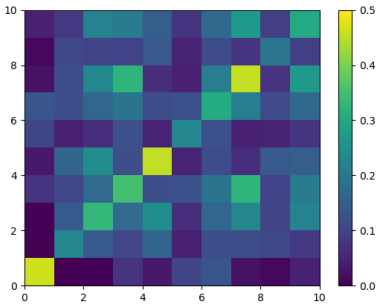

Figure 9: Average pairwise inner product between features from two clusters of **cats** features. The features are clustered into 10 clusters; Each pixel $(i, j), 1 \leq i, j \leq 10$ represents the average inner product between features from cluster i and cluster j.

Multi-cluster structure of extracted feature We first collect extracted features of the entire cat v.s. dog dataset (Cukierski, 2013), center these features by the global mean feature vector and then normalized all the features. Then we take a subset of the centered, normalized features (**for the sake**

of simplicity, we call the centered, normalized features as features) from the same class (cat or dog), do spectral clustering (Ng et al., 2001) on the features, then compute the inner product between the features. From Figure 6 and 7, we see even within the same (dog) class, the extracted features have a multi-cluster structure, and we conjecture that this is because when the feature extractor is trained on ImageNet, dogs are further labeled by their breeds. Interestingly, if we perform the same visualization for cat images, as in Figure 8 and 9, the multi-cluster structure still exists but with less prominent clusters; We conjecture that this is because ImageNet has much less cat classes than dog classes.

Training pReLU as classification head Now, with the extracted features of cat v.s. dog dataset, we train two-layer pReLU networks with different choices of p using Adam, following the same experiment settings in (Min & Vidal, 2024). After training, we compute the robust accuracy of the trained networks under adaptive adversarial ℓ_2 and ℓ_∞ attacks (Croce & Hein, 2020). We observe that pReLU networks with larger p achieve better robust accuracy than ReLU networks ($p = 1$).

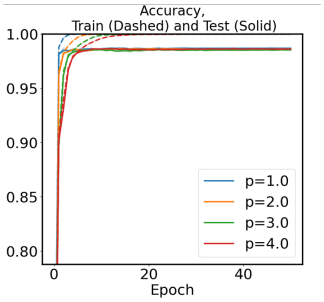

Figure 10: Cat and dog classification: Training and test accuracy v.s. training epochs

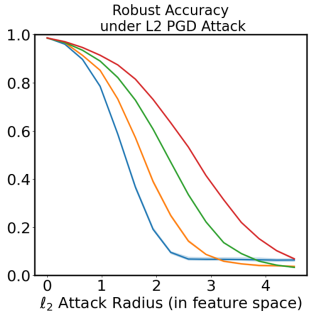

Figure 11: Robust accuracy of trained networks under ℓ_2 PGD attacks.

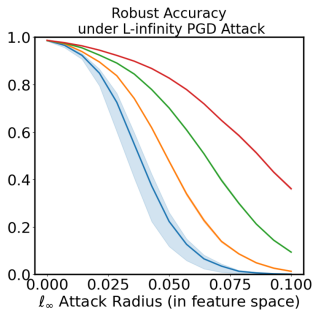

Figure 12: Robust accuracy of trained networks under ℓ_∞ PGD attacks.

In summary, we show that in a transfer learning scenario, the multi-cluster structure arises due to the distinguishing power of the feature extractor trained on large datasets with finer labels, and we show that in this case, pReLU networks with larger p achieve better robustness compared to its ReLU counterpart. Admittedly, our current Theorems cannot fully explain the observed experimental results since the extracted features form clusters with large variances, and there are some correlations among these clusters, which does not follow our data assumption. Relaxing our data assumption to large variance, and allowing inter-cluster correlation is an import future research direction.

B Optimal Robust Classifier for Orthonormal Clusters

In this section, we discuss the optimal robust classifier for orthonormal clusters. We first show that any measurable classifier can not defend against an adversarial attack of ℓ_2 radius $\frac{\sqrt{2}}{2}$, leading to a robust error of at least $\frac{\min\{K_1,K_2\}}{K}$. Then we consider the Bayes optimal classifier $f^*(\boldsymbol{x}) = \arg\max_y \mathbb{P}(Y=y|\boldsymbol{x})$ and show that it is also optimally robust: it can defend against any adversarial attack of ℓ_2 radius $\frac{\sqrt{2}}{2} - o(1)$, as the dimension of the data D increases.

B.1 Maximum robustness against ℓ_2 adversarial attacks

We need the following lemma (we provide proof after proving Theorem 1)

Lemma 1. *For any $n \times m$ matrix, let a be the number of rows that contain at least one non-positive entry and b be the number of columns that contain at least one non-negative entry. Then $a + b \geq \min\{n, m\}$.*

With Lemma 1, we are ready to prove Theorem 1.

Theorem 1 (Restated)**.** *Let $f : \mathbb{R}^D \to \mathbb{R}$ be any Lebesgue measurable function such that the random variable $\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]$ is also measurable. Given a sample $(\boldsymbol{x}, y) \sim \mathcal{D}_{X,Y}$, we have*

$$\mathbb{P}_{(\boldsymbol{x},y)\sim\mathcal{D}_{X,Y}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\leq 0\right) \geq \frac{\min\{K_1,K_2\}}{K}. \tag{B.1}$$

Proof. We start with the following:

$$\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\leq 0\right) = \sum_{k=1}^{K}\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\leq 0 \mid z=k\right)\mathbb{P}(z=k) \tag{B.2}$$

For $k \leq K_1$,

$$\begin{aligned}\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\leq 0 \mid z=k\right) &= \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{\mu}_k+\boldsymbol{\varepsilon}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)\right]\leq 0\right)\\ &\geq \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{K_1+1\leq l\leq K}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\leq 0\right).\end{aligned}$$

The measurability of f ensures this lower bound exists. Similarly, we have for $K_1 + 1 \leq k \leq K$

$$\begin{aligned}\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\leq 0 \mid z=k\right) &= \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[-f\left(\boldsymbol{\mu}_k+\boldsymbol{\varepsilon}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)\right]\leq 0\right)\\ &\geq \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{1\leq l\leq K_1}\left[-f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\leq 0\right)\\ &= \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\max_{1\leq l\leq K_1}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\geq 0\right).\end{aligned}$$

Therefore,

$$\begin{aligned}&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\leq 0\right)\\ &= \sum_{k=1}^{K}\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\leq 0 \mid z=k\right)\mathbb{P}(z=k)\\ &= \frac{1}{K}\left[\sum_{1\leq k\leq K_1}\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\leq 0 \mid z=k\right)\right.\end{aligned}$$

$$
\begin{aligned}
&\quad + \sum_{K_1+1\le k\le K} \mathbb{P}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\le 0 \mid z=k\right)\Bigg] \\
&\ge \frac{1}{K}\Bigg[\sum_{1\le k\le K_1} \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{K_1+1\le l\le K}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\le 0\right) \\
&\qquad\qquad + \sum_{K_1+1\le k\le K} \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\max_{1\le l\le K_1}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\ge 0\right)\Bigg] \\
&= \frac{1}{K}\Bigg[\sum_{1\le k\le K_1}\int \mathbb{1}\left(\min_{K_1+1\le l\le K}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\le 0\right)p(\boldsymbol{\varepsilon}) \\
&\qquad\qquad + \sum_{K_1+1\le k\le K}\int \mathbb{1}\left(\max_{1\le l\le K_1}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\ge 0\right)p(\boldsymbol{\varepsilon})\Bigg] \\
&= \frac{1}{K}\int\Bigg[\sum_{1\le k\le K_1} \mathbb{1}\left(\min_{K_1+1\le l\le K}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\le 0\right) \qquad \text{(B.3)} \\
&\qquad\qquad + \sum_{K_1+1\le k\le K} \mathbb{1}\left(\max_{1\le l\le K_1}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\ge 0\right)\Bigg]p(\boldsymbol{\varepsilon})\,, \qquad \text{(B.4)}
\end{aligned}
$$

and if we define the $K_1 \times K_2$ matrix

$$
M_f(\boldsymbol{\varepsilon}) := \left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]_{1\le k\le K_1,\ K_1+1\le l\le K} \qquad \text{(B.5)}
$$

and examine carefully enough, we notice that $\sum_{1\le k\le K}\mathbb{1}\left(\min_{K_1+1\le l\le K}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\le 0\right)$ is the number of rows of $M_f(\boldsymbol{\varepsilon})$ that contains at least one non-positive entry and $\sum_{K_1+1\le k\le K}\mathbb{1}\left(\max_{1\le l\le K_1}\left[f\left(\frac{\boldsymbol{\mu}_k+\boldsymbol{\mu}_l}{2}+\boldsymbol{\varepsilon}\right)\right]\ge 0\right)$ is the number of columns of $M_f(\boldsymbol{\varepsilon})$ that contains at least one non-negative entry. By Lemma 1, we have

$$
\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\le 0\right) \ge \text{(B.4)} \ge \frac{1}{K}\int \min\{K_1,K_2\}p(\boldsymbol{\varepsilon})\,.
$$

Therefore

$$
\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}}{2}\boldsymbol{d}\right)y\right]\le 0\right) \ge \frac{\min\{K_1,K_2\}}{K}\,. \qquad \text{(B.6)}
$$

□

Proof of Lemma 1. We denote $C^*(n,m)$ the minimum value of $a+b$ over all possible choice of $n\times m$ matrices. It suffices to show $C^*(n,m)\ge\min\{n,m\}$ (The equality is obtained by an all-positive matrix when $n\le m$ and an all-negative matrix otherwise), and we prove it by induction.

For $n=1,m=1$, $C^*(n,m)=1$. This is trivial. We need to show that if $C^*(n,m)=\min\{n,m\}$ holds for some n and m, then

- $C^*(n,m+1)=\min\{n,m+1\}$;
- and $C^*(n+1,m)=\min\{n+1,m\}$.

We shall prove these two cases:

Case 1 $C^*(n,m) \geq \min\{n,m\} \Rightarrow C^*(n,m+1) \geq \min\{n,m+1\}$

Given an $n \times m$ matrix $\boldsymbol{M}$ and an agumented matrix $\boldsymbol{M'} = [\boldsymbol{M} \quad \boldsymbol{v}]$, we let a, b and a', b' be the row/column counts of our interest for $\boldsymbol{M}$ and $\boldsymbol{M'}$ respectively. Without loss of generality, we suppose the first a rows of M all contain at least one non-positive entry (and the rest do not, by definition of a). We know that $a + b \geq \min\{n, m\}$, and

$$a' = a + \sum_{i=a+1}^{n} \mathbb{1}(\boldsymbol{v}_i \leq 0), \qquad b' = b + \mathbb{1}(\max_i \boldsymbol{v}_i \geq 0)\,, \tag{B.7}$$

which is

$$a' + b' = a + b + \sum_{i=a+1}^{n} \mathbb{1}(\boldsymbol{v}_i \leq 0) + \mathbb{1}(\max_i \boldsymbol{v}_i \geq 0)\,. \tag{B.8}$$

There are two scenarios:

1. When $a = n$, we have $\sum_{i=a+1}^{n} \mathbb{1}(\boldsymbol{v}_i \leq 0) + \mathbb{1}(\max_i \boldsymbol{v}_i \geq 0) \geq 0$
2. When $a < n$, we have $\sum_{i=a+1}^{n} \mathbb{1}(\boldsymbol{v}_i \leq 0) + \mathbb{1}(\max_i \boldsymbol{v}_i \geq 0) \geq 1\,.$

Therefore, we find that

$$a'+b' \geq \min\{n+b, a+b+1\} \geq \min\{n, \min\{n,m\}+1\} = \min\{n, n+1, m+1\} = \min\{n, m+1\}\,. \tag{B.9}$$

This shows $C^*(n, m+1) \geq \min\{n, m+1\}$.

Case 2 $C^*(n+1,m) \geq \min\{n+1,m\} \Rightarrow C^*(n+1,m) \geq \min\{n+1,m\}$

Given an $n \times m$ matrix $\boldsymbol{M}$ and an agumented matrix $\boldsymbol{M'} = \begin{bmatrix} \boldsymbol{M} \\ \boldsymbol{v} \end{bmatrix}$, we let a, b and a', b' be the row/column counts of our interest for $\boldsymbol{M}$ and $\boldsymbol{M'}$ respectively. Without loss of generality, we suppose the first b columns of M all contain at least one non-negative entry (and the rest do not, by definition of b). We know that $a + b \geq \min\{n, m\}$, and

$$a' = a + \mathbb{1}(\min_i \boldsymbol{v}_i \leq 0), \qquad b' = b + \sum_{i=b+1}^{m} \mathbb{1}(\boldsymbol{v}_i \geq 0)\,, \tag{B.10}$$

which is

$$a' + b' = a + b + \sum_{i=b+1}^{m} \mathbb{1}(\boldsymbol{v}_i \geq 0) + \mathbb{1}(\min_i \boldsymbol{v}_i \leq 0)\,. \tag{B.11}$$

There are two scenarios:

1. When $b = m$, we have $\sum_{i=b+1}^{m} \mathbb{1}(\boldsymbol{v}_i \geq 0) + \mathbb{1}(\min_i \boldsymbol{v}_i \leq 0) \geq 0$
2. When $b < m$, we have $\sum_{i=b+1}^{m} \mathbb{1}(\boldsymbol{v}_i \geq 0) + \mathbb{1}(\min_i \boldsymbol{v}_i \leq 0) \geq 1\,.$

Therefore, we find that

$$a'+b' \geq \min\{a+m, a+b+1\} \geq \min\{m, \min\{n,m\}+1\} = \min\{m, n+1, m+1\} = \min\{n+1, m\}\,. \tag{B.12}$$

This shows $C^*(n+1, m) \geq \min\{n+1, m\}$. □

B.2 Bayes Optimal Classifier w.r.t. 0-1 loss

Our proof will use Hoeffding's inequality for high-dimensional Gaussian vectors

Lemma 2 (Hoeffding inequality)**.** *For any unit vector $\boldsymbol{\mu} \in \mathbb{S}^{D-1}$, we have*

$$\mathbb{P}_{\boldsymbol{\varepsilon} \sim \mathcal{N}\left(0, \frac{\alpha^2}{D}\boldsymbol{I}\right)} \left(|\left\langle \boldsymbol{\mu}, \boldsymbol{\varepsilon} \right\rangle| > t\right) \leq 2\exp\left(-\frac{Dt^2}{2\alpha^2}\right)\,. \tag{B.13}$$

And the concentration result of the norm of high-dimensional Gaussian vectors

Lemma 3. *We have*

$$\mathbb{P}_{\boldsymbol{\varepsilon}\sim\mathcal{N}\left(0,\frac{\alpha^2}{D}\boldsymbol{I}\right)}\left(\|\boldsymbol{\varepsilon}\|>t\right)\leq 4\exp\left(-\frac{t^2}{8\alpha^2}\right), \tag{B.14}$$

Theorem 2 (Restated)**.** *The Bayes optimal classifier for label Y given observation $\boldsymbol{x}$ w.r.t. 0-1 loss is* $\operatorname{sign}\left(f^*(\boldsymbol{x})\right)$*, where* $f^*(\boldsymbol{x})=\sum_{k=1}^{K_1}\exp\left(\frac{D\langle\boldsymbol{x},\boldsymbol{\mu}_k\rangle}{\alpha^2}\right)-\sum_{k=K_1+1}^{K}\exp\left(\frac{D\langle\boldsymbol{x},\boldsymbol{\mu}_k\rangle}{\alpha^2}\right)$ *. Moreover, given a sample $(\boldsymbol{x},y)\sim\mathcal{D}_{X,Y}$, we have, for any* $\frac{2\sqrt{2}\alpha^2\log K}{D}\leq\nu\leq\sqrt{2}$*,*

$$\mathbb{P}_{(\boldsymbol{x},y)\sim\mathcal{D}_{X,Y}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f^*\left(\boldsymbol{x}+\frac{\sqrt{2}-\nu}{2}\boldsymbol{d}\right)y\right]>0\right)\geq 1-2K\exp\left(-\frac{D\nu^2}{64\alpha^2}\right). \tag{B.15}$$

Proof. **Bayes optimal classifier for $\mathcal{D}_{X,Y}$** The Bayes optimal classifier w.r.t. 0-1 loss is given by

$$\begin{aligned}
f^*(\boldsymbol{x}) &= \arg\max_y \mathbb{P}\left(Y=y\mid X=\boldsymbol{x}\right)\\
&= \arg\max_y \sum_{k=1}^{K}\mathbb{P}\left(Y=y\mid Z=k,X=\boldsymbol{x}\right)\mathbb{P}\left(Z=k\mid X=\boldsymbol{x}\right)\\
&= \begin{cases}1, & \text{if } \sum_{k=1}^{K_1}\mathbb{P}\left(Z=k\mid X=\boldsymbol{x}\right)>\sum_{k=K_1+1}^{K}\mathbb{P}\left(Z=k\mid X=\boldsymbol{x}\right)\\ -1, & \text{o.w.}\end{cases}\\
&= \operatorname{sign}\left(\sum_{k=1}^{K_1}\mathbb{P}\left(Z=k\mid X=\boldsymbol{x}\right)-\sum_{k=K_1+1}^{K}\mathbb{P}\left(Z=k\mid X=\boldsymbol{x}\right)\right).
\end{aligned} \tag{B.16}$$

Bayes rule and a few derivations give:

$$\begin{aligned}
\mathbb{P}\left(Z=k\mid X=\boldsymbol{x}\right) &= \frac{\mathbb{P}\left(X=\boldsymbol{x}\mid Z=k\right)\mathbb{P}\left(Z=k\right)}{\sum_{l=1}^{K}\mathbb{P}\left(X=\boldsymbol{x}\mid Z=l\right)\mathbb{P}\left(Z=l\right)}\\
&= \frac{\exp\left(-\frac{D\|\boldsymbol{x}-\boldsymbol{\mu}_k\|^2}{2\alpha^2}\right)}{\sum_{l=1}^{K}\exp\left(-\frac{D\|\boldsymbol{x}-\boldsymbol{\mu}_l\|^2}{2\alpha^2}\right)}\\
&= \frac{\exp\left(-\frac{D(\|\boldsymbol{x}\|^2-2\langle\boldsymbol{x},\boldsymbol{\mu}_k\rangle+\|\boldsymbol{\mu}_k\|^2))}{2\alpha^2}\right)}{\sum_{l=1}^{K}\exp\left(-\frac{D(\|\boldsymbol{x}\|^2-2\langle\boldsymbol{x},\boldsymbol{\mu}_l\rangle+\|\boldsymbol{\mu}_l\|^2)}{2\alpha^2}\right)}=\frac{\exp\left(\frac{D\langle\boldsymbol{x},\boldsymbol{\mu}_k\rangle}{\alpha^2}\right)}{\sum_{l=1}^{K}\exp\left(\frac{D\langle\boldsymbol{x},\boldsymbol{\mu}_l\rangle}{\alpha^2}\right)}.
\end{aligned} \tag{B.17}$$

Combining (B.16) and (B.17), we have

$$f^*(\boldsymbol{x})=\operatorname{sign}\left(\sum_{k=1}^{K_1}\exp\left(\frac{D\left\langle\boldsymbol{x},\boldsymbol{\mu}_k\right\rangle}{\alpha^2}\right)-\sum_{k=K_1+1}^{K}\exp\left(\frac{D\left\langle\boldsymbol{x},\boldsymbol{\mu}_k\right\rangle}{\alpha^2}\right)\right). \tag{B.18}$$

Robustness of f^*. We now proceed to show that f^* is robust near-optimally. Since

$$\begin{aligned}
&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f^*\left(\boldsymbol{x}+\frac{\sqrt{2}-\nu}{2}\boldsymbol{d}\right)y\right]\leq 0\right)\\
&=\sum_{k=1}^{K}\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f^*\left(\boldsymbol{x}+\frac{\sqrt{2}-\nu}{2}\boldsymbol{d}\right)y\right]\leq 0\,\middle|\, z=k\right)\mathbb{P}\left(z=k\right),
\end{aligned}$$

It suffices to show that $\forall 1\leq k\leq K$

$$\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f^*\left(\boldsymbol{x}+\frac{\sqrt{2}-\nu}{2}\boldsymbol{d}\right)y\right]\leq 0\,\middle|\, z=k\right)\leq K\exp\left(-\frac{CD\nu^2}{16\alpha^2}\right). \tag{B.19}$$

When $k\leq K_1$, we have

$$\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f^*\left(\boldsymbol{x}+\frac{\sqrt{2}-\nu}{2}\boldsymbol{d}\right)y\right]\leq 0\,\middle|\, z=k\right)$$

$$
\begin{aligned}
&= \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[f^*\left(\boldsymbol{x}+\frac{\sqrt{2}-\nu}{2}\boldsymbol{d}\right)\right]\le 0\right)\\
&= \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[\exp\left(\frac{D}{\alpha^2}\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)\right)\right.\right.\\
&\qquad\qquad + \sum_{l\neq k,1\le l\le K_1}\exp\left(\frac{D}{\alpha^2}\left(\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle\right)\right)\\
&\qquad\qquad \left.\left. - \sum_{K_1+1\le l\le K}\exp\left(\frac{D}{\alpha^2}\left(\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle\right)\right)\right]\le 0\right)\\
&\le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[\exp\left(\frac{D}{\alpha^2}\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)\right)\right.\right.\\
&\qquad\qquad \left.\left. - \sum_{K_1+1\le l\le K}\exp\left(\frac{D}{\alpha^2}\left(\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle\right)\right)\right]\le 0\right)\\
&\le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[\exp\left(\frac{D}{\alpha^2}\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)\right)\right.\right.\\
&\qquad\qquad \left.\left. - \sum_{K_1+1\le l\le K}\exp\left(\frac{D}{\alpha^2}\left(|\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle|+\frac{\sqrt{2}-\nu}{2}|\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle|\right)\right)\right]\le 0\right)\\
&\le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[\exp\left(\frac{D}{\alpha^2}\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)\right)\right.\right.\\
&\qquad\qquad \left.\left. - K_2\exp\left(\frac{D}{\alpha^2}\left(\max_{K_1+1\le l\le K}|\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle|+\frac{\sqrt{2}-\nu}{2}\max_{K_1+1\le l\le K}|\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle|\right)\right)\right]\le 0\right)\\
&\le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right.\right.\\
&\qquad\qquad \left.\left. - \frac{\alpha^2}{D}\log K_2 - \max_{K_1+1\le l\le K}|\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle| - \frac{\sqrt{2}-\nu}{2}\max_{K_1+1\le l\le K}|\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle|\right]\le 0\right)\\
&\le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[1+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle - \frac{\sqrt{2}-\nu}{2}\max_{K_1+1\le l\le K}|\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle|\right]\right.\\
&\qquad\qquad \left. - \frac{\alpha^2}{D}\log K_2 - |\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle| - \max_{K_1+1\le l\le K}|\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle|\le 0\right), \quad \text{(B.20)}
\end{aligned}
$$

Since

$$
\begin{aligned}
&\min_{\|\boldsymbol{d}\|\le 1}\left[1+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle - \frac{\sqrt{2}-\nu}{2}\max_{K_1+1\le l\le K}|\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle|\right]\\
&\ge \min_{\|\boldsymbol{d}\|\le 1}\left[1+\frac{\sqrt{2}-\nu}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle - \frac{\sqrt{2}-\nu}{2}\sqrt{\sum_{K_1+1\le l\le K}|\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle|^2}\right]\\
&\ge \min_{\|\boldsymbol{d}\|\le 1}\left[1-\frac{\sqrt{2}-\nu}{2}\sqrt{2}\sqrt{|\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle|^2+\sum_{K_1+1\le l\le K}|\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle|^2}\right] \ge \min_{\|\boldsymbol{d}\|\le 1}\left[1-\frac{\sqrt{2}-\nu}{\sqrt{2}}\|\boldsymbol{d}\|\right] = \frac{\nu}{\sqrt{2}},
\end{aligned}
$$

we finally have

$$
\text{(B.20)} \le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\frac{\nu}{\sqrt{2}} - \frac{\alpha^2}{D}\log K_2 - |\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle| - \max_{K_1+1\le l\le K}|\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle|\le 0\right)
$$

$$\leq \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\frac{\nu}{2\sqrt{2}} - 2\max_{1\leq l\leq K}|\langle \boldsymbol{\mu}_l, \boldsymbol{\varepsilon}\rangle| \leq 0\right)$$

$$\leq K\mathbb{P}_{\boldsymbol{\varepsilon}}\left(|\langle \boldsymbol{\mu}_1, \boldsymbol{\varepsilon}\rangle| \geq \frac{\nu}{4\sqrt{2}}\right) \leq 2K\exp\left(-\frac{D\nu^2}{64\alpha^2}\right). \tag{B.21}$$

The proof for the case $k \geq K_1 + 1$ is almost identical. □

C PRELU CONVERGES TO OPTIMAL ℓ_2-ROBUST CLASSIFIER, PART ONE: CONVERGENCE IMPLIES ROBUSTNESS

We prove Proposition 1 here.

Proposition 1 (Restated). *Given a classifier f that satisfies $f(\gamma \boldsymbol{x}) = \gamma f(\boldsymbol{x}), \forall \boldsymbol{x} \in \mathbb{R}^D$, $\forall \gamma > 0$ and $\operatorname{dist}(f, F^{(p)}) = \inf_{c>0} \sup_{\boldsymbol{x} \in \mathbb{S}^{D-1}} |cf(\boldsymbol{x}) - F^{(p)}(\boldsymbol{x})| \leq \nu$ for some $p > 2$ and $0 < \nu \leq \left(\frac{\sqrt{2}}{8}\right)^p$. Then for a sample $(\boldsymbol{x}, y) \sim \mathcal{D}_{X,Y}$, we have*

$$\mathbb{P}_{(\boldsymbol{x},y)\sim\mathcal{D}_{X,Y}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]>0\right)\geq 1-2K\exp\left(-\frac{D\nu^{\frac{2}{p}}}{2K^2\alpha^2}\right)-4\exp\left(-\frac{3}{8\alpha^2}\right). \tag{C.1}$$

Proof. First of all, since $f(\gamma \boldsymbol{x}) = \gamma f(\boldsymbol{x}), \forall \boldsymbol{x} \in \mathbb{R}^D, \forall \gamma > 0$ and the same holds for $F^{(p)}(\cdot)$, we suppose the infimum is attained at $c^* \geq 0$, then

$$\sup_{\boldsymbol{x}\in\mathbb{R}^D} |c^* f(\boldsymbol{x}) - F^{(p)}(\boldsymbol{x})| = \sup_{\boldsymbol{x}\in\mathbb{R}^D} \left| c^* f\left(\frac{\boldsymbol{x}}{\|\boldsymbol{x}\|}\right) - F^{(p)}\left(\frac{\boldsymbol{x}}{\|\boldsymbol{x}\|}\right)\right| \|\boldsymbol{x}\| \leq \|\boldsymbol{x}\|\nu\,, \tag{C.2}$$

where the last inequality uses $\operatorname{dist}(f, F^{(p)}) \leq \nu$. With (C.2), we have

$$\begin{aligned}
&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[f\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 0\right)\\
\leq&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[c^*f\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 0\right)\\
=&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[c^*f\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y-F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y+F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 0\right)\\
\leq&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]-\max_{\|\boldsymbol{d}\|\leq 1}\left|c^*f\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y-F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right|\leq 0\right)\\
\leq&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]-\max_{\|\boldsymbol{z}\|^2\leq 9}\left|c^*f\left(\boldsymbol{z}\right)y-F^{(p)}\left(\boldsymbol{z}\right)y\right|\leq 0,\ \|\boldsymbol{x}\|^2\leq\frac{17}{2}\right)+\mathbb{P}\left(\|\boldsymbol{x}\|^2>\frac{17}{2}\right)\\
\leq&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]-\max_{\|\boldsymbol{z}\|^2\leq 9}\left|c^*f\left(\boldsymbol{z}\right)y-F^{(p)}\left(\boldsymbol{z}\right)y\right|\leq 0\right)+\mathbb{P}\left(\|\boldsymbol{x}\|^2>\frac{17}{2}\right)\\
\leq&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 3\nu\right)+\mathbb{P}\left(\|\boldsymbol{x}\|^2>\frac{17}{2}\right).
\end{aligned}$$

The second term $\mathbb{P}\left(\|\boldsymbol{x}\|^2 > \frac{17}{2}\right)$ is easy to bound, our focus is to show

$$\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 3\nu\right)\geq 2(K+1)\exp\left(-\frac{CD\nu^2}{K^2\alpha^2}\right), \tag{C.3}$$

which resembles the result in Min & Vidal (2024, Theorem 1), but one can not directly obtain (C.3) from this existing result. Nonetheless, we can partially follow Min & Vidal (2024, Theorem 1)'s proof and obtain (C.3) (with non-trivial new derivations), as shown below:

Since

$$\begin{aligned}
&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 3\nu\right)\\
=&\sum_{k=1}^{K}\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 3\nu\middle| z=k\right)\mathbb{P}\left(z=k\right),
\end{aligned}$$

It suffices to show that $\forall 1 \leq k \leq K$

$$\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 3\nu\middle| z=k\right)\leq 2(K_2+2)\exp\left(-\frac{CD\delta^2}{2(K_2+1)^2\alpha^2}\right). \tag{C.4}$$

When $k \leq K_1$, we have

$$\begin{aligned}
&\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 3\nu\middle| z=k\right)\\
&=\mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[F^{(p)}\left(\boldsymbol{x}+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right]\leq 3\nu\right)\\
&=\mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[\sigma^p\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)\right.\right.\\
&\qquad\qquad+\sum_{l\neq k,1\leq l\leq K_1}\sigma^p\left(\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle\right)\\
&\qquad\qquad\left.\left.-\sum_{K_1+1\leq l\leq K}\sigma^p\left(\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle\right)\right]\leq 3\nu\right)\\
&\leq\mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[\sigma^p\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)\right.\right.\\
&\qquad\qquad\left.\left.-\sum_{K_1+1\leq l\leq K}\sigma^p\left(\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle\right)\right]\leq 3\nu\right)
\end{aligned}\tag{C.5}$$

We define the event

$$\mathcal{E}:=\left\{1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\geq 0,\forall d\in\mathbb{S}^{D-1}\right\}, \tag{C.6}$$

Then, by Min & Vidal (2024, Lemma 2),

$$\begin{aligned}
\text{(C.5)}\ &=\mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[\sigma^p\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)\right.\right.\\
&\qquad\qquad\left.\left.-\sum_{K_1+1\leq l\leq K}\sigma^p\left(\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle\right)\right]\leq 3\nu\right)\\
&\leq\ \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[\sigma^p\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)\right.\right.\\
&\qquad\qquad\left.\left.-\sum_{K_1+1\leq l\leq K}\sigma^p\left(\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_l\rangle\right)\right]\leq 3\nu,\mathcal{E}\right)+\mathbb{P}\left(\mathcal{E}^c\right)
\end{aligned}\tag{C.7}$$

Since under event $\mathcal{E}$, we have $\sigma^p\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)=\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)^p$, we can proceed with

$$\text{(C.7)}=\mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\leq 1}\left[\left(1+\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}\rangle+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle\boldsymbol{d},\boldsymbol{\mu}_k\rangle\right)^p\right.\right.$$

$$
\begin{aligned}
&\quad - \sum_{K_1+1\le l\le K} \sigma^p\left(\langle \boldsymbol{\mu}_l, \boldsymbol{\varepsilon}\rangle + \frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle \boldsymbol{d}, \boldsymbol{\mu}_l\rangle\right)\Bigg] \le 3\nu, \mathcal{E}\Bigg) + \mathbb{P}\left(\mathcal{E}^c\right) \\
&\le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[\left(1+\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle + \frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle \boldsymbol{d}, \boldsymbol{\mu}_k\rangle\right)^p \right.\right. \\
&\qquad\qquad \left.\left. - \sum_{K_1+1\le l\le K}\left(|\langle \boldsymbol{\mu}_l, \boldsymbol{\varepsilon}\rangle| + \frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}|\langle \boldsymbol{d}, \boldsymbol{\mu}_l\rangle|\right)^p - 3\nu\right] < 0, \mathcal{E}\right) + \mathbb{P}\left(\mathcal{E}^c\right) \\
&\le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[1+\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle + \frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle \boldsymbol{d}, \boldsymbol{\mu}_k\rangle \right.\right. \\
&\qquad\qquad \left.\left. - \left(\sum_{K_1+1\le l\le K}\left(|\langle \boldsymbol{\mu}_l, \boldsymbol{\varepsilon}\rangle| + \frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}|\langle \boldsymbol{d}, \boldsymbol{\mu}_l\rangle|\right)^p + 3\nu\right)^{1/p}\right] < 0, \mathcal{E}\right) + \mathbb{P}\left(\mathcal{E}^c\right) \\
&\le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\underbrace{\min_{\|\boldsymbol{d}\|\le 1}\left[1+\frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\langle \boldsymbol{d}, \boldsymbol{\mu}_k\rangle - \frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\left(\sum_{K_1+1\le l\le K}|\langle \boldsymbol{d}, \boldsymbol{\mu}_l\rangle|^p\right)^{1/p}\right]}_{:=M^*(\nu)} \right. \\
&\qquad\qquad \left. - \left(\sum_{K_1+1\le l\le K}(|\langle \boldsymbol{\mu}_l, \boldsymbol{\varepsilon}\rangle|)^p + 3\nu\right)^{1/p} - |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle| < 0, \mathcal{E}\right) + \mathbb{P}\left(\mathcal{E}^c\right) \\
&\le \mathbb{P}_{\boldsymbol{\varepsilon}}\left(M^*(\nu) - \sum_{K_1+1\le l\le K}|\langle \boldsymbol{\mu}_l, \boldsymbol{\varepsilon}\rangle| - (3\nu)^{\frac{1}{p}} - |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle| < 0\right) + \mathbb{P}\left(\mathcal{E}^c\right), \qquad \text{(C.8)}
\end{aligned}
$$

From the proof of Min & Vidal (2024, Theorem 1), we have $M^*(\nu) = 4\sqrt{2}\nu^{\frac{1}{p}}$. Therefore we have

$$
\begin{aligned}
\text{(C.8)} &= \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\sum_{K_1+1\le l\le K}|\langle \boldsymbol{\mu}_l, \boldsymbol{\varepsilon}\rangle| + |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle| > M^*(\nu) - (3\nu)^{\frac{1}{p}}\right) + \mathbb{P}\left(\mathcal{E}^c\right) \\
&\ge \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\sum_{K_1+1\le l\le K}|\langle \boldsymbol{\mu}_l, \boldsymbol{\varepsilon}\rangle| + |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle| > \left(4\sqrt{2}-3^{\frac{1}{p}}\right)\nu^{\frac{1}{p}}\right) + \mathbb{P}\left(\mathcal{E}^c\right) \\
&\ge \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\sum_{K_1+1\le l\le K}|\langle \boldsymbol{\mu}_l, \boldsymbol{\varepsilon}\rangle| + |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle| > \sqrt{2}\nu^{\frac{1}{p}}\right) + \mathbb{P}\left(\mathcal{E}^c\right) \\
&\ge \mathbb{P}_{\boldsymbol{\varepsilon}}\left(\max_{1\le k\le K}|\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle| > \frac{\sqrt{2}\nu^{\frac{1}{p}}}{K}\right) + \mathbb{P}\left(\mathcal{E}^c\right) \\
&\ge K\mathbb{P}_{\boldsymbol{\varepsilon}}\left(|\langle \boldsymbol{\mu}_1, \boldsymbol{\varepsilon}\rangle| > \frac{\sqrt{2}\nu^{\frac{1}{p}}}{K}\right) + \mathbb{P}\left(\mathcal{E}^c\right) \ge 2K\exp\left(-\frac{D\nu^{\frac{2}{p}}}{K^2\alpha^2}\right) + \mathbb{P}\left(\mathcal{E}^c\right).
\end{aligned}
$$

Therefore, we have

$$
\mathbb{P}\left(\min_{\|\boldsymbol{d}\|\le 1}\left[f\left(\boldsymbol{x} + \frac{\sqrt{2}-8\nu^{\frac{1}{p}}}{2}\boldsymbol{d}\right)y\right] \le 0\right) \le 2K\exp\left(-\frac{D\nu^{\frac{2}{p}}}{K^2\alpha^2}\right) + \mathbb{P}\left(\mathcal{E}^c\right) + \mathbb{P}\left(\|\boldsymbol{x}\|^2 > \frac{3}{2}\right).
$$

Finally, by

$$
\mathbb{P}\left(\mathcal{E}^c\right) \le \mathbb{P}\left(|\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle| \ge 1 - \frac{\sqrt{2}}{2}\right) \le \mathbb{P}\left(|\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}\rangle| \ge \frac{2}{5}\right) \le 2\exp\left(-\frac{2D}{25\alpha^2}\right)
$$

$$\mathbb{P}\left(\|\boldsymbol{x}\|^2 > \frac{17}{2}\right) \leq \mathbb{P}\left(\|\boldsymbol{\varepsilon}\| \geq \sqrt{\frac{17}{2}} - 1\right) \leq 4\exp\left(-\left(\sqrt{\frac{17}{2}} - 1\right)^2 \frac{1}{8\alpha^2}\right) \leq 4\exp\left(-\frac{3}{8\alpha^2}\right),$$

The proof is finished, notice that the bad event $\|\boldsymbol{x}\|^2 > \frac{17}{2}$ is chosen arbitrarily, so one can derive more general results by letting the results depend on the choice of a bad event. But for our purpose, we do not need it. □

D PRELU CONVERGES TO OPTIMAL ℓ_2-ROBUST CLASSIFIER, PART TWO: BASIC RESULTS ON NEURON DYNAMICS AND GOOD EVENTS

In this and the following sections, we let $\ell_i(t) := \ell(y_i, f^{(p)}(\boldsymbol{x}_i; \boldsymbol{\theta}(t)))$ denote the loss on data point $(\boldsymbol{x}_i, y_i)$, and $\nabla_{\hat{y}}\ell_i$ denotes the derivation of ℓ_i w.r.t. its second argument, the network output. Moreover, we let $c_{kj} := \cos(\boldsymbol{\mu}_i, \boldsymbol{w}_j(t))$ denote the cosine angle between cluster center $\boldsymbol{\mu}_k$ and neuron $\boldsymbol{w}_j$. Note: For simplicity, we drop the time dependence in $\boldsymbol{\theta}(t), v_j(t), \boldsymbol{w}_j(t), \mathcal{L}(t), \ell_i(t), c_{kj}(t)$ and write $\boldsymbol{\theta}, v_j, \boldsymbol{w}_j, \mathcal{L}, \ell_i, c_{kj}$ whenever it is clear that they come from the GF solution thus depend on time. Note: **It suffices to prove the case $\alpha = \alpha_0$, we thus use α to both denote the intra-class variance and the α_0 we use to control the order of all the relevant quantities in our proofs.**

We also let $\mathcal{I}_k := \{i : (k-1)N + 1 \le i \le kN\}$, the index set of data sampled from k-th cluster.

D.1 RESULTS ON NEURON DYNAMICS

Neuron dynamics: Under GF, we have

$$\begin{aligned}\frac{d}{dt}\boldsymbol{w}_j =& -\frac{1}{N}\sum_{i=1}^{KN}\nabla_{\hat{y}}\ell_i\, v_j\left(\frac{p[\sigma(\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle)]^{p-1}}{\|\boldsymbol{w}_j\|^{p-1}}\boldsymbol{x}_i - (p-1)\frac{[\sigma(\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle)]^p}{\|\boldsymbol{w}_j\|^{p+1}}\boldsymbol{w}_j\right)\\ =& -\frac{1}{N}\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0}\nabla_{\hat{y}}\ell_i\, v_j\left(\frac{p[\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle]^{p-1}}{\|\boldsymbol{w}_j\|^{p-1}}\boldsymbol{x}_i - (p-1)\frac{[\langle \boldsymbol{x}_k, \boldsymbol{w}_j\rangle]^p}{\|\boldsymbol{w}_j\|^{p+1}}\boldsymbol{w}_j\right)\end{aligned}$$

and similarly,

$$\frac{d}{dt}v_j = -\frac{1}{N}\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0}\nabla_{\hat{y}}\ell_i\frac{[\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle]^p}{\|\boldsymbol{w}_j\|^{p-1}}$$

Balancedness: We compute

$$\begin{aligned}\frac{d}{dt}(\boldsymbol{w}_j^\top \boldsymbol{w}_j) =& \ 2\left\langle \frac{d}{dt}\boldsymbol{w}_j, \boldsymbol{w}_j\right\rangle\\ =& -\frac{1}{N}\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0}\nabla_{\hat{y}}\ell_i\, v_j\left(\frac{p[\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle]^p}{\|\boldsymbol{w}_j\|^{p-1}} - (p-1)\frac{[\langle \boldsymbol{x}_k, \boldsymbol{w}_j\rangle]^p}{\|\boldsymbol{w}_j\|^{p-1}}\right)\\ =& -\frac{2}{N}\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0}\nabla_{\hat{y}}\ell_i\, v_j\frac{[\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle]^p}{\|\boldsymbol{w}_j\|^{p-1}},\end{aligned}$$

and

$$\frac{d}{dt}v_j^2 = 2\, v_j\frac{d}{dt}v_j = -\frac{2}{N}\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0}\nabla_{\hat{y}}\ell_i\, v_j\frac{[\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle]^p}{\|\boldsymbol{w}_j\|^{p-1}}$$

Therefore, we have

$$\frac{d}{dt}(\boldsymbol{w}_j^\top \boldsymbol{w}_j - v_j^2) \equiv 0\,, \tag{D.1}$$

thus $\boldsymbol{w}_j^\top(t)\boldsymbol{w}_j(t) - v_j^2(t) = \boldsymbol{w}_j^\top(0)\boldsymbol{w}_j(0) - v_j^2(0), \forall t$, since we have a balanced initialization such that $\boldsymbol{w}_j^\top(0)\boldsymbol{w}_j(0) - v_j^2(0), \forall j$. Such balancedness holds for all time t. Using this balancedness $v_j^2 \equiv \|\boldsymbol{w}_j\|^2, \forall j \in [h]$, we can write

$$\frac{d}{dt}\boldsymbol{w}_j = -\frac{\mathrm{sign}(v_j(0))}{N}\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0}\nabla_{\hat{y}}\ell_i\,\|\boldsymbol{w}_j\|\left(p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\boldsymbol{x}_i - (p-1)\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right), \tag{D.2}$$

where we use that $\mathrm{sign}(v_j(t)) = \mathrm{sign}(v_j(0))$, which is another consequence of balancedness Boursier et al. (2022); Min et al. (2024). We will study the dynamics of $\boldsymbol{w}_j$ from now on, and one can write the time derivatives of the norm and direction of these neurons:

Neuron norm dynamics:

$$
\begin{aligned}
&\frac{d}{dt}\|\boldsymbol{w}_j\|^2 \\
&= 2\left\langle \boldsymbol{w}_j, \frac{d}{dt}\boldsymbol{w}_j \right\rangle \\
&= -2\,\frac{\operatorname{sign}(v_j(0))}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \,\|\boldsymbol{w}_j\| \left(p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1} \langle \boldsymbol{w}_j, \boldsymbol{x}_i\rangle - (p-1)\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p} \|\boldsymbol{w}_j\| \right) \\
&= -2\,\frac{\operatorname{sign}(v_j(0))}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_k \,\|\boldsymbol{w}_j\| \left(p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p} \|\boldsymbol{w}_j\| - (p-1)\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p} \|\boldsymbol{w}_j\| \right) \\
&= -2\,\frac{\operatorname{sign}(v_j(0))}{N} \left(\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \,\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p} \right) \|\boldsymbol{w}_j\|^2 \qquad \text{(D.3)}
\end{aligned}
$$

Neuron angular dynamics:

$$
\begin{aligned}
&\frac{d}{dt}\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \\
&= \left(I - \frac{\boldsymbol{w}_j\boldsymbol{w}_j^\top}{\|\boldsymbol{w}_j\|^2}\right)\frac{1}{\|\boldsymbol{w}_j\|}\frac{d}{dt}\boldsymbol{w}_j \\
&= -\frac{\operatorname{sign}(v_j(0))}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \,\left(I - \frac{\boldsymbol{w}_j\boldsymbol{w}_j^\top}{\|\boldsymbol{w}_j\|^2}\right) \left(p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1} \boldsymbol{x}_i - (p-1)\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p} \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right) \\
&= -\frac{\operatorname{sign}(v_j(0))}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \, p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1} \left(\boldsymbol{x}_i - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right). \qquad \text{(D.4)}
\end{aligned}
$$

Finally, from the directional dynamics $\frac{d}{dt}\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}$, we obtain

$$
\begin{aligned}
\frac{d}{dt}c_{kj} &= \left\langle \boldsymbol{\mu}_k, \frac{d}{dt}\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \\
&= -\frac{\operatorname{sign}(v_j(0))}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \, p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1} \left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i\rangle - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj} \right), \qquad \text{(D.5)}
\end{aligned}
$$

and whenever $|c_{kj}| \neq 0$, we have

$$
\begin{aligned}
&\frac{d}{dt}\log|c_{kj}| \\
&= \frac{1}{c_{kj}}\frac{d}{dt}c_{kj} \\
&= -\frac{\operatorname{sign}(v_j(0))}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \, p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1} \left(\frac{\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i\rangle}{c_{kj}} - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle \right) \qquad \text{(D.6)}
\end{aligned}
$$

Our proof has the same structure as prior works Boursier et al. (2022); Min et al. (2024): We will study neuron's angular dynamics (D.5) at the early phase (alignment phase) of the GF training, and then study neuron's norm dynamics (D.3) at the later phase (convergence phase).

Lastly, in order to prove Lemma 7 and Proposition 2 in the next subsection, we need the following:

We let $\{\boldsymbol{\mu}_{K+1}, \cdots, \boldsymbol{\mu}_D\}$ be an orthonormal basis for the subspace that is orthogonal to span$\{\boldsymbol{\mu}_1, \cdots, \boldsymbol{\mu}_K\}$, and we can define $c_{kj} = \cos(\boldsymbol{\mu}_k, \boldsymbol{w}_j), k = K+1, \cdots, D$. Since $\{\boldsymbol{\mu}_1, \cdots, \boldsymbol{\mu}_D\}$

forms an orthonormal basis for the ambient space $\mathbb{R}^D$, we have

$$\sum_{k=1}^{D} c_{kj}^2 = \sum_{k=1}^{D} \left| \left\langle \boldsymbol{\mu}_k, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right|^2 = 1\,. \tag{D.7}$$

Moreover, we can write the same time-derivatives $\frac{d}{dt}c_{kj}$, $\frac{d}{dt}\log|c_{kj}|$ for $c_{kj} = \cos(\boldsymbol{\mu}_k, \boldsymbol{w}_j), k = K+1, \cdots, D$ as in (D.5) and (D.6), respectively.

Lastly, the following inequality will be used frequently in our proof:

$$\sum_{l\neq k} c_{lj}^p \leq \sum_{1\leq l\leq D, l\neq k} |c_{lj}|^p \leq \left(\sum_{1\leq l\leq D, l\neq k} c_{lj}^2 \right)^{\frac{p}{2}} = \left(1 - c_{kj}^2\right)^{\frac{p}{2}} \tag{D.8}$$

Note: The sum operation $\sum_{l\neq k}$ implicitly assumes $l \leq K$. We will explicitly indicate the range of l if it can take values between $K+1$ and D.

D.2 Good Event

For a balanced dataset $\hat{\mathcal{D}} = \{\boldsymbol{x}_i, y_i\}_{i=1}^{KN}$, notice that $\boldsymbol{x}_i = \boldsymbol{\mu}_{\lceil \frac{i}{N} \rceil} + \boldsymbol{\varepsilon}_i$ for some $\boldsymbol{\varepsilon}_i \in \mathcal{N}\left(0, \frac{\alpha^2}{D}\boldsymbol{I}\right)$. We define the following good event w.r.t. these $\boldsymbol{\varepsilon}_i$s and show that they happen with high probability:

Lemma 4. *We define the event $\mathcal{E}_{good}$ when the following happens:*

1. $\|\boldsymbol{\varepsilon}_i\| \leq \sqrt{8\log\frac{16KN}{\delta}}\alpha,\ \forall 1 \leq i \leq KN;$
2. $|\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i \rangle| \leq \sqrt{2\log\frac{8K^2N}{\delta}}\frac{\alpha}{\sqrt{D}},\ \forall 1 \leq i \leq KN, 1 \leq k \leq K;$
3. $\|\sum_{i\in\mathcal{I}_k} \boldsymbol{\varepsilon}_i\| \leq \sqrt{2\log\frac{8K}{\delta}}\alpha\sqrt{N},\ \forall 1 \leq k \leq K$
4. $\sum_{i\in\mathcal{I}_k} \|\boldsymbol{\varepsilon}_i\|^2 \leq 8\log\frac{16K}{\delta}\alpha^2 N,\ \forall 1 \leq k \leq K$

We have $\mathbb{P}(\mathcal{E}_{good}) \geq 1-\delta$. Furthermore, for simplicity, we write

1. $\|\boldsymbol{\varepsilon}_i\| \leq C\sqrt{\log\frac{K^2N}{\delta}}\alpha,\ \forall 1 \leq i \leq KN;$
2. $|\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i \rangle| \leq C\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}},\ \forall 1 \leq i \leq KN, 1 \leq k \leq K;$
3. $\|\sum_{i\in\mathcal{I}_k} \boldsymbol{\varepsilon}_i\| \leq C\sqrt{\log\frac{K}{\delta}}\alpha\sqrt{N},\ \forall 1 \leq k \leq K;$
4. $\sum_{i\in\mathcal{I}_k} \|\boldsymbol{\varepsilon}_i\|^2 \leq C\log\frac{K}{\delta}\alpha^2 N,\ \forall 1 \leq k \leq K\,,$

for some universal constant $C > 0$.

Proof. We proof relavent probabilities one by one:

1. By Lemma 3, we have
$$\mathbb{P}(\|\boldsymbol{\varepsilon}_i\| \geq t) \leq 4\exp\left(-\frac{t^2}{8\alpha^2}\right)\,. \tag{D.9}$$
2. By Lemma 2, we have
$$\mathbb{P}(|\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i \rangle| \geq t) \leq 2\exp\left(-\frac{Dt^2}{2\alpha^2}\right)\,. \tag{D.10}$$

3. Apply Lemma 3 to the vector $\sum_{i\in\mathcal{I}_k}\boldsymbol{\varepsilon}_i$, we have

$$\mathbb{P}\left(\left\|\sum_{i\in\mathcal{I}_k}\boldsymbol{\varepsilon}_i\right\|\geq t\right)\leq 4\exp\left(-\frac{t^2}{8N\alpha^2}\right). \tag{D.11}$$

4. Apply Lemma 3 to the vector that is the concatenation of all $\boldsymbol{\varepsilon}_i,\ i\in\mathcal{N}_k$ and notice that its norm is equal to $\sqrt{\sum_{i\in\mathcal{I}_k}\|\boldsymbol{\varepsilon}_i\|^2}$, hence

$$\mathbb{P}\left(\sum_{i\in\mathcal{I}_k}\|\boldsymbol{\varepsilon}_i\|^2\geq t^2\right)\leq 4\exp\left(-\frac{t^2}{8N\alpha^2}\right). \tag{D.12}$$

Therefore,

$$\mathbb{P}\left(\|\boldsymbol{\varepsilon}_i\|\geq\sqrt{8\log\frac{16KN}{\delta}}\alpha\right)\leq\frac{\delta}{4KN}, \qquad \forall 1\leq i\leq KN,$$

$$\mathbb{P}\left(|\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle|\geq\sqrt{2\log\frac{8K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}\right)\leq\frac{\delta}{4K^2N}, \qquad \forall 1\leq i\leq KN, 1\leq k\leq K,$$

$$\mathbb{P}\left(\left\|\sum_{i\in\mathcal{I}_k}\boldsymbol{\varepsilon}_i\right\|\geq\sqrt{8\log\frac{16K}{\delta}}\alpha\sqrt{N}\right)\leq\frac{\delta}{4K}, \qquad \forall 1\leq k\leq K,$$

$$\mathbb{P}\left(\sum_{i\in\mathcal{I}_k}\|\boldsymbol{\varepsilon}_i\|^2\geq 8\log\frac{16K}{\delta}\alpha^2N\right)\leq 4\exp\left(-\frac{t^2}{8N\alpha^2}\right)\leq\frac{\delta}{4K}, \qquad \forall 1\leq k\leq K.$$

The union bound shows that $\mathbb{P}\left(\mathcal{E}_{good}\right)\leq 1-\delta$. □

E PRELU CONVERGES TO OPTIMAL ℓ_2-ROBUST CLASSIFIER, PART THREE: ALIGNMENT PHASE

E.1 AUXILIARY LEMMAS

We need the following lemmas (proofs provided in Appendix G)

Lemma 5. *Given an initialization shape that satisfies Assumption 2 with non-degeneracy gap $\Delta > 0$, then for $j \in \mathcal{N}_k$, we have*

$$c_{kj}(0) = \cos(\boldsymbol{\mu}_k, \boldsymbol{w}_j(0)) \geq \sqrt{\frac{1}{2}\left(\frac{1}{(1-\Delta)^2} - 1\right)} := \tilde{\Delta}_1, \tag{E.1}$$

$$\frac{c_{lj}^{p-2}(0)}{c_{kj}^{p-2}(0)} \leq (1-\sqrt{2\Delta})^{p-2} := 1 - \tilde{\Delta}_2, \forall l \neq k \text{ with } y_l = y_k \text{ and } c_{lj}(0) > 0 \tag{E.2}$$

Lemma 6. *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Given some $1 \leq k \leq K$ and some $j \in \mathcal{N}_k$ and suppose the following is true at some point on the GF trajectory:*

1. $c_{kj} \geq \tilde{\Delta}_1$;
2. $\frac{|c_{lj}|}{c_{kj}} \leq (1-\sqrt{2\Delta}), \forall l \neq k$.

Then the following holds:

$$\frac{d}{dt}c_{kj} \geq p c_{kj}^{p-1}\tilde{\Delta}_2(1-c_{kj}) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2 \max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t)|\,,$$

for some universal constant C_1, C_2 that depends on p. If one further assume $c_{kj} \geq \sqrt{\frac{4}{5}}$, then the lower bound can be improved as

$$\frac{d}{dt}c_{kj} \geq p c_{kj}^{p-1}\left(1 - \frac{1}{2^{p-2}}\right)(1-c_{kj}) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2 \max_i |f^{(p)}(\boldsymbol{x}_i; \boldsymbol{\theta})|\,,$$

Lemma 7. *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Given an initialization shape that satisfies Assumption 2 with non-degeneracy gap $\Delta > 0$, define*

$$t_{1a} := \inf\left\{t : \max_i |f^{(p)}(\boldsymbol{x}_i; \boldsymbol{\theta}(t)| > \min\left\{\frac{\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2(1-\tilde{\Delta}_1)}{2^{p+1}}, \frac{\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2(1-\sqrt{2\Delta})}{2K2^{p+1}}\right\}\right\}. \tag{E.3}$$

Then the following holds $\forall t \leq t_{1a}$:

$$c_{kj}(t) \geq c_{kj}(0) \geq \tilde{\Delta}_1, \forall 1 \leq k \leq K, j \in \mathcal{N}_k\,, \tag{E.4}$$

and

$$\frac{|c_{lj}^{p-2}(t)|}{c_{kj}^{p-2}(t)} \leq \frac{|c_{lj}^{p-2}(0)|}{c_{kj}^{p-2}(0)} \leq 1 - \tilde{\Delta}_2\,. \text{ and } \forall l \neq k, j \in \mathcal{N}_k\,. \tag{E.5}$$

Lemma 8. *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$, then with any balanced initialization scale $\epsilon \leq \frac{1}{4\sqrt{h}W_{\max}^2}$, the solution to gradient flow dynamics satisfies*

$$\max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t))| \leq 2\epsilon\sqrt{h}W_{\max}^2\,, \quad \forall t \leq \frac{1}{2^{p+2}K}\log\left(\frac{1}{2^{p-1}\sqrt{h}\epsilon}\right). \tag{E.6}$$

The following lemma will be used to upper-bound the time each neuron spends until reaching a neighborhood of some data $\boldsymbol{\mu}_k$.

Lemma 9. *Let $p > 2$. Given some $C > 0$, if for some $z(t)$, the following holds*

$$\frac{d}{dt}z \geq Cz^{p-1}\,, \forall t \in [0, T],\ z(0) = z_0,\ z(T) = z_1\,, \tag{E.7}$$

for some $0 < z_0 \leq z_1 < 1$. Then the travel time T for $z(t)$ to go from z_0 to z_1 satifies:

$$T \leq \frac{1}{(p-2)Cz_0^{p-2}}\,. \tag{E.8}$$

Lemma 10. *Let $p > 2$. Given some $C > 0$, if for some $z(t)$, the following holds*

$$\frac{d}{dt}z \geq C(1-z)\,, \forall t \in [0,T],\ z(0) = z_0,\ z(T) = z_1\,, \tag{E.9}$$

for some $0 < z_0 \leq z_1 < 1$. Then the travel time T for $z(t)$ to go from z_0 to z_1 satifies:

$$T \leq \frac{1}{C}\log\frac{1}{1-z_1}\,. \tag{E.10}$$

The following lemma will be used to lower-bound the time each neuron can stay around the neighborhood of some data $\boldsymbol{\mu}_k$.

E.2 Proof of Proposition 2

Proposition 2 (Restated)**.** *Given the same assumptions as in Theorem 3 and consider the same GF solution $\boldsymbol{\theta}(t), t \geq 0$. There exist some $t_1 = \mathcal{O}\left(\log\frac{1}{\alpha}\right)$ and $t_2 = \mathcal{O}\left(\log\frac{1}{\epsilon}\right)$ such that $\forall k$ and $\forall j \in \mathcal{N}_k$, $\cos\left(\boldsymbol{\mu}_k, w_j(t)\right) \geq 1 - \tilde{\mathcal{O}}(\alpha^2),\ \forall t \in [t_1, t_2]$.*

Proof of Proposition 2. **Breakdown the proofs** We let

$$t_1 := \inf\left\{t:\ \min_k \min_{j\in\mathcal{N}_k} c_{kj}(t) \geq 1 - C\log\frac{K}{\delta}\alpha^2\right\}\,. \tag{E.11}$$

We define

$$\begin{aligned}\epsilon_0 := \min\Bigg\{ & \frac{\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2(1-\tilde{\Delta}_1)}{2^{p+2}\sqrt{h}W_{\max}^2}, \\ & \frac{\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2(1-\sqrt{2\Delta})}{2K2^{p+2}\sqrt{h}W_{\max}^2}, \\ & \frac{p\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2\alpha^2}{8\sqrt{h}W_{\max}^2}, \\ & \frac{1}{\sqrt{h}}\exp\left(-4K\left(\frac{20}{(p-2)p\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}} + \frac{2}{p(2^{p-1}-2)}\log\frac{1}{C\log\frac{K}{\delta}\alpha^2}\right)\right)\Bigg\}\,.\end{aligned} \tag{E.12}$$

Our goal is to show that if the initialization scale $\epsilon \leq \epsilon_0$ (Notice that our assumption $\epsilon = \Theta(\alpha^{8K})$ can satisfies this inequality), then

1. $\min_k \min_{j\in\mathcal{N}_k} c_{kj}(t)$ grows above $1 - C\log\frac{K}{\delta}\alpha^2$ before
   $\bar{t}_1 := \frac{20}{(p-2)p\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}} + \frac{2}{p(2^{p-1}-2)}\log\frac{1}{C\log\frac{K}{\delta}\alpha^2}$;
2. Any $c_{kj}(t)$ staying above $1 - C\log\frac{K}{\delta}\alpha^2$ during $[t_1, t_2]$, where $t_2 := \frac{1}{2^{p+2}K}\log\left(\frac{1}{2^{p-1}\sqrt{h}\epsilon}\right)$;

The remaining proof is to show them one by one.

Upper bound on t_1 When $1 \leq k \leq K_1$, $j \in \mathcal{N}_k$ implies that $\boldsymbol{w}_{j0} \in \mathcal{R}_k$ and $\mathrm{sign}(v_j) = 1$. We shall primarily focus on this case as the proof is nearly identical for $K_1 + 1 \leq k \leq K$. We prove it by contradiction.

$\forall t \leq \bar{t}_1$, we have

$$\max_i |f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})| \leq \min\left\{\frac{\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2(1-\tilde{\Delta}_1)}{2^{p+1}}, \frac{\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2(1-\sqrt{2\Delta})}{2K2^{p+1}}\right\}\,, \text{ (By Lemma 8 and (E.12))} \tag{E.13}$$

and

$$c_{kj}(t) \geq \tilde{\Delta}_1,\ \frac{c_{lj}^{p-2}}{c_{kj}^{p-2}} \leq 1 - \tilde{\Delta}_2\,, \forall l \neq k, j \in \mathcal{N}_k\,. \qquad \text{(By (E.13) and Lemma 7)} \tag{E.14}$$

Suppose $t_1 \geq \bar{t}_1$, then $\exists k, j \in \mathcal{N}_k$ such that $t_{1j}^{(k)} := \inf\{t : c_{kj}(t) \geq 1 - \frac{\alpha^2}{2}\} > \bar{t}_1$. However, for $0 \leq t \leq \bar{t}_1$, we have, by Lemma 6, for this particular k, j,

Whenever $c_{kj} \geq \tilde{\Delta}_1$,

$$\frac{d}{dt}c_{kj} \geq pc_{kj}^{p-1}\tilde{\Delta}_2(1 - c_{kj}) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2 \max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t)|\,, \tag{E.15}$$

Whenever $c_{kj} \geq \sqrt{\frac{4}{5}}$,

$$\frac{d}{dt}c_{kj} \geq pc_{kj}^{p-1}\left(1 - \frac{1}{2^{p-2}}\right)(1 - c_{kj}) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2 \max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t)|\,, \tag{E.16}$$

Notice that by Lemma 8 and (E.12), we have

$$\max_i |f^{(p)}(\boldsymbol{x}_i; \boldsymbol{\theta})| \leq \frac{p\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2\alpha^2}{4} \tag{E.17}$$

These suffices to show that c_{kj} will reach $1 - \frac{C\alpha^2}{2}$ in less than $\bar{t}_1$ time.

For some choice of C and sufficiently small α, we have: Whenever, $\tilde{\Delta}_1 \leq c_{kj} \leq \sqrt{\frac{4}{5}}$,

$$\begin{aligned}
\frac{d}{dt}c_{kj} &\geq pc_{kj}^{p-1}\tilde{\Delta}_2(1 - c_{kj}) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2 \max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t)| \\
&\geq pc_{kj}^{p-1}\tilde{\Delta}_2\left(1 - \sqrt{\frac{4}{5}}\right) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2 \max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t)| \\
&\geq pc_{kj}^{p-1}\tilde{\Delta}_2\left(1 - \sqrt{\frac{4}{5}}\right) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2\frac{p\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2\alpha^2}{4}\,. \\
&\geq \frac{p}{2}c_{kj}^{p-1}\tilde{\Delta}_2\left(1 - \sqrt{\frac{4}{5}}\right) \geq \frac{p}{20}c_{kj}^{p-1}\tilde{\Delta}_2\,,
\end{aligned} \tag{E.18}$$

where we uses the fact that $c_{kj} \geq \tilde{\Delta}_1$ in the last inequality. Whenever, $\sqrt{\frac{4}{5}} \leq c_{kj} \leq 1 - \frac{C\alpha^2}{2}$,

$$\begin{aligned}
\frac{d}{dt}c_{kj} &\geq pc_{kj}^{p-1}\left(1 - \frac{1}{2^{p-2}}\right)(1 - c_{kj}) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2 \max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t)| \\
&\geq p(2^{p-1} - 2)(1 - c_{kj}) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2 \max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t)| \\
&\geq p(2^{p-1} - 2)(1 - c_{kj}) - C_1 \log\frac{K}{\delta}\alpha^2 - C_2\frac{p\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2\alpha^2}{4} \\
&\geq \frac{p}{2}(2^{p-1} - 2)(1 - c_{kj})\,,
\end{aligned} \tag{E.19}$$

where we uses the fact that $c_{kj} \leq 1 - C\log\frac{K}{\delta}\alpha^2$ in the last inequality. The right-hand sides of (E.18) and (E.19) is positive, which proves that c_{kj} is monotonically increasing before reaching $1 - C\log\frac{K}{\delta}\alpha^2$. Lastly,

1. by Lemma 9 and (E.18), it takes at most $\frac{20}{(p-2)p\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}}$ time for c_{kj} to travel from $\tilde{\Delta}_1$ to $\sqrt{\frac{4}{5}}$;
2. by Lemma 10 and (E.19), it takes at most $\frac{2}{p(2^{p-1}-2)}\log\frac{1}{C\log\frac{K}{\delta}\alpha^2}$ time for c_{kj} to travel from $\sqrt{\frac{4}{5}}$ to $1 - C\log\frac{K}{\delta}\alpha^2$.

Therefore, we have

$$t_{1j}^{(k)} := \inf\{t : c_{kj}(t) \geq 1 - \frac{\alpha^2}{2}\} \leq \frac{20}{(p-2)p\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}} + \frac{2}{p(2^{p-1}-2)} \log \frac{1}{C \log \frac{K}{\delta}\alpha^2} = \bar{t}_1 \,, \tag{E.20}$$

which contradicts our initial assumption that $c_{kj}(t) > \bar{t}_1$. Hence $t_1 \leq \bar{t}_1$.

Maintaining $C \log \frac{K}{\delta}\alpha^2$ alignment until t_2 We have shown that at some $t_1 \leq \bar{t}_1$, all c_{kj} have grown above $1 - C \log \frac{K}{\delta}\alpha^2$. Now we show that any $c_{kj}(t)$ stays above $1 - C \log \frac{K}{\delta}\alpha^2$ between $[t_1, t_2]$. It suffices to show that for any $t \leq t_2$,

$$\frac{d}{dt} c_{kj} \bigg|_{c_{kj} = 1 - C \log \frac{K}{\delta}\alpha^2} \geq 0 \,. \tag{E.21}$$

Indeed, the inequality (E.16) is still valid before t_2, i.e.

$$\begin{aligned} \frac{d}{dt} c_{kj} &\geq p c_{kj}^{p-1} \left(1 - \frac{1}{2^{p-2}}\right)(1 - c_{kj}) - C_1 \log \frac{K}{\delta}\alpha^2 - C_2 \max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t)| \\ &\geq p(2^{p-1} - 2)(1 - c_{kj}) - C_1 \log \frac{K}{\delta}\alpha^2 - C_2 \frac{p\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2\alpha^2}{4} \,. \end{aligned}$$

Therefore, for some choice of C and sufficiently small α,

$$\frac{d}{dt} c_{kj} \bigg|_{c_{kj} = 1 - C \log \frac{K}{\delta}\alpha^2} \geq p(2^{p-1} - 2) C \log \frac{K}{\delta}\alpha^2 - C_1 \log \frac{K}{\delta}\alpha^2 - C_2 \frac{p\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2\alpha^2}{4} \geq 0 \,. \tag{E.22}$$

Hence

$$\min_k \min_{j \in \mathcal{N}_k} c_{kj}(t) \geq 1 - C \log \frac{K}{\delta}\alpha^2, \forall t \in [t_1, t_2] \,. \tag{E.23}$$

□

F PRELU CONVERGES TO OPTIMAL ℓ_2-ROBUST CLASSIFIER, PART FOUR: CONVERGENCE PHASE

F.1 AXUILIARY LEMMAS

We need the following lemmas (proofs provided in Appendix G):

Lemma 11. *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Suppose the following is true at some point on the GF trajectory:*

1. $c_{kj}(t) \geq 1 - 2C_a \log \frac{K}{\delta}\alpha^2,\ \forall k, j \in \mathcal{N}_k$;
2. $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \leq 1 + C_w \log \frac{K}{\delta}\alpha^2,\ \forall k$;
3. $\sum_{j\in\mathcal{N}_c} \|\boldsymbol{w}_j\|^2 = \tilde{o}(\alpha^2)$.

Then the following holds for every $1 \leq k \leq K$, $i \in \mathcal{I}_k$,

$$f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}) \leq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 + 2^{p+2}C\sqrt{\log\frac{K^2N}{\delta}}\alpha^2\right) + 2KC\alpha^p\,;$$

$$f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}) \geq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 - 4pC\sqrt{\log\frac{K^2N}{\delta}}\alpha^2\right) - 2KC\alpha^p\,.$$

Lemma 12. *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Suppose the following is true at some point on the GF trajectory:*

1. $c_{kj}(t) \geq 1 - 2C_a \log \frac{K}{\delta}\alpha^2,\ \forall k, j \in \mathcal{N}_k$;
2. $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \leq 1 + C_w \log \frac{K}{\delta}\alpha^2,\ \forall k$;
3. $\sum_{j\in\mathcal{N}_c} \|\boldsymbol{w}_j\|^2 = \tilde{o}(\alpha^2)$.

Furthermore, suppose additionally that for some $k, j \in \mathcal{N}_k$:

$$1 - 2C_a \log\frac{K}{\delta}\alpha^2 \leq c_{kj}(t) \leq 1 - C_a \log\frac{K}{\delta}\alpha^2;$$

Then the following holds for the same k, j,

$$\frac{d}{dt}c_{kj} \geq -CK\log\frac{K^2N}{\delta}\alpha^{\min\{p,4\}}\,.$$

Lemma 13. *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Suppose the following is true at some point on the GF trajectory :*

1. $c_{kj}(t) \geq 1 - 2C_a \log \frac{K}{\delta}\alpha^2,\ k, j \in \mathcal{N}_k$;
2. $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \leq 1 + C_w \log \frac{K}{\delta}\alpha^2,\ \forall k$;
3. $\sum_{j\in\mathcal{N}_c} \|\boldsymbol{w}_j\|^2 = \tilde{o}(\alpha^2)$.

Then the following holds for every $1 \leq k \leq K$,

$$\frac{d}{dt}\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right) \leq 2\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 + C\log\frac{K}{\delta}\alpha^2\right)\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right),$$

and

$$\frac{d}{dt}\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right) \geq 2\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 - C\log\frac{K}{\delta}\alpha^2\right)\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right),$$

where C is some universal constant such that $C < C_w$.

Lemma 14. *Consider the same assumptions as in Proposition 2. Given the t_1 in Proposition 2, the following holds $\forall 1 \leq k \leq K$:*

$$\sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j(t_1)\|^2 \geq \exp\left(-\frac{2p^{p+2}K}{p(p-2)\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}}\right) W_{\min}^2 \epsilon^2 \,. \tag{F.1}$$

Lemma 15. *Given some $0 < \Delta < \frac{1}{4}$, if for some $z(t)$, the following holds*

$$\frac{d}{dt} z \geq (1 - z - \Delta) z, \; z(0) = z_0, \; z(T) = z_1 \,, \tag{F.2}$$

for some $0 < z_0 \leq \frac{1}{4}$, and $z_0 \leq z_1 < 1 - \Delta$. Then the travel time T for $z(t)$ to go from z_0 to z_1 satisfies:

$$T \leq 2\left(\log \frac{1}{1 - z_1 - \Delta} + \log \frac{1}{z_0}\right) . \tag{F.3}$$

Lemma 16. *Condition on good event $\mathcal{E}_{good}$, we have*

$$\sum_{j \in \mathcal{N}_c} \|\boldsymbol{w}_j(t)\|^2 = \tilde{o}(\alpha^2) \,, \; \forall t \leq T^* \,. \tag{F.4}$$

Lemma 17. *If the neurons $\{\boldsymbol{w}_j\}_{j=1}^h$ satisfies the following for some $0 \leq \delta \leq 1$ and $\nu, \zeta > 0$:*

- $\max_k \max_{j \in \mathcal{N}_k} c_{kj}(t) \geq 1 - \delta$;
- $\left|1 - \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2\right| \leq \nu$;
- $\sum_{j \in \mathcal{N}^c} \|\boldsymbol{w}_j\|^2 \leq \zeta$,

then $\sup_{\boldsymbol{x} \in \mathbb{S}^{D-1}} \left|f^{(p)}(\boldsymbol{x}; \boldsymbol{\theta}) - F^{(p)}(\boldsymbol{x})\right| \leq K(1+\nu)(2^p - 1)2\delta + K\nu + \zeta$

F.2 Proof of Theorem 3

Theorem 3 (Restated)**.** *Let $p > 2$. Given $0 \leq \delta \leq 1$ and a sufficiently small α_0^2, consider data dimension $D \geq \tilde{\Omega}(\alpha_0^{-2})$ and per-cluster sample size $\tilde{\Omega}(\alpha_0^{-2}) \leq N \leq \tilde{o}(\exp(\alpha_0^{-2}))$. With probability at least $1 - \delta$, the GF dynamics with a balanced dataset $\hat{\mathcal{D}} = \{\boldsymbol{x}_i, y_i\}_{i=1}^{KN}$ sampled with intra-cluster variance $\alpha^2 \leq \alpha_0^2$, starting from some ϵ-small and balanced (Assumption 1) initialization $\boldsymbol{\theta}(0)$ that satisfies Assumption 2 with a non-degeneracy gap $\Delta = \Theta(1)$ and has a sufficiently small initialization scale $\epsilon = \tilde{\Theta}\left(\alpha_0^{8K}\right)$, leads to a solution $\boldsymbol{\theta}(t), t \geq 0$ such that: for some $t^* = \tilde{\mathcal{O}}\left(\log \frac{1}{\alpha_0}\right)$ and $T^* = \tilde{\Theta}\left(\log \frac{1}{\alpha_0}\right) + \tilde{\Omega}\left(\frac{1}{\alpha_0^{\min\{p-2,2\}}}\right)$ with $[t^*, T^*] \neq \emptyset$, we have $\mathcal{L}(\boldsymbol{\theta}(t)) = \tilde{\mathcal{O}}(\alpha_0^4), \forall t \in [t^*, T^*]$ and*

$$\sup_{t \in [t^*, T^*]} \sup_{\boldsymbol{x} \in \mathbb{S}^{D-1}} \left|f^{(p)}(\boldsymbol{x}; \boldsymbol{\theta}(t)) - F^{(p)}(\boldsymbol{x})\right| \leq \tilde{\mathcal{O}}\left(\alpha_0^2\right) \,. \tag{F.5}$$

Proof. We have shown in Proposition 2, and Lemma 14 that:

1. Any $c_{kj}(t)$ staying above $1 - C_a \log \frac{K}{\delta} \alpha^2$ during $[t_1, t_2]$;
2. $\sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j(t_1)\|^2 \geq \exp\left(-\frac{2p^{p+2}K}{p(p-2)\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}}\right) W_{\min}^2 \epsilon^2$, for every $1 \leq k \leq K$.

We define

$$t^* = \underbrace{t_1}_{\mathcal{O}(1)} + 2\left(\log \frac{1}{(C - C_w)\log \frac{K}{\delta}\alpha^2} + \frac{2p^{p+2}K}{p(p-2)\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}} + \log \frac{1}{W_{\min}^2 \epsilon^2}\right) \tag{F.6}$$

$$T^* = \underbrace{t_2}_{\Theta(\log \frac{1}{\epsilon})} + \frac{C}{\log \frac{K^2 N}{\delta}} \alpha^{\max\{2-p, -2\}} \tag{F.7}$$

Since $\epsilon = \Theta(\alpha^{8K})$. For sufficiently small α, we have $\mathcal{O}(\log \frac{1}{\alpha}) = t^* \leq T^* = \Theta(\alpha^{\min\{2-p,-2\}})$. Our goal is to show that

1. Before T^*, one must have $\max_k \max_{j\in\mathcal{N}_k} c_{kj}(t) \geq 1 - 2C_a \log \frac{K}{\delta}\alpha^2$ and $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j(t)\|^2 \leq 1 + C_w \log \frac{K}{\delta}\alpha^2$;
2. Before T^*, for all k, whenever $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j(t)\|^2$ reaches $1 - C_w \log \frac{K}{\delta}\alpha^2$, it can not drop below $1 - C_w \log \frac{K}{\delta}\alpha^2$;
3. After t^*, for all k, one must have $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \geq 1 - 2C_w \log \frac{K}{\delta}\alpha^2$.

We also have $\sum_{j\in\mathcal{N}_c} \|\boldsymbol{w}_j\|^2 = \tilde{o}(\alpha^2)$, then applying Lemma 17 gives the desired result. The statement that $\mathcal{L}(t) = \tilde{O}(\alpha^4)$ is due to the fact that $|y_i - f^{(p)}(\boldsymbol{x}_i; \boldsymbol{\theta}(t))| = \tilde{O}(\alpha^2)$ during $[t^*, T^*]$.

First claim: The two inequalities hold before t_2, thus it suffices to study

$$\tau_3 := \inf\left\{ t \geq t_2 : \max_k \max_{j\in\mathcal{N}_k} c_{kj}(t) \leq 1 - 2C \log \frac{K}{\delta}\alpha^2 \right\},$$

$$\tau_4 := \inf\left\{ t \geq t_2 : \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \geq 1 + C \log \frac{K}{\delta}\alpha^2 \right\},$$

and show that $\min\{\tau_3, \tau_4\} \geq T^*$. We proof it by contradiction, suppose $\min\{\tau_3, \tau_4\} \leq T^*$, then it must be either $\tau_3 = \min\{\tau_3, \tau_4\} \leq T^*$ or $\tau_4 = \min\{\tau_3, \tau_4\} \leq T^*$.

Consider the first case that $\tau_3 = \min\{\tau_3, \tau_4\} \leq T^*$, then there exists some k and $j \in \mathcal{N}_k$ and some $\tau_{3^-} \geq t_2$ such that

$$1 - 2C \log \frac{K}{\delta}\alpha^2 \leq c_{kj}(t) \leq 1 - C \log \frac{K}{\delta}\alpha^2, \forall t \in [\tau_{3^-}, \tau_3], \tag{F.8}$$

$$c_{kj}(\tau_{3^-}) = 1 - C \log \frac{K}{\delta}\alpha^2,\ c_{kj}(\tau_3) = 1 - 2C \log \frac{K}{\delta}\alpha^2 \tag{F.9}$$

since $c_{kj}(t)$ is continuous and has to travel from $1 - C \log \frac{K}{\delta}\alpha^2$ to $1 - 2C \log \frac{K}{\delta}\alpha^2$. By Lemma 6, we have

$$\frac{d}{dt} c_{kj} \geq -CK \log \frac{K^2 N}{\delta} \alpha^{\min\{p,4\}}, \forall t \in [\tau_{3^-}, \tau_3].$$

Then by the fundamental theorem of calculus, we have

$$\begin{aligned} -C \log \frac{K}{\delta}\alpha^2 = c_{kj}(\tau_3) - c_{kj}(\tau_{3^-}) = \int_{\tau_{3^-}}^{\tau_3} \frac{d}{dt} c_{kj} &\geq \int_{\tau_{3^-}}^{\tau_3} -CK \log \frac{K^2 N}{\delta} \alpha^{\min\{p,4\}} \\ &= -(\tau_3 - \tau_{3^-}) CK \log \frac{K^2 N}{\delta} \alpha^{\min\{p,4\}}, \end{aligned} \tag{F.10}$$

Therefore, for some constant $C > 0$,

$$(\tau_3 - \tau_{3^-}) \geq \frac{C}{\log \frac{K^2 N}{\delta}} \alpha^{\max\{2-p,-2\}} \Rightarrow (\tau_3 - t_2) \geq \frac{C}{\log \frac{K^2 N}{\delta}} \alpha^{\max\{2-p,-2\}}. \tag{F.11}$$

$[t_2, \tau_3]$ has length at least $\frac{C}{\log \frac{K^2 N}{\delta}} \alpha^{\max\{2-p,-2\}}$ thus is an interval that contains $[t_2, T^*]$. Contradicting our assumption that $\tau_3 \leq T^*$. The case one is thus eliminated.

Consider the second case that $\tau_4 = \min\{\tau_3, \tau_4\} \leq T^*$, then by the continuity of $\|w_j\|$, we know that there exists some k such that $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j(\tau_4)\|^2 = 1 + C_w \log \frac{K}{\delta}\alpha^2$. However, by Lemma 11, we have, at τ_4,

$$\frac{d}{dt}\left(\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \right) \leq 2 \left(1 - \underbrace{\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2}_{=1+C_w \log \frac{K}{\delta}\alpha^2} + C \log \frac{K}{\delta}\alpha^2 \right) \left(\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \right),$$

$$= 2\left((C - C_w)\log\frac{K}{\delta}\alpha^2\right)\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right) < 0\,,$$

which indicates that $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2$ can not surpass $1 + C_w\log\frac{K}{\delta}\alpha^2$ after τ_4, violating the definition of τ_4, leading to a contradiction. Therefore the second case is eliminated as well. We must have $\min\{\tau_3, \tau_4\} \geq T^*$. The first claim is proved.

Second claim By Lemma 13 (it applies to any $t \leq T^*$ given the proof in our first step), we have

$$\begin{aligned}\frac{d}{dt}\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right)\Bigg|_{\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 = 1 - C_w\log\frac{K}{\delta}\alpha^2} &\geq 2\left(C_w\log\frac{K}{\delta}\alpha^2 - C\log\frac{K}{\delta}\alpha^2\right)\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right)\,,\\ &\geq 0\,.\end{aligned}$$

Therefore, whenever $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(t)\|^2$ reaches $1 - C_w\log\frac{K}{\delta}\alpha^2$, it can not drop below $1 - C_w\log\frac{K}{\delta}\alpha^2$. The second claim is proved.

Third claim Lastly, we just need an upper bound on the travel time for $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(t)\|^2$ to go from $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(t_1)\|^2$ to $1 - C_w\log\frac{K}{\delta}\alpha^2$, for which we simply combine Lemma 13, 14,and 15 to see the travel time is upper bounded by

$$2\left(\log\frac{1}{(C - C_w)\log\frac{K}{\delta}\alpha^2} + \frac{2p^{p+2}K}{p(p-2)\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}} + \log\frac{1}{W_{\min}^2\epsilon^2}\right)\,. \tag{F.12}$$

Thus $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(t)\|^2$ must reach $1 - C_w\log\frac{K}{\delta}\alpha^2$ by t^*. □

G PRELU CONVERGES TO OPTIMAL ℓ_2-ROBUST CLASSIFIER, PART FIVE: PROOFS FOR AUXILIARY LEMMAS

Lemma 5 (Restated). *Given an initialization shape that satisfies Assumption 2 with non-degeneracy gap $\Delta > 0$, then for $j \in \mathcal{N}_k$, we have*

$$c_{kj}(0) = \cos(\boldsymbol{\mu}_k, \boldsymbol{w}_j(0)) \geq \sqrt{\frac{1}{2}\left(\frac{1}{(1-\Delta)^2} - 1\right)} := \tilde{\Delta}_1, \tag{G.1}$$

$$\frac{c_{lj}^{p-2}(0)}{c_{kj}^{p-2}(0)} \leq (1-\sqrt{2\Delta})^{p-2} := 1 - \tilde{\Delta}_2, \forall l \neq k \text{ with } y_l = y_k \text{ and } c_{lj}(0) > 0 \tag{G.2}$$

Proof. We prove both inequalities by contradiction.

First inequality Suppose $0 < c_{kj}(0) = \cos(\boldsymbol{\mu}_k, \boldsymbol{w}_j(0)) = \cos(\boldsymbol{\mu}_k, \boldsymbol{w}_{j0}) < \tilde{\Delta}_1$, then consider $\tilde{\boldsymbol{w}}_{j0} = \frac{\boldsymbol{w}_{j0}}{\|\boldsymbol{w}_{j0}\|}$, and

$$\tilde{\boldsymbol{w}} = \tilde{\boldsymbol{w}}_{j0} - \frac{c_{kj}(0)}{1 - c_{kj}(0)}(\boldsymbol{\mu}_k - \tilde{\boldsymbol{w}}_{j0})\,. \tag{G.3}$$

Notice that here $c_{kj}(0) = \cos(\boldsymbol{\mu}_k, \boldsymbol{w}_{j0}) = \langle \boldsymbol{\mu}_k, \tilde{\boldsymbol{w}}_{j0} \rangle$. It is easy to verify that $\langle \boldsymbol{\mu}_l, \tilde{\boldsymbol{w}} \rangle = 0, \forall 1 \leq l \leq K$, thus $\tilde{\boldsymbol{w}} \in \partial\big(\bigcup_{k\in\mathcal{K}} \mathcal{R}_k\big)$, and

$$d\left(\boldsymbol{w}_{j0}, \partial\big(\bigcup_{k\in\mathcal{K}} \mathcal{R}_k\big)\right) = 1 - \sup_{\boldsymbol{w}\in\partial\left(\bigcup_{k\in\mathcal{K}} \mathcal{R}_k\right)} \cos\left(\tilde{\boldsymbol{w}}_{j0}, \boldsymbol{w}\right) \leq 1 - \cos(\tilde{\boldsymbol{w}}_{j0}, \tilde{\boldsymbol{w}})\,, \tag{G.4}$$

Since one can compute

$$\cos(\tilde{\boldsymbol{w}}_{j0}, \tilde{\boldsymbol{w}}) = \frac{\langle \tilde{\boldsymbol{w}}_{j0}, \tilde{\boldsymbol{w}} \rangle}{\|\tilde{\boldsymbol{w}}_{j0}\|\|\tilde{\boldsymbol{w}}\|} = \frac{1 + c_{kj}(0)(1 - c_{kj}(0))}{\sqrt{1 + 2c_{kj}^2(0)}} \geq \frac{1}{\sqrt{1 + 2c_{kj}^2(0)}} > 1 - \Delta\,, \tag{G.5}$$

where the last inequality is due to our assumption that $c_{kj}(0) < \tilde{\Delta}_1$. Combining (G.4)(G.5), we have

$$d\left(\boldsymbol{w}_{j0}, \partial\big(\bigcup_{k\in\mathcal{K}} \mathcal{R}_k\big)\right) < \Delta\,, \tag{G.6}$$

which contradicts our assumption that the non-degeneracy gap is at least Δ.

Second inequality Suppose there exists an $l \neq k$ such that $y_l = y_k$ and $\frac{c_{lj}^{p-2}(0)}{c_{kj}^{p-2}(0)} > (1-\sqrt{2\Delta})^{p-2}$ and $c_{lj}(0) > 0$, we pick the l that has the largest $c_{lj}(0)$, then consider $\tilde{\boldsymbol{w}}_{j0} = \frac{\boldsymbol{w}_{j0}}{\|\boldsymbol{w}_{j0}\|}$, and

$$\tilde{\boldsymbol{w}} = \tilde{\boldsymbol{w}}_{j0} - \frac{c_{kj}(0) - c_{lj}(0)}{2}(\boldsymbol{\mu}_k - \boldsymbol{\mu}_l)\,. \tag{G.7}$$

It can be verified that $\|\tilde{\boldsymbol{w}}\| = 1$, $\cos(\boldsymbol{\mu}_k, \tilde{\boldsymbol{w}}) = \cos(\boldsymbol{\mu}_l, \tilde{\boldsymbol{w}}) = \frac{c_{kj}(0)+c_{lj}(0)}{2}$, and $\cos(\boldsymbol{\mu}_m, \tilde{\boldsymbol{w}}) = \cos(\boldsymbol{\mu}_m, \tilde{\boldsymbol{w}}_{j0}) \leq \cos(\boldsymbol{\mu}_l, \tilde{\boldsymbol{w}}), \forall m \neq k$ or l. All of the above together implies $\tilde{\boldsymbol{w}} \in (\partial\mathcal{R}_k) \cap (\partial\mathcal{R}_l) \subset \partial\big(\bigcup_{k\in\mathcal{K}} \mathcal{R}_k\big)$, and

$$d\left(\boldsymbol{w}_{j0}, \partial\big(\bigcup_{k\in\mathcal{K}} \mathcal{R}_k\big)\right) = 1 - \sup_{\boldsymbol{w}\in\partial\left(\bigcup_{k\in\mathcal{K}} \mathcal{R}_k\right)} \cos\left(\tilde{\boldsymbol{w}}_{j0}, \boldsymbol{w}\right) \leq 1 - \cos(\tilde{\boldsymbol{w}}_{j0}, \tilde{\boldsymbol{w}})\,, \tag{G.8}$$

One can compute

$$\begin{aligned}\cos(\tilde{\boldsymbol{w}}_{j0}, \tilde{\boldsymbol{w}}) = \frac{\langle \tilde{\boldsymbol{w}}_{j0}, \tilde{\boldsymbol{w}} \rangle}{\|\tilde{\boldsymbol{w}}_{j0}\|\|\tilde{\boldsymbol{w}}\|} &= 1 - \frac{(c_{kj}(0) - c_{lj}(0))^2}{2} \\ &\geq 1 - \frac{\left(1 - \frac{c_{lj}(0)}{c_{kj}(0)}\right)^2}{2}\end{aligned}$$

$$\geq 1 - \frac{\left(1 - \left(\frac{c_{lj}^{p-2}(0)}{c_{kj}^{p-2}(0)}\right)^{\frac{1}{p-2}}\right)^2}{2}$$
$$\geq 1 - \frac{\left(1 - (1-\tilde{\Delta}_2)^{\frac{1}{p-2}}\right)^2}{2} = 1 - \Delta\,, \tag{G.9}$$

where the last inequality is due to our assumption that $\frac{c_{lj}^{p-2}(0)}{c_{kj}^{p-2}(0)} > (1-\sqrt{2\Delta})^{p-2}$. Combining (G.4)(G.5), we have

$$d\left(\boldsymbol{w}_{j0}, \partial(\bigcup_{k\in\mathcal{K}} \mathcal{R}_k)\right) < \Delta\,, \tag{G.10}$$

which contradicts our assumption that the non-degeneracy gap is at least Δ. □

Lemma 6 (Restated)**.** *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Given some $1 \leq k \leq K$ and some $j \in \mathcal{N}_k$ and suppose the following is true at some point on the GF trajectory:*

1. $c_{kj} \geq \tilde{\Delta}_1$;
2. $\frac{|c_{lj}|}{c_{kj}} \leq (1-\sqrt{2\Delta}), \forall l \neq k$.

Then the following holds:

$$\frac{d}{dt}c_{kj} \geq pc_{kj}^{p-1}\tilde{\Delta}_2(1-c_{kj}) - C_1\log\frac{K}{\delta}\alpha^2 - C_2\max_k|f^{(p)}(\boldsymbol{\mu}_k;\boldsymbol{\theta}(t)|\,,$$

for some universal constant C_1, C_2 that depends on p. If one further assume $c_{kj} \geq \sqrt{\frac{4}{5}}$, then the lower bound can be improved as

$$\frac{d}{dt}c_{kj} \geq pc_{kj}^{p-1}\left(1 - \frac{1}{2^{p-2}}\right)(1-c_{kj}) - C_1\log\frac{K}{\delta}\alpha^2 - C_2\max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})|\,,$$

Proof. When $1 \leq k \leq K_1$, $j \in \mathcal{N}_k$ implies that $j \in \mathcal{N}_+$ thus $\mathrm{sign}(v_j) = 1$. We shall primarily focus on this case as the proof is nearly identical for $K_1 + 1 \leq k \leq K$.

$$\begin{aligned}
&\frac{d}{dt}c_{kj} \\
&= -\frac{1}{N}\sum_{i:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}\nabla_{\hat{y}}\ell_i\; p\left(\left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle - \left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right) \\
&= \frac{1}{N}\sum_{i:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}(y_i - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\; p\left(\left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle - \left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right) \\
&= \frac{1}{N}\sum_{i:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\; p\left(\left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle - \left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right) \\
&\qquad \underbrace{-\frac{1}{N}\sum_{i:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})\; p\left(\left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle - \left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)}_{:=\Gamma_1\,\text{(will be treated later)}} \\
&= \underbrace{\frac{1}{N}\sum_{i\in\mathcal{I}_k:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\; p\left(\left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle - \left\langle\boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)}_{(a)}
\end{aligned}$$

$$\left. \underbrace{- \frac{1}{N} \sum_{l \neq k} \sum_{i \in \mathcal{I}_l : \langle \boldsymbol{x}_i, \boldsymbol{w}_j \rangle > 0} y_i \, p \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i \rangle - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle c_{kj} \right)}_{(b)} \right) + \Gamma_1 \tag{G.11}$$

We handle these two terms differently:

$$\begin{aligned}
(a) &= \frac{1}{N} \sum_{i \in \mathcal{I}_k : \langle \boldsymbol{x}_i, \boldsymbol{w}_j \rangle > 0} y_i \, p \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i \rangle - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle c_{kj} \right) \\
&= \frac{1}{N} \sum_{i \in \mathcal{I}_k} p \left(\left\langle \boldsymbol{\mu}_k + \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(\langle \boldsymbol{\mu}_k, \boldsymbol{\mu}_k + \boldsymbol{\varepsilon}_i \rangle - \left\langle \boldsymbol{\mu}_k + \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle c_{kj} \right) \\
&= \frac{1}{N} \sum_{i \in \mathcal{I}_k} p \left(\left\langle \boldsymbol{\mu}_k + \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(1 - c_{kj}^2 + \langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i \rangle - \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle c_{kj} \right) \\
&= \frac{1}{N} \sum_{i \in \mathcal{I}_k} p \left(\left\langle \boldsymbol{\mu}_k + \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(1 - c_{kj}^2 - \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle c_{kj} \right) \\
&\qquad + \underbrace{\frac{1}{N} \sum_{i \in \mathcal{I}_k} y_i \, p \left(\left\langle \boldsymbol{\mu}_k + \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i \rangle}_{:= \Gamma_2 \text{ (will be treated later)}} \\
&= \frac{1}{N} \sum_{i \in \mathcal{I}_k} p \left(c_{kj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(1 - c_{kj}^2 - \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle c_{kj} \right) + \Gamma_2
\end{aligned} \tag{G.12}$$

With the Taylor expansion

$$\left(c_{kj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} = c_{kj}^{p-1} + (p-1) c_{kj}^{p-2} \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle + R_L \left| \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right|^2 , \tag{G.13}$$

where $R_L = \frac{(p-1)(p-2)(c_{kj}+\zeta_L)^{p-2}}{2}$ and ζ_L between 0 and $\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle$ comes from the Lagrange residual. Clearly $|R_L| \leq 2^{p-3} p^2$. Combining (G.12)(G.13), we have

$$\begin{aligned}
&(a) \\
&= \text{(G.12)} \\
&= p c_{kj}^{p-1} (1 - c_{kj}^2) + \left(-p c_{kj}^p + p(p-1) c_{kj}^{p-2} (1 - c_{kj}^2) \right) \sum_{i \in \mathcal{I}_k} \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \\
&\qquad + \frac{1}{N} \left(-p(p-1) c_{kj} + p R_L (1 - c_{kj}^2) \right) \sum_{i \in \mathcal{I}_k} \left| \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right|^2 \\
&\qquad - \frac{1}{N} p c_{kj} R_L \sum_{i \in \mathcal{I}_k} \left| \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right|^2 \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle + \Gamma_2 \\
&\geq p c_{kj}^{p-1} (1 - c_{kj}^2) - \frac{1}{N} p^2 \left\| \sum_{i \in \mathcal{I}_k} \boldsymbol{\varepsilon}_i \right\| - \frac{1}{N} 2^{p-1} p^2 \sum_{i \in \mathcal{I}_k} \|\boldsymbol{\varepsilon}_i\|^2 - \frac{1}{N} 2^{p-3} p^3 \sum_{i \in \mathcal{I}_k} \|\boldsymbol{\varepsilon}_i\|^3 + \Gamma_2 \\
&\geq p c_{kj}^{p-1} (1 - c_{kj}^2) - \frac{1}{N} p^2 \left\| \sum_{i \in \mathcal{I}_k} \boldsymbol{\varepsilon}_i \right\| - \frac{1}{N} 2^{p-1} p^2 \sum_{i \in \mathcal{I}_k} \|\boldsymbol{\varepsilon}_i\|^2 - \frac{1}{N} 2^{p-3} p^3 \sum_{i \in \mathcal{I}_k} \|\boldsymbol{\varepsilon}_i\|^2 \max_i \|\boldsymbol{\varepsilon}_i\| + \Gamma_2 \\
&\geq p c_{kj}^{p-1} (1 - c_{kj}^2) - C p^2 \sqrt{\log \frac{K}{\delta}} \frac{\alpha}{\sqrt{N}} - 2^{p-1} p^3 C^2 \log \frac{K}{\delta} \alpha^2 - 2^{p-3} p^3 C^3 \log \frac{K^2 N}{\delta} \alpha^3 + \Gamma_2 \, .
\end{aligned} \tag{G.14}$$

We leave the bound as the last one for now and turn to the other term:

$$
\begin{aligned}
&(b)\\
&= -\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i\rangle - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)\\
&= \frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(c_{lj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p} c_{kj}\\
&\qquad \underbrace{-\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(c_{lj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i\rangle}_{:=\Gamma_3\,(\text{will be treated later})}\\
&\geq -\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l} p\left(|c_{lj}| + \left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|\right)^{p} c_{kj} + \Gamma_3 \qquad \text{(G.15)}
\end{aligned}
$$

With the Taylor expansion

$$
\left(|c_{lj}| + \left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|\right)^{p} = |c_{lj}|^p + p|c_{lj}|^{p-1}\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right| + R_L\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^2, \quad \text{(G.16)}
$$

where $R_L = \frac{p(p-1)(|c_{lj}|+\zeta_L)^{p-2}}{2}$ and ζ_L between 0 and $\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|$ comes from the Lagrange residual. Clearly $|R_L| \leq 2^{p-2}p^2$. Combining (G.12)(G.13), we have

$$
\begin{aligned}
&(b)\\
&= \text{(G.15)}\\
&= -\sum_{l\neq k} p|c_{lj}|^p c_{kj} - \frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l} p(p-1)|c_{lj}|^{p-1}c_{kj}\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right| - \frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l} pR_L c_{kj}\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^2 + \Gamma_3\\
&\geq -\sum_{l\neq k} p|c_{lj}|^p c_{kj} - \frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l} p(p-1)|c_{lj}|^{p-1}c_{kj}\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right| - K2^{p-2}p^3C^2\log\frac{K}{\delta}\alpha^2 + \Gamma_3\,,\\
&\geq -\sum_{l\neq k} p|c_{lj}|^p c_{kj} - \frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l} p(p-1)|c_{lj}|^{p-1}c_{kj}\left(\|\boldsymbol{\varepsilon}_i\|\sqrt{1-c_{kj}^2} + |\langle \boldsymbol{\varepsilon}_i, \boldsymbol{\mu}_k\rangle|\right) - K2^{p-2}p^3C^2\log\frac{K}{\delta}\alpha^2 + \Gamma_3\,,\\
&\geq -\sum_{l\neq k} p|c_{lj}|^p c_{kj} - \sum_{l\neq k} p^2|c_{lj}|^{p-1}c_{kj}C\sqrt{\log\frac{K^2N}{\delta}}\alpha\sqrt{1-c_{kj}^2} - K2^{p-2}p^3C^2\log\frac{K}{\delta}\alpha^2 + \Gamma_3\\
&\qquad \underbrace{+ -\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l} p(p-1)|c_{lj}|^{p-1}c_{kj}\,|\langle \boldsymbol{\varepsilon}_i, \boldsymbol{\mu}_k\rangle|}_{:=\Gamma_4\,(\text{will be treated later})}\\
&= -pc_{kj}^{p-1}\left(\sum_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}|c_{lj}|^2 - \sum_{l\neq k} p\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}|c_{lj}|C\sqrt{\log\frac{K^2N}{\delta}}\alpha\sqrt{1-c_{kj}^2}\right) - K2^{p-2}p^3C^2\log\frac{K}{\delta}\alpha^2 + \Gamma_3 + \Gamma_4\\
&= -pc_{kj}^{p-1}\left(\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)\left(\sum_{l\neq k}|c_{lj}|^2 - \sum_{l\neq k} p|c_{lj}|C\sqrt{\log\frac{K^2N}{\delta}}\alpha\sqrt{1-c_{kj}^2}\right) - K2^{p-2}p^3C^2\log\frac{K}{\delta}\alpha^2 + \Gamma_3 + \Gamma_4\\
&\geq -pc_{kj}^{p-1}\left(\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)\left(\sum_{l\neq k}|c_{lj}|^2 - pC\sqrt{\log\frac{K^2N}{\delta}}\alpha\sqrt{1-c_{kj}^2}\sum_{l\neq k}|c_{lj}|\right) - K2^{p-2}p^3C^2\log\frac{K}{\delta}\alpha^2 + \Gamma_3 + \Gamma_4\\
&\geq -pc_{kj}^{p-1}\left(\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)\left(\sum_{l\neq k}|c_{lj}|^2 - pC\sqrt{K\log\frac{K^2N}{\delta}}\alpha\sqrt{1-c_{kj}^2}\sqrt{\sum_{l\neq k}|c_{lj}|^2}\right) - K2^{p-2}p^3C^2\log\frac{K}{\delta}\alpha^2 + \Gamma_3 + \Gamma_4
\end{aligned}
$$

$$\geq -pc_{kj}^{p-1}\left(\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}(1-c_{kj}^2)\right)\left(1-pC\sqrt{K\log\frac{K^2N}{\delta}}\alpha(1-c_{kj}^2)\right)-K2^{p-2}p^3C^2\log\frac{K}{\delta}\alpha^2+\Gamma_3+\Gamma_4$$

$$\geq -\frac{p}{2}c_{kj}^{p-1}\left(\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)(1-c_{kj}^2)-K2^{p-2}p^3C^2\log\frac{K}{\delta}\alpha^2+\Gamma_3+\Gamma_4 \tag{G.17}$$

Finally, combining (G.14)(G.17), we have

$$\begin{aligned}\frac{d}{dt}c_{kj} &\geq pc_{kj}^{p-1}\left(1-\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)(1-c_{kj}^2)-C_1'\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}}-C_2'\log\frac{K}{\delta}\alpha^2-C_3'\log\frac{K^2N}{\delta}\alpha^3\\ &\quad-|\Gamma_1|-|\Gamma_2|-|\Gamma_3|-|\Gamma_4|\\ &\geq pc_{kj}^{p-1}\left(1-\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)(1-c_{kj})-C_1'\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}}-C_2'\log\frac{K}{\delta}\alpha^2-C_3'\log\frac{K^2N}{\delta}\alpha^3\\ &\quad-|\Gamma_1|-|\Gamma_2|-|\Gamma_3|-|\Gamma_4|\,,\end{aligned}$$

where the readers should be able to find universal constants C_1', C_2', C_3' from the derivation. It remains to bound these $|\Gamma_i|, i=1,\cdots,4$. Indeed, we can find the following bound:

$$\begin{aligned}|\Gamma_1| &= \left|\frac{1}{N}\sum_{i:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})\,p\left(\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle-\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)\right|\\ &\leq \max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})|\frac{1}{N}\sum_{i:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}\left|\,p\|\boldsymbol{x}_i\|^{p-1}\left(2\|\boldsymbol{x}_i\|\right)\right|\\ &\leq p2^{p+1}\max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})|\,,\\ |\Gamma_2| &= \left|\frac{1}{N}\sum_{i\in\mathcal{I}_k}y_i\,p\left(\left\langle\boldsymbol{\mu}_k+\boldsymbol{\varepsilon}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle\right|\\ &\leq \frac{1}{N}\sum_{i\in\mathcal{I}_k}p\|\boldsymbol{x}_i\|^{p-1}\left|\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle\right|\leq p2^{p-1}C\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}\\ |\Gamma_3| &= \left|-\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}y_i\,p\left(c_{lj}+\left\langle\boldsymbol{\varepsilon}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle\right|\\ &\leq \frac{1}{N}\sum_{i\in\mathcal{I}_k}p\|\boldsymbol{x}_i\|^{p-1}\left|\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle\right|\leq p2^{p-1}C\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}\\ |\Gamma_4| &= \left|-\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l}p(p-1)|c_{lj}|^{p-1}c_{kj}\left|\langle\boldsymbol{\varepsilon}_i,\boldsymbol{\mu}_k\rangle\right|\right|\\ &\leq \frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_k}p^2\left|\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle\right|\leq Kp^2C\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}\,.\end{aligned}$$

With these norm bounds, we have

$$\begin{aligned}&\frac{d}{dt}c_{kj}\\ &\geq pc_{kj}^{p-1}\left(1-\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)(1-c_{kj}^2)-C_1'\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}}-C_2'\log\frac{K}{\delta}\alpha^2\\ &\qquad-C_3'\log\frac{K^2N}{\delta}\alpha^3-C_4'\max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})|-C_5'\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}\\ &\geq pc_{kj}^{p-1}\left(1-\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)(1-c_{kj})-C_1\log\frac{K}{\delta}\alpha^2-C_2\max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})|\,.\end{aligned}$$

Lastly, our bound is

1. When we only assumed $c_{kj} \geq \tilde{\Delta}_1$:

$$\begin{aligned}\frac{d}{dt}c_{kj} &\geq pc_{kj}^{p-1}\left(1-\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)(1-c_{kj}) - C_1\log\frac{K}{\delta}\alpha^2 - C_2\max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})| \\ &\geq pc_{kj}^{p-1}\tilde{\Delta}_2(1-c_{kj}) - C_1\log\frac{K}{\delta}\alpha^2 - C_2\max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})|\end{aligned}$$

2. When we further assume $c_{kj} \geq \sqrt{\frac{4}{5}}$, we have that $\sum_{l\neq k} c_{lj}^2 = 1 - c_{kj}^2 \leq \frac{1}{5}$, then $\max_{l\neq k}|c_{lj}| \leq \sqrt{\frac{1}{5}}$. Therefore

$$\left(1-\max_{l\neq k}\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right) = \left(1-\left(\frac{\max_{l\neq k}|c_{lj}|}{c_{kj}}\right)^{p-2}\right) \geq 1-\frac{1}{2^{p-2}}\,, \tag{G.18}$$

which leads to

$$\frac{d}{dt}c_{kj} \geq pc_{kj}^{p-1}\left(1-\frac{1}{2^{p-2}}\right)(1-c_{kj}) - C_1\log\frac{K}{\delta}\alpha^2 - C_2\max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})|\,.$$

□

Lemma 7 (Restated). *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Given an initialization shape that satisfies Assumption 2 with non-degeneracy gap $\Delta > 0$, define*

$$t_{1a} := \inf\left\{t:\ \max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}(t)| > \min\left\{\frac{\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2(1-\tilde{\Delta}_1)}{2^{p+1}}, \frac{\tilde{\Delta}_1^{p-1}\tilde{\Delta}_2(1-\sqrt{2\Delta})}{2K2^{p+1}}\right\}\right\}. \tag{G.19}$$

Then the following holds $\forall t \leq t_{1a}$:

$$c_{kj}(t) \geq c_{kj}(0) \geq \tilde{\Delta}_1, \forall 1 \leq k \leq K, j \in \mathcal{N}_k\,, \tag{G.20}$$

and

$$\frac{|c_{lj}^{p-2}(t)|}{c_{kj}^{p-2}(t)} \leq \frac{|c_{lj}^{p-2}(0)|}{c_{kj}^{p-2}(0)} \leq 1-\tilde{\Delta}_2\,. \textit{and } \forall l\neq k, j\in\mathcal{N}_k\,. \tag{G.21}$$

Proof. When $1 \leq k \leq K_1, j \in \mathcal{N}_k$ implies that $j \in \mathcal{N}_+$ thus $\mathrm{sign}(v_j) = 1$. We shall primarily focus on this case as the proof is nearly identical for $K_1 + 1 \leq k \leq K$.

Overview of the proof: We will prove by contradiction, we let $\tau_1 := \inf\{t : \exists k, j \in \mathcal{N}_k,\ s.t.\ c_{kj}(t) < c_{kj}(0)\}$ and $\tau_2 := \inf\left\{t : \exists k, j \in \mathcal{N}_k, \&l \neq k,\ s.t.\ \frac{|c_{lj}^{p-2}(t)|}{c_{kj}(t)} > \frac{|c_{lj}^{p-2}(0)|}{c_{kj}(0)}\right\}$, by the continuity of every $c_{kj}(t)$ and every $\frac{|c_{lj}^{p-2}(t)|}{c_{kj}(t)}$ on the interval $[0, \tau_1]$ and $[0, \tau_2]$ respectively, we know that $c_{kj}(\tau_1) = c_{kj}(0)$ for some k, j and $\frac{|c_{lj}^{p-2}(\tau_2)|}{c_{kj}(\tau_2)} = \frac{|c_{lj}^{p-2}(0)|}{c_{kj}(0)}$ for some k, j, l. If $\min\{\tau_1, \tau_2\} > t_{1a}$ then there is nothing to be proved, otherwise, there are two cases:

1. When $\tau_1 = \min\{\tau_1, \tau_2\} \leq t_{1a}$, we show that for the k, j such that $c_{kj}(\tau_1) = c_{kj}(0)$

$$\frac{d}{dt}c_{kj}\bigg|_{t=\tau_1} \geq 0\,, \tag{G.22}$$

which says $c_{kj}(\tau_1 + \Delta t) \geq c_{kj}(0)$ for every sufficiently small Δt, contradicting the definition of τ_1.

2. When $\tau_2 = \min\{\tau_1, \tau_2\} \le t_{1a}$, we show that for the k, j, l such that $\frac{|c_{lj}^{p-2}(\tau_2)|}{c_{kj}(\tau_2)} = \frac{|c_{lj}^{p-2}(0)|}{c_{kj}(0)}$

$$\frac{d}{dt} \log \frac{|c_{lj}|}{c_{kj}}\bigg|_{t=\tau_2} \le 0\,, \tag{G.23}$$

which says $\frac{|c_{lj}(\tau_1+\Delta t)|}{c_{kj}(\tau_1+\Delta t)} \le c_{kj}(0)$ for every sufficiently small Δt (due to the monotonicity of $\log$ function), contradicting the definition of τ_2.

Time derivatives of log cosine angles We have shown in (D.6) that for every $1 \le l \le D$, whenever $|c_{lj}| > 0$,

$$\begin{aligned}
&\frac{d}{dt} \log |c_{lj}| \\
&= -\frac{1}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j \rangle > 0} \nabla_{\hat{y}} \ell_i \, p \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(\frac{\langle \boldsymbol{\mu}_l, \boldsymbol{x}_i \rangle}{c_{lj}} - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right) \\
&= -\frac{1}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j \rangle > 0} \nabla_{\hat{y}} \ell_i \, p \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \frac{\langle \boldsymbol{\mu}_l, \boldsymbol{x}_i \rangle}{c_{lj}} \\
&\qquad + \frac{1}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j \rangle > 0} \nabla_{\hat{y}} \ell_i \, p \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p} .
\end{aligned}$$

Case One: $\tau_1 = \min\{\tau_1, \tau_2\}$. This case is relatively easier as we have already shown Lemma 6. For the k, j such that $c_{kj} = \tilde{\Delta}$

$$\frac{d}{dt} c_{kj}\bigg|_{t=\tau_1} \ge p c_{kj}^{p-1} \tilde{\Delta}_2 (1 - c_{kj}) - C_1 \log \frac{K}{\delta} \alpha^2 - \underbrace{p 2^{p+1} \max_i |f^{(p)}(\boldsymbol{x}_i; \boldsymbol{\theta})|}_{(*)}\,,$$

by Lemma 6 (conditions are satisified at $t = \tau_1$ and one should be able to get (*) using the intermediate results in the proof of Lemma 6). Then

$$\begin{aligned}
\frac{d}{dt} c_{kj}\bigg|_{t=\tau_1} &\ge p \tilde{\Delta}_1^{p-1} \tilde{\Delta}_2 (1 - \tilde{\Delta}_1) - C_1 \log \frac{K}{\delta} \alpha^2 - p 2^{p+1} \max_i |f^{(p)}(\boldsymbol{x}_i; \boldsymbol{\theta})|\,, \\
&\overset{(\tau_1 \le t_{1a})}{\ge} p \tilde{\Delta}_1^{p-1} \tilde{\Delta}_2 (1 - \tilde{\Delta}_1) - C_1 \log \frac{K}{\delta} \alpha^2 - \frac{1}{2} p \tilde{\Delta}_1^{p-1} \tilde{\Delta}_2 (1 - \tilde{\Delta}_1) \\
&\ge \frac{1}{2} p \tilde{\Delta}_1^{p-1} \tilde{\Delta}_2 (1 - \tilde{\Delta}_1) - C_1 \log \frac{K}{\delta} \alpha^2 \ge 0\,,
\end{aligned}$$

for sufficiently small α.

Case Two: $\tau_2 = \min\{\tau_1, \tau_2\}$. For the k, j, l such that $\frac{|c_{lj}^{p-2}(\tau_2)|}{c_{kj}(\tau_2)} = \frac{|c_{lj}^{p-2}(0)|}{c_{kj}(0)}$, we have (although we omit the notation, **all the derivations are at** τ_2, so that c_{lj} can appear in the denominator of a fraction.)

$$\begin{aligned}
&\frac{d}{dt} \log \frac{|c_{lj}|}{c_{kj}} \\
&= \frac{d}{dt} \log |c_{lj}| - \frac{d}{dt} \log c_{kj} \\
&= -\frac{1}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j \rangle > 0} \nabla_{\hat{y}} \ell_i \, p \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(\frac{\langle \boldsymbol{\mu}_l, \boldsymbol{x}_i \rangle}{c_{lj}} - \frac{\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i \rangle}{c_{kj}} \right) \\
&= \frac{1}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j \rangle > 0} (y_i - f^{(p)}(\boldsymbol{x}_i; \boldsymbol{\theta})) \, p \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(\frac{\langle \boldsymbol{\mu}_l, \boldsymbol{x}_i \rangle}{c_{lj}} - \frac{\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i \rangle}{c_{kj}} \right) \\
&= \frac{1}{N} \sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j \rangle > 0} y_i \, p \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} \right\rangle \right)^{p-1} \left(\frac{\langle \boldsymbol{\mu}_l, \boldsymbol{x}_i \rangle}{c_{lj}} - \frac{\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i \rangle}{c_{kj}} \right)
\end{aligned}$$

$$
\begin{aligned}
&\underbrace{-\frac{1}{N}\sum_{i:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})\, p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{\langle \boldsymbol{\mu}_l,\boldsymbol{x}_i\rangle}{c_{lj}}-\frac{\langle \boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle}{c_{kj}}\right)}_{:=\Gamma_1}\\
=\;& \frac{1}{N}\sum_{i\in\mathcal{I}_k:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(\left\langle \boldsymbol{\mu}_k+\boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{\langle \boldsymbol{\mu}_l,\boldsymbol{\mu}_k+\boldsymbol{\varepsilon}_i\rangle}{c_{lj}}-\frac{\langle \boldsymbol{\mu}_k,\boldsymbol{\mu}_k+\boldsymbol{\varepsilon}_i\rangle}{c_{kj}}\right)\\
&\frac{1}{N}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(\left\langle \boldsymbol{\mu}_l+\boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{\langle \boldsymbol{\mu}_l,\boldsymbol{\mu}_l+\boldsymbol{\varepsilon}_i\rangle}{c_{lj}}-\frac{\langle \boldsymbol{\mu}_k,\boldsymbol{\mu}_l+\boldsymbol{\varepsilon}_i\rangle}{c_{kj}}\right)\\
&\frac{1}{N}\sum_{\substack{1\le l'\le K\\ l'\neq l,l'\neq k}}\sum_{i\in\mathcal{I}_{l'}:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(\left\langle \boldsymbol{\mu}_{l'}+\boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{\langle \boldsymbol{\mu}_l,\boldsymbol{\mu}_{l'}+\boldsymbol{\varepsilon}_i\rangle}{c_{lj}}-\frac{\langle \boldsymbol{\mu}_k,\boldsymbol{\mu}_{l'}+\boldsymbol{\varepsilon}_i\rangle}{c_{kj}}\right)+\Gamma_1\\
=\;& \frac{1}{N}\sum_{i\in\mathcal{I}_k:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(c_{kj}+\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(-\frac{1}{c_{kj}}+\frac{\langle \boldsymbol{\mu}_l,\boldsymbol{\varepsilon}_i\rangle}{c_{lj}}-\frac{\langle \boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle}{c_{kj}}\right)\\
&\frac{1}{N}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(c_{lj}+\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{1}{c_{lj}}+\frac{\langle \boldsymbol{\mu}_l,\boldsymbol{\varepsilon}_i\rangle}{c_{lj}}-\frac{\langle \boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle}{c_{kj}}\right)\\
&\frac{1}{N}\sum_{\substack{1\le l'\le K\\ l'\neq l,l'\neq k}}\sum_{i\in\mathcal{I}_{l'}:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(c_{l'j}+\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{\langle \boldsymbol{\mu}_l,\boldsymbol{\varepsilon}_i\rangle}{c_{lj}}-\frac{\langle \boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle}{c_{kj}}\right)+\Gamma_1\\
=\;& \frac{1}{N}\sum_{i\in\mathcal{I}_k:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(c_{kj}+\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(-\frac{1}{c_{kj}}\right)\\
&\frac{1}{N}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(c_{lj}+\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{1}{c_{lj}}\right)+\Gamma_1+\Gamma_2\,, \qquad \text{(G.24)}
\end{aligned}
$$

We view Γ_1, Γ_2 as "perturbation term" and will control their norms later. For the first two terms in (G.24), we have, respectively:

$$
\begin{aligned}
&\frac{1}{N}\sum_{i\in\mathcal{I}_k:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(c_{kj}+\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(-\frac{1}{c_{kj}}\right)\\
&=-\frac{p}{N}\sum_{i\in\mathcal{I}_k}\left(c_{kj}+\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\frac{1}{c_{kj}}\\
&=-\frac{p}{N}\sum_{i\in\mathcal{I}_k} c_{kj}^{p-2}\left(1-\frac{\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|}{c_{kj}}\right)^{p-1}\\
&\le-\frac{p}{N}\sum_{i\in\mathcal{I}_k} c_{kj}^{p-2}\left(1-\frac{\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|}{c_{kj}}\right)^{p-1}\\
&\le-\frac{p}{N}\sum_{i\in\mathcal{I}_k} c_{kj}^{p-2}\left(1-(p-1)\frac{\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|}{c_{kj}}\right)\\
&\le-pc_{kj}^{p-2}+p(p-1)\frac{\max_i\|\boldsymbol{\varepsilon}_i\|}{c_{kj}(0)}\ge-pc_{kj}^{p-2}+p(p-1)\sqrt{8\log\frac{4K^2N}{\delta}}\alpha\,,
\end{aligned}
$$

and similarly,

$$\begin{aligned}
&\frac{1}{N}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(c_{lj}+\left\langle \boldsymbol{\varepsilon}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{1}{c_{lj}}\right)\\
&\le \frac{p}{N}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} |y_i|\,|c_{lj}|^{p-2}\left(1+\frac{\left|\left\langle \boldsymbol{\varepsilon}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|}{c_{lj}}\right)^{p-1}\\
&\le \frac{p}{N}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} |c_{lj}|^{p-2}\left(1+(p-1)\frac{\left|\left\langle \boldsymbol{\varepsilon}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|}{c_{lj}}\right)\\
&\begin{cases}\le p|c_{lj}|^{p-2}+p(p-1)\sqrt{8\log\frac{4K^2N}{\delta}}\alpha, & 1\le l\le K\\ =0, & K<l\le D\end{cases}
\end{aligned}$$

Therefore we have

$$\begin{aligned}
\frac{d}{dt}\log\frac{|c_{lj}|}{c_{kj}} &\le -p(c_{kj}^{p-2}-|c_{lj}|^{p-2}\mathbb{1}_{l\le K})+2p(p-1)\sqrt{8\log\frac{4K^2N}{\delta}}\alpha-|\Gamma_1|-|\Gamma_2|\\
&\le -p(c_{kj}^{p-2}-|c_{lj}|^{p-2})+2p(p-1)\sqrt{8\log\frac{4K^2N}{\delta}}\alpha-|\Gamma_1|-|\Gamma_2|\\
&\le -pc_{kj}^{p-2}\left(1-\frac{|c_{lj}|^{p-2}}{c_{kj}^{p-2}}\right)+2p(p-1)\sqrt{8\log\frac{4K^2N}{\delta}}\alpha-|\Gamma_1|-|\Gamma_2|\\
&\le -p\tilde{\Delta}_1^{p-2}\tilde{\Delta}_2+2p(p-1)\sqrt{8\log\frac{4K^2N}{\delta}}\alpha-|\Gamma_1|-|\Gamma_2|\,.
\end{aligned}$$

It remains to bound these $|\Gamma_1|, |\Gamma_2|$. Indeed, we can find the following bound[4] (note that at τ_2, we have $|c_{lj}| = c_{kj}(1-\sqrt{2\Delta})$) and $c_{kj}\ge\tilde{\Delta}_1$):

$$\begin{aligned}
|\Gamma_1| &= \left|\frac{1}{N}\sum_{i:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})\, p\left(\left\langle \boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{\langle\boldsymbol{\mu}_l,\boldsymbol{x}_i\rangle}{c_{lj}}-\frac{\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle}{c_{kj}}\right)\right|\\
&\le \left|\frac{1}{N}\sum_{1\le i\le KN}|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})|\, p\left|\left\langle \boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^{p-1}\left(\frac{|\langle\boldsymbol{\mu}_l,\boldsymbol{x}_i\rangle|}{c_{kj}(1-\sqrt{2\Delta})}+\frac{|\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle|}{c_{kj}}\right)\right|\\
&\le \max_i|f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})|\frac{Kp2^{p+1}}{\tilde{\Delta}_1(1-\sqrt{2\Delta})} \overset{(\tau_2\le t_{1a})}{\le} \frac{1}{2}p\tilde{\Delta}_1^{p-2}\tilde{\Delta}_2\,,\\
|\Gamma_2| &= \left|\frac{1}{N}\sum_{i:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0} y_i\, p\left(\left\langle \boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\frac{\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}_i\rangle}{c_{lj}}-\frac{\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle}{c_{kj}}\right)\right|\\
&\le \left|\frac{1}{N}\sum_{1\le i\le KN} p\left|\left\langle \boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^{p-1}\left(\frac{|\langle\boldsymbol{\mu}_l,\boldsymbol{\varepsilon}_i\rangle|}{c_{kj}(1-\sqrt{2\Delta})}+\frac{|\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle|}{c_{kj}}\right)\right|\\
&\le \max_{i,k}|\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle|\frac{Kp2^{p+1}}{\tilde{\Delta}_1(1-\sqrt{2\Delta})} \le \frac{CKp2^{p+1}}{\tilde{\Delta}_1(1-\sqrt{2\Delta})}\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}
\end{aligned}$$

Finally, we arrived at

$$\begin{aligned}
&\frac{d}{dt}\log\frac{|c_{lj}|}{c_{kj}}\bigg|_{t=\tau_2}\\
&\le -p\tilde{\Delta}_1^{p-2}\tilde{\Delta}_2+2p(p-1)\sqrt{8\log\frac{4K^2N}{\delta}}\alpha+\frac{1}{2}p\tilde{\Delta}_1^{p-2}\tilde{\Delta}_2+\frac{CKp2^{p+1}}{\tilde{\Delta}_1(1-\sqrt{2\Delta})}\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}
\end{aligned}$$

[4] It may take some time to recollect the terms we omitted in (G.24) and regroup them into Γ_2

$$\leq -\frac{1}{2}p\tilde{\Delta}_1^{p-2}\tilde{\Delta}_2 + 2p(p-1)\sqrt{8\log\frac{4K^2N}{\delta}}\alpha + \frac{CKp2^{p+1}}{\tilde{\Delta}_1(1-\sqrt{2\Delta})}\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}} \leq 0\,, \quad \text{(G.25)}$$

for sufficiently small α. □

Lemma 8 (Restated). *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$, then with any balanced initialization scale $\epsilon \leq \frac{1}{4\sqrt{h}W_{\max}^2}$, the solution to gradient flow dynamics satisfies*

$$\max_k |f^{(p)}(\boldsymbol{\mu}_k; \boldsymbol{\theta}(t))| \leq 2\epsilon\sqrt{h}W_{\max}^2\,, \quad \forall t \leq \frac{1}{2^{p+2}K}\log\left(\frac{1}{2^{p-1}\sqrt{h}\epsilon}\right)\,. \quad \text{(G.26)}$$

Proof. Let $T := \inf\{t : \max_i |f(\boldsymbol{x}_k; \boldsymbol{\theta}(t))| > 2\epsilon\sqrt{h}W_{\max}^2\}$, then $\forall t \leq T, j \in [h]$, we have

$$\begin{aligned}
\frac{d}{dt}\|\boldsymbol{w}_j\|^2 =& -2\,\frac{\operatorname{sign}(v_j(0))}{N}\left(\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right)\|\boldsymbol{w}_j\|^2 \\
\leq& \; 2\frac{1}{N}\sum_{i=1}^{KN}|\nabla_{\hat{y}}\ell_i|\|\boldsymbol{w}_j\|^2\frac{(\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle)^p}{\|\boldsymbol{w}_j\|^p} \\
\leq& \; 2\frac{1}{N}\sum_{i=1}^{KN}|\nabla_{\hat{y}}\ell_i|\|\boldsymbol{w}_j\|^2\|\boldsymbol{x}_i\|^p \\
\leq& \; \frac{2^{p+1}}{N}\sum_{i=1}^{KN}(1+|f(\boldsymbol{x}_k;\boldsymbol{\theta}(t))|)\|\boldsymbol{w}_j\|^2 \\
\leq& \; \frac{2^{p+1}}{N}\sum_{i=1}^{KN}(1+4\epsilon\sqrt{h}W_{\max}^2)\|\boldsymbol{w}_j\|^2 \\
\leq& \; 2^{p+1}K(1+4\epsilon\sqrt{h}W_{\max}^2)\|\boldsymbol{w}_j\|^2\,. \qquad \text{(G.27)}
\end{aligned}$$

Let $\tau_j := \inf\{t : \|\boldsymbol{w}_j(t)\|^2 > \frac{2\epsilon M^2}{2^{p-1}\sqrt{h}}\}$, and let $j^* := \arg\min_j \tau_j$, then $\tau_{j^*} = \min_j \tau_j \leq T$ due to the fact that

$$|f(\boldsymbol{x}_i;\boldsymbol{\theta})| = \left|\sum_{j\in[h]}\mathbb{1}_{\langle \boldsymbol{w}_j, \boldsymbol{x}_i\rangle > 0}v_j\frac{(\langle \boldsymbol{w}_j, \boldsymbol{x}_k\rangle)^p}{\|\boldsymbol{w}_j\|^{p-1}}\right| \leq 2^p\sum_{j\in[h]}\|\boldsymbol{w}_j\|^2 \leq 2^p h\max_{j\in[h]}\|\boldsymbol{w}_j\|^2\,,$$

which implies "$|f(\boldsymbol{x}_k;\boldsymbol{\theta}(t))| > 2\epsilon\sqrt{h}W_{\max}^2 \Rightarrow \exists j, s.t. \|\boldsymbol{w}_j(t)\|^2 > \frac{\epsilon W_{\max}^2}{2^{p-1}\sqrt{h}}$".

Then for $t \leq \tau_{j^*}$, we have

$$\frac{d}{dt}\|\boldsymbol{w}_{j^*}\|^2 \leq 2^{p+1}K(+4\epsilon\sqrt{h}W_{\max}^2)\|\boldsymbol{w}_{j^*}\|^2\,. \quad \text{(G.28)}$$

By Grönwall's inequality, we have $\forall t \leq \tau_{j^*}$

$$\begin{aligned}
\|\boldsymbol{w}_{j^*}(t)\|^2 \leq& \; \exp\left(2^{p+1}K(1+4\epsilon\sqrt{h}W_{\max}^2)t\right)\|\boldsymbol{w}_{j^*}(0)\|^2\,, \\
=& \; \exp\left(2^{p+1}K(1+4\epsilon\sqrt{h}W_{\max}^2)t\right)\epsilon^2\|\boldsymbol{w}_{j^*0}\|^2 \\
\leq& \; \exp\left(2^{p+1}K(1+4\epsilon\sqrt{h}W_{\max}^2)t\right)\epsilon^2 W_{\max}^2\,.
\end{aligned}$$

Suppose $\tau_{j^*} < \frac{1}{2^{p+2}K}\log\left(\frac{1}{2^{p-1}\sqrt{h}\epsilon}\right)$, then by the continuity of $\|w_{j^*}(t)\|^2$, we have

$$\begin{aligned}
\frac{2\epsilon W_{\max}^2}{2^{p-1}\sqrt{h}} \leq \|\boldsymbol{w}_{j^*}(\tau_{j^*})\|^2 \leq& \; \exp\left(2^{p+1}K(1+4\epsilon\sqrt{h}W_{\max}^2)\tau_{j^*}\right)\epsilon^2 W_{\max}^2 \\
\leq& \; \exp\left(2^{p+1}K(1+4\epsilon\sqrt{h}W_{\max}^2)\frac{1}{2^{p+2}K}\log\left(\frac{1}{2^{p-1}\sqrt{h}\epsilon}\right)\right)\epsilon^2 W_{\max}^2
\end{aligned}$$

$$\leq \exp\left(\frac{1+4\epsilon\sqrt{h}W_{\max}^2}{2}\log\left(\frac{1}{2^{p-1}\sqrt{h}\epsilon}\right)\right)\epsilon^2 W_{\max}^2$$
$$\leq \exp\left(\log\left(\frac{1}{2^{p-1}\sqrt{h}\epsilon}\right)\right)\epsilon^2 W_{\max}^2 = \frac{\epsilon W_{\max}^2}{2^{p-1}\sqrt{h}},$$

which leads to a contradiction $2\epsilon \leq \epsilon$. Therefore, one must have $T \geq \tau_{j^*} \geq \frac{1}{2^{p+2}K}\log\left(\frac{1}{2^{p-1}\sqrt{h}\epsilon}\right)$. This finishes the proof. □

Lemma 9 (Restated). *Let $p > 2$. Given some $C > 0$, if for some $z(t)$, the following holds*

$$\frac{d}{dt}z \geq Cz^{p-1}, \forall t \in [0,T],\ z(0) = z_0,\ z(T) = z_1, \tag{G.29}$$

for some $0 < z_0 \leq z_1 < 1$. Then the travel time T for $z(t)$ to go from z_0 to z_1 satifies:

$$T \leq \frac{1}{(p-2)Cz_0^{p-2}}. \tag{G.30}$$

Proof. We have

$$\int_{z_0}^{z_1}\frac{1}{Cz^{p-1}}dz \geq \int_0^T dt, \tag{G.31}$$

thus

$$T \leq \frac{1}{(p-2)C}\left(\frac{1}{z_0^{p-2}} - \frac{1}{z_1^{p-2}}\right) \leq \frac{1}{(p-2)Cz_0^{p-2}}. \tag{G.32}$$

□

Lemma 10 (Restated). *Let $p > 2$. Given some $C > 0$, if for some $z(t)$, the following holds*

$$\frac{d}{dt}z \geq C(1-z), \forall t \in [0,T],\ z(0) = z_0,\ z(T) = z_1, \tag{G.33}$$

for some $0 < z_0 \leq z_1 < 1$. Then the travel time T for $z(t)$ to go from z_0 to z_1 satifies:

$$T \leq \frac{1}{C}\log\frac{1}{1-z_1}. \tag{G.34}$$

Proof. We have

$$\int_{z_0}^{z_1}\frac{1}{C(1-z)}dz \geq \int_0^T dt, \tag{G.35}$$

thus

$$T \leq \frac{1}{C}\left(\log\frac{1-z_0}{1-z_1}\right) \leq \frac{1}{C}\log\frac{1}{1-z_1}. \tag{G.36}$$

□

Lemma 11 (Restated). *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Suppose the following is true at some point on the GF trajectory:*

1. $c_{kj}(t) \geq 1 - 2C_a\log\frac{K}{\delta}\alpha^2,\ \forall k, j \in \mathcal{N}_k$;
2. $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 \leq 1 + C_w\log\frac{K}{\delta}\alpha^2,\ \forall k$;
3. $\sum_{j\in\mathcal{N}_c}\|\boldsymbol{w}_j\|^2 = \tilde{o}(\alpha^2)$.

Then the following holds for every $1 \leq k \leq K$, $i \in \mathcal{I}_k$,

$$f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}) \leq \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\left(1 + 2^{p+2}C\sqrt{\log\frac{K^2N}{\delta}}\alpha^2\right) + 2KC\alpha^p;$$
$$f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}) \geq \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\left(1 - 4pC\sqrt{\log\frac{K^2N}{\delta}}\alpha^2\right) - 2KC\alpha^p.$$

Proof. Our proof ignores terms related to neurons in $\mathcal{N}_c$ as they only introduce a $\tilde{o}(\alpha^2)$ perturbation.

$$
\begin{aligned}
&f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}) \\
&= \sum_{j=1}^{h} v_j \frac{\sigma^p(\langle \boldsymbol{w}_j, \boldsymbol{x}_i\rangle)}{\|\boldsymbol{w}_j\|^{p-1}} \\
&= \sum_{j=1}^{h} \|\boldsymbol{w}_j\|^2 \sigma^p\left(\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{x}_i\right\rangle\right) \\
&= \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{x}_i\right\rangle\right)^p + \sum_{l\neq k}\sum_{j\in\mathcal{N}_l} \|\boldsymbol{w}_j\|^2 \sigma^p\left(\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{x}_i\right\rangle\right) \\
&= \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(c_{kj} + \left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{\varepsilon}_i\right\rangle\right)^p + \sum_{l\neq k}\sum_{j\in\mathcal{N}_l} \|\boldsymbol{w}_j\|^2 \sigma^p\left(c_{lj} + \left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{\varepsilon}_i\right\rangle\right) \qquad \text{(G.37)}
\end{aligned}
$$

Upper bound:

$$
\begin{aligned}
&f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}) \\
&= \text{(G.37)} \\
&\leq \underbrace{\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(c_{kj} + \left|\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{\varepsilon}_i\right\rangle\right|\right)^p}_{(a)} + \underbrace{\left|\sum_{l\neq k}\sum_{j\in\mathcal{N}_l} \|\boldsymbol{w}_j\|^2 \sigma^p\left(c_{lj} + \left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{\varepsilon}_i\right\rangle\right)\right|}_{(b)}.
\end{aligned}
$$

For the first term, we have

$$
\begin{aligned}
(a) &\leq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 + \|\boldsymbol{\varepsilon}_i\|\sqrt{1-c_{kj}^2} + |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i\rangle|\right)^p \\
&\leq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 + \|\boldsymbol{\varepsilon}_i\|\sqrt{2(1-c_{kj})} + |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i\rangle|\right)^p \\
&\leq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 + 2C\sqrt{\log\frac{K^2N}{\delta}}\alpha^2 + C\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}\right)^p \\
&\leq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 + 2^{p+2}C\sqrt{\log\frac{K^2N}{\delta}}\alpha^2\right),
\end{aligned}
$$

for sufficiently small α. For the second term, we have

$$
\begin{aligned}
(b) &\leq 2\sum_{l\neq k} \left(|c_{lj}| + \left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|\right)^p \\
&\leq 2K \left(\sqrt{1-c_{kj}^2} + \|\boldsymbol{\varepsilon}_i\|\sqrt{1-c_{kj}^2} + |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i\rangle|\right)^p \\
&\leq 2K \left(\sqrt{2(1-c_{kj})} + \|\boldsymbol{\varepsilon}_i\|\sqrt{(1-c_{kj})} + |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i\rangle|\right)^p \\
&\leq 2K \left(C\alpha + C\sqrt{\log\frac{K^2N}{\delta}}\alpha^2 + C\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}\right)^p \leq 2KC\alpha^p. \qquad \text{(G.38)}
\end{aligned}
$$

Therefore

$$
f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}) \leq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 + 2^{p+2}C\sqrt{\log\frac{K^2N}{\delta}}\alpha^2\right) + 2KC\alpha^p. \qquad \text{(G.39)}
$$

Lower bound:

$$
f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})
$$

$$= \text{(G.37)}$$

$$\geq \underbrace{\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(c_{kj} + \left|\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{\varepsilon}_i \right\rangle\right|\right)^p}_{(a)} - \underbrace{\left|\sum_{l\neq k}\sum_{j\in\mathcal{N}_l} \|\boldsymbol{w}_j\|^2 \sigma^p \left(c_{lj} + \left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{\varepsilon}_i \right\rangle\right)\right|}_{\leq \text{(G.38)}}.$$

For the first term, we have

$$\begin{aligned}
(a) &\geq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 - \|\boldsymbol{\varepsilon}_i\|\sqrt{1-c_{kj}^2} - |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i\rangle|\right)^p \\
&\geq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 - \|\boldsymbol{\varepsilon}_i\|\sqrt{2(1-c_{kj})} - |\langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i\rangle|\right)^p \\
&\geq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 - 2C\sqrt{\log\frac{K^2N}{\delta}}\alpha^2 - C\sqrt{\log\frac{K^2N}{\delta}}\frac{\alpha}{\sqrt{D}}\right)^p \\
&\geq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 - 4pC\sqrt{\log\frac{K^2N}{\delta}}\alpha^2\right),
\end{aligned}$$

for sufficiently small α. Therefore

$$f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}) \geq \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \left(1 - 4pC\sqrt{\log\frac{K^2N}{\delta}}\alpha^2\right) - 2KC\alpha^p. \tag{G.40}$$

□

Lemma 12 (Restated). *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Suppose the following is true at some point on the GF trajectory:*

1. $c_{kj}(t) \geq 1 - 2C_a \log\frac{K}{\delta}\alpha^2,\ \forall k, j \in \mathcal{N}_k$;
2. $\sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \leq 1 + C_w \log\frac{K}{\delta}\alpha^2,\ \forall k$;
3. $\sum_{j\in\mathcal{N}_c} \|\boldsymbol{w}_j\|^2 = \tilde{o}(\alpha^2)$.

Furthermore, suppose additionally that for some $k, j \in \mathcal{N}_k$:

$$1 - 2C_a \log\frac{K}{\delta}\alpha^2 \leq c_{kj}(t) \leq 1 - C_a \log\frac{K}{\delta}\alpha^2;$$

Then the following holds for the same k, j,

$$\frac{d}{dt}c_{kj} \geq -CK\log\frac{K^2N}{\delta}\alpha^{\min\{p,4\}}.$$

Proof. When $1 \leq k \leq K_1$, $j \in \mathcal{N}_k$ implies that $j \in \mathcal{N}_+$ thus $\operatorname{sign}(v_j) = 1$. We shall primarily focus on this case as the proof is nearly identical for $K_1 + 1 \leq k \leq K$.

$$\begin{aligned}
&\frac{d}{dt}c_{kj} \\
&= -\frac{1}{N}\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i\, p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i\rangle - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right) \\
&= \frac{1}{N}\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} (y_i - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\, p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i\rangle - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right) \\
&= \underbrace{\frac{1}{N}\sum_{i\in\mathcal{I}_k}\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right)\, p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i\rangle - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)}_{(a)}
\end{aligned}$$

$$+\underbrace{\frac{1}{N}\sum_{i\in\mathcal{I}_k}\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2-f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})\right)\,p\left(\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle-\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)}_{(b)}$$

$$+\underbrace{\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}(y_i-f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\,p\left(\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle-\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)}_{(c)}. \tag{G.41}$$

We deal with these terms one by one:

Since $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\le 1+C\alpha^2$, for (a), there are two cases:

1. When $1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\ge 0$, Follow the same derivations from (G.12) to (G.14), we have

$$\begin{aligned}
(a)&=\left(1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right)\frac{1}{N}\sum_{i\in\mathcal{I}_k}p\left(\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle-\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)\\
&\ge\left(1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right)\left(pc_{kj}^{p-1}(1-c_{kj}^2)-Cp^2\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}}-2^{p-1}p^3C^2\log\frac{K}{\delta}\alpha^2-o(\alpha^2)\right)\\
&\ge\left(1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right)\left(p(1-C\alpha^2)^{p-1}\left(C\alpha^2-\frac{C^2}{4}\alpha^4\right)-Cp^2\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}}-2^{p-1}p^3C^2\log\frac{K}{\delta}\alpha^2-o(\alpha^2)\right)\\
&\ge 0\,,
\end{aligned}$$

   for some choice of C and sufficiently small α.

2. When $-C\alpha^2\le 1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\le 0$, we have

$$\begin{aligned}
(a)&=\left(1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right)\frac{1}{N}\sum_{i\in\mathcal{I}_k}p\left(\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle-\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)\\
&\ge-\left|1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right|\frac{1}{N}\sum_{i\in\mathcal{I}_k}p\left(\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(1-c_{kj}^2+|\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle|+\left|\left\langle\boldsymbol{\varepsilon}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|c_{kj}\right)\\
&\ge-\left|1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right|p2^{p-1}\left(1-c_{kj}^2+2|\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle|+\|\boldsymbol{\varepsilon}_i\|\sqrt{1-c_{kj}^2}c_{kj}\right)\\
&\ge C\sqrt{\log\frac{K^2N}{\delta}}\alpha^4\,,
\end{aligned}\tag{G.42}$$

Therefore, we always have

$$(a)\ge C\sqrt{\log\frac{K^2N}{\delta}}\alpha^4\,. \tag{G.43}$$

The second term (b) is easy: by Lemma 11, we know that $\left|\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2-f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})\right|=\mathcal{O}(\sqrt{\log\frac{K^2N}{\delta}}\alpha^2)$, then by the a similar derivation as in (G.42), we have

$$(b)=\frac{1}{N}\sum_{i\in\mathcal{I}_k}\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2-f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})\right)\,p\left(\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle-\left\langle\boldsymbol{x}_i,\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)$$

$$\geq -\left|\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta})\right| \frac{1}{N}\sum_{i\in\mathcal{I}_k} p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(1-c_{kj}^2 + |\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle| + \left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right| c_{kj}\right)$$

$$\geq C\log\frac{K^2N}{\delta}\alpha^4\,, \tag{G.44}$$

For the last term, we have

$$(c) = \frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}(y_i - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\, p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}_i\rangle - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right)$$

$$\geq -\frac{2}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l} p\left(c_{lj} + \left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle + c_{lj}c_{kj} + \left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right| c_{kj}\right)$$

$$\geq -\frac{2}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l} p\left(\sqrt{1-c_{kj}^2} + \|\boldsymbol{\varepsilon}_i\|\sqrt{1-c_{kj}^2}\right)^{p-1}\left(\langle\boldsymbol{\mu}_k,\boldsymbol{\varepsilon}_i\rangle + \sqrt{1-c_{kj}^2}c_{kj} + \|\boldsymbol{\varepsilon}_i\|\sqrt{1-c_{kj}^2}c_{kj}\right)$$

$$\geq -CK\sqrt{\log\frac{K^2N}{\delta}}\alpha^p\,.$$

Finally, we can conclude that

$$\frac{d}{dt}c_{kj} \geq -CK\log\frac{K^2N}{\delta}\alpha^{\min\{p,4\}}\,. \tag{G.45}$$

□

Lemma 13 (Restated). *Let $p > 2$. Condition on good event $\mathcal{E}_{good}$. Suppose the following is true at some point on the GF trajectory :*

1. $c_{kj}(t) \geq 1 - 2C_a\log\frac{K}{\delta}\alpha^2,\ k,j\in\mathcal{N}_k$;
2. $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 \leq 1 + C_w\log\frac{K}{\delta}\alpha^2,\ \forall k$;
3. $\sum_{j\in\mathcal{N}_c}\|\boldsymbol{w}_j\|^2 = \tilde{o}(\alpha^2)$.

Then the following holds for every $1\leq k\leq K$,

$$\frac{d}{dt}\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right) \leq 2\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 + C\log\frac{K}{\delta}\alpha^2\right)\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right),$$

and

$$\frac{d}{dt}\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right) \geq 2\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 - C\log\frac{K}{\delta}\alpha^2\right)\left(\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right),$$

where C is some universal constant such that $C < C_w$.

Proof. When $1\leq k\leq K_1, j\in\mathcal{N}_k$ implies that $j\in\mathcal{N}_+$ thus $\mathrm{sign}(v_j) = 1$. We shall primarily focus on this case as the proof is nearly identical for $K_1+1\leq k\leq K$. We start with (D.3):

$$\frac{d}{dt}\|\boldsymbol{w}_j\|^2 = \frac{2}{N}\left(\sum_{i:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}(y_i - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\,\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right)\|\boldsymbol{w}_j\|^2$$

$$= 2\Bigg(\underbrace{\frac{1}{N}\sum_{i\in\mathcal{I}_k:\langle\boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}(y_i - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\,\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p}_{(a)}$$

$$+ \underbrace{\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}(y_i - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p}_{:=\Gamma_1}\Bigg)\|\boldsymbol{w}_j\|^2$$

For the first term, we have

$$\begin{aligned}
(a) &= \frac{1}{N}\sum_{i\in\mathcal{I}_k:\langle \boldsymbol{x}_i,\boldsymbol{w}_j\rangle>0}(y_i - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p \\
&= \frac{1}{N}\sum_{i\in\mathcal{I}_k}(1 - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p \\
&= \frac{1}{N}\sum_{i\in\mathcal{I}_k}\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p + \sum_{l\neq k}\sum_{j\in\mathcal{N}_l}\|\boldsymbol{w}_j\|^2\sigma^p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)\right)\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p \\
&= \frac{1}{N}\sum_{i\in\mathcal{I}_k}\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right)\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p + \underbrace{\frac{1}{N}\sum_{i\in\mathcal{I}_k}\sum_{l\neq k}\sum_{j\in\mathcal{N}_l}\|\boldsymbol{w}_j\|^2\sigma^{2p}\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)}_{:=\Gamma_2}. \\
&= \frac{1}{N}\sum_{i\in\mathcal{I}_k}\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\left(c_{kj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right)\left(c_{kj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p + \Gamma_2\,.
\end{aligned}$$

We shall focus on the first term. With the Taylor expansion

$$\left(c_{kj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p = c_{kj}^p + pc_{kj}^{p-1}\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle + R_L\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^2, \tag{G.46}$$

where $R_L = \frac{p(p-1)(c_{kj}+\zeta_L)^{p-2}}{2}$ and ζ_L between 0 and $\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|$ comes from the Lagrange residual. Clearly $|R_L| \leq 2^{p-2}p^2$. Then we have

$$\begin{aligned}
&\frac{1}{N}\sum_{i\in\mathcal{I}_k}\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\left(c_{kj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right)\left(c_{kj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p \\
=& c_{kj}^p - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 c_{kj}^{2p} \\
&\qquad\left(pc_{kj}^{p-1} - 2\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 c_{kj}^{2p-1}\right)\frac{1}{N}\sum_{i\in\mathcal{I}_k}\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle \\
&\qquad\left(R_L - p^2c_{kj}^{2p-2} - 2c_{kj}^p R_L\right)\frac{1}{N}\sum_{i\in\mathcal{I}_k}\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^2 + o\left(\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^2\right)
\end{aligned}$$

Finally, we are ready to derive the upper and lower bound. For lower bound,

$$\begin{aligned}
&\frac{d}{dt}\|\boldsymbol{w}_j\|^2 \\
&= 2\left((a) + \Gamma_1\right)\|\boldsymbol{w}_j\|^2 \\
&\geq 2\left(\frac{1}{N}\sum_{i\in\mathcal{I}_k}\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\left(c_{kj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right)\left(c_{kj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p - |\Gamma_1| - |\Gamma_2|\right)\|\boldsymbol{w}_j\|^2 \\
&\geq 2\left(c_{kj}^p - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 c_{kj}^{2p} - C_1\frac{1}{N}\left|\left\langle \sum_{i\in\mathcal{I}_k}\boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right| - C_2\frac{1}{N}\sum_{i\in\mathcal{I}_k}\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^2\right.
\end{aligned}$$

$$
\begin{aligned}
&\quad -o\left(\left|\left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^2\right) - |\Gamma_1| - |\Gamma_2|\Bigg) \|\boldsymbol{w}_j\|^2 \\
&\geq 2\left(c_{kj}^p - \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 c_{kj}^{2p} - C\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}} - C^2\log\frac{K}{\delta}\alpha^2 - o(\alpha^2) - |\Gamma_1| - |\Gamma_2|\right)\|\boldsymbol{w}_j\|^2 \\
&\geq 2\left(\left(1-\frac{C\alpha^2}{2}\right)^p - \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 - C\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}} - C^2\log\frac{K}{\delta}\alpha^2 - o(\alpha^2) - |\Gamma_1| - |\Gamma_2|\right)\|\boldsymbol{w}_j\|^2 \\
&\geq 2\left(1 - p\frac{C\alpha^2}{2} - \sum_{j\in\mathcal{N}_k} \|\boldsymbol{w}_j\|^2 - C\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}} - C^2\log\frac{K}{\delta}\alpha^2 - o(\alpha^2) - |\Gamma_1| - |\Gamma_2|\right)\|\boldsymbol{w}_j\|^2
\end{aligned}
$$

It remains to bound these $|\Gamma_1|, |\Gamma_2|$. Indeed, we can find the following bound:

$$
\begin{aligned}
|\Gamma_1| &= \left|\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle>0} (y_i - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right| \\
&\leq \left|\frac{1}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l} |y_i - f^{(p)}(\boldsymbol{x}_i;\boldsymbol{\theta}))|\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right| \\
&\leq \left|\frac{2}{N}\sum_{l\neq k}\sum_{i\in\mathcal{I}_l}\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right| \\
&\leq \left|\frac{2}{N}\sum_{i\in\mathcal{I}_l}\sum_{l\neq k}\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right| \\
&\leq \left|\frac{2}{N}\sum_{i\in\mathcal{I}_l}\sum_{l\neq k}\left(c_{lj} + \left\langle \boldsymbol{\varepsilon}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right| \\
&\leq \left|\frac{2}{N}\sum_{i\in\mathcal{I}_l}\sum_{l\neq k}\left(\sqrt{1-c_{kj}^2} + \|\boldsymbol{\varepsilon}_i\|\sqrt{1-c_{kj}^2} + \langle \boldsymbol{\mu}_k, \boldsymbol{\varepsilon}_i\rangle\right)^p\right| \leq KC\alpha^p\,, \\
|\Gamma_2| &= \left|\frac{1}{N}\sum_{i\in\mathcal{I}_k}\sum_{l\neq k}\sum_{j\in\mathcal{N}_l}\|\boldsymbol{w}_j\|^2\sigma^{2p}\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)\right| \\
&\leq \left|\frac{2}{N}\sum_{i\in\mathcal{I}_k}\sum_{l\neq k}\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{2p}\right| \leq KC\alpha^{2p}\,.
\end{aligned}
$$

Therefore,

$$
\frac{d}{dt}\|\boldsymbol{w}_j\|^2 \geq 2\left(1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 - C\log\frac{K}{\delta}\alpha^2\right)\|\boldsymbol{w}_j\|^2\,,
$$

since when α is sufficiently small, the dominant term is of order α^2.

Similarly, for the upper bound, we can have

$$
\begin{aligned}
&\frac{d}{dt}\|\boldsymbol{w}_j\|^2 \\
&= 2\left((a) + \Gamma_1\right)\|\boldsymbol{w}_j\|^2 \\
&\leq 2\left(c_{kj}^p - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 c_{kj}^{2p} + C\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}} + C^2\log\frac{K}{\delta}\alpha^2 + o(\alpha^2) + |\Gamma_1| + |\Gamma_2|\right)\|\boldsymbol{w}_j\|^2
\end{aligned}
$$

$$\leq 2\left(1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\left(1-\frac{C\alpha^2}{2}\right)^{2p}-C\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}}+C^2\log\frac{K}{\delta}\alpha^2+o(\alpha^2)+|\Gamma_1|+|\Gamma_2|\right)\|\boldsymbol{w}_j\|^2$$

$$\leq 2\left(1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2+4p\frac{C\alpha^2}{2}+C\sqrt{\log\frac{K}{\delta}}\frac{\alpha}{\sqrt{N}}+C^2\log\frac{K}{\delta}\alpha^2+o(\alpha^2)+|\Gamma_1|+|\Gamma_2|\right)\|\boldsymbol{w}_j\|^2$$

$$\leq 2\left(1-\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2+C\log\frac{K}{\delta}\alpha^2\right)\|\boldsymbol{w}_j\|^2$$

□

Lemma 14 (Restated)**.** *Consider the same assumptions as in Proposition 2. Given the t_1 in Proposition 2, the following holds $\forall 1\leq k\leq K$:*

$$\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(t_1)\|^2\geq\exp\left(-\frac{2p^{p+2}K}{p(p-2)\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}}\right)W_{\min}^2\epsilon^2\,. \tag{G.47}$$

Proof. **The proof will be in two parts**: first, we define, for each k,

$$t_{\text{aux}}^{(k)}:=\inf\left\{t:\min_{j\in\mathcal{N}_k}c_{kj}(t)\geq\frac{2}{3}\right\}\overset{\text{(By its definition)}}{\leq}t_1\,, \tag{G.48}$$

and show that

$$\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(t_{\text{aux}}^{(k)})\|^2\geq\exp\left(-\frac{2p^{p+2}K}{p(p-2)\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}}\right)\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(0)\|^2\,. \tag{G.49}$$

Then we show that $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(t_1)\|^2$ is non-decreasing during $[t_{\text{aux}}^{(k)},t_1]$.

Lower bound at $t_{\text{aux}}^{(k)}$: We shall focus on the case $1\leq k\leq K_1$. In the proofs of Proposition 2, we have shown in (E.18) that when $t\leq t_{\text{aux}}^{(k)}\leq\bar{t}_1$, the following is true: $\forall j\in\mathcal{N}_k$

$$\frac{d}{dt}c_{kj}\geq\tilde{\Delta}_2pc_{kj}^{p-1}\,, \tag{G.50}$$

By Lemma 9, we have

$$t_{\text{aux}}^{(k)}=\inf\left\{t:c_{kj}\geq\frac{2}{3}\right\}\leq\frac{1}{p(p-2)\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}}\,. \tag{G.51}$$

Now we are ready to lower bound $\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(t_{\text{aux}}^{(k)})\|^2$: In the same way we derived (G.27), we can also obtain: for $t\leq t_1$,

$$\frac{d}{dt}\|\boldsymbol{w}_j\|^2\geq-2^{p+1}K(1+4\epsilon\sqrt{h}W_{\max}^2)\|\boldsymbol{w}_j\|^2\geq-2^{p+2}K\|\boldsymbol{w}_j\|^2\,, \tag{G.52}$$

thus

$$\frac{d}{dt}\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\geq-2^{p+2}K\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\,. \tag{G.53}$$

Finally, by Grönwall's inequality, we have

$$\begin{aligned}\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(t_{\text{aux}}^{(k)})\|^2&\geq\exp\left(-2p^{p+2}Kt_{\text{aux}}^{(k)}\right)\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j(0)\|^2\\&\geq\exp\left(-\frac{2p^{p+2}K}{p(p-2)\tilde{\Delta}_2\tilde{\Delta}_1^{p-2}}\right)W_{\min}^2\epsilon^2\,.\end{aligned}$$

Norm is non-decreasing afterward The techniques we will be using here is similar to those used in proving previous lemma, so we describe the argument briefly.

Suppose $1 \leq k \leq K$, we have the norm dynamics

$$
\begin{aligned}
&\frac{d}{dt}\|\boldsymbol{w}_j\|^2 \\
&= -\frac{2}{N}\left(\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}} \ell_i \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right)\|\boldsymbol{w}_j\|^2 \\
&= \frac{2}{N}\left(\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} y_i \left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p\right)\|\boldsymbol{w}_j\|^2 + \underbrace{\mathcal{O}(\epsilon)}_{\text{Recall how we handle } \Gamma_1 \text{ in the proof of Lemma 6}} \\
&\geq \frac{2}{N}\left(\sum_{i\in\mathcal{I}_k}\left|\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^p - \sum_{l\neq k}\sum_{i\in\mathcal{I}_l}\left|\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|^p\right)\|\boldsymbol{w}_j\|^2 + \mathcal{O}(\epsilon) \\
&\geq \frac{2}{N}\left(\sum_{i\in\mathcal{I}_k}\underbrace{\left(c_{kj} + \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^p}_{\text{Taylor expansion, refer to (G.46)}} - \sum_{l\neq k}\sum_{i\in\mathcal{I}_l}\underbrace{\left(|c_{lj}| + \left|\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right|\right)^p}_{\text{Taylor expansion, refer to (G.16)}}\right)\|\boldsymbol{w}_j\|^2 + \mathcal{O}(\epsilon) \\
&\geq 2\left(c_{kj}^p - \sum_{l\neq k}|c_{lj}|^p - \mathcal{O}\left(\sqrt{\log\frac{K^2N}{\delta}}\alpha\right) - \mathcal{O}\left(\alpha^2\right)\right)\|\boldsymbol{w}_j\|^2 + \mathcal{O}(\epsilon)\,.
\end{aligned}
$$

When $c_{kj} \geq \frac{2}{3}$, we have

$$
c_{kj}^p - \sum_{l\neq k}|c_{lj}|^p \geq c_{kj}^p - (1-c_{kj}^2)^{\frac{p}{2}} > 0\,, \tag{G.54}
$$

then for sufficiently small α and ϵ, we have $\frac{d}{dt}\|\boldsymbol{w}_j\|^2 \geq 0$. Then during $t_{\text{aux}}^{(k)} \leq t \leq t_1$, we have

$$
\frac{d}{dt}\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2 \geq 0\,. \tag{G.55}
$$

The proof is finished. □

Lemma 18. *15[Restated] Given some $0 < \Delta < \frac{1}{4}$, if for some $z(t)$, the following holds*

$$
\frac{d}{dt}z \geq (1-z-\Delta)z,\ z(0) = z_0,\ z(T) = z_1\,, \tag{G.56}
$$

for some $0 < z_0 \leq \frac{1}{4}$, and $z_0 \leq z_1 < 1-\Delta$. Then the travel time T for $z(t)$ to go from z_0 to z_1 satisfies:

$$
T \leq 2\left(\log\frac{1}{1-z_1-\Delta} + \log\frac{1}{z_0}\right)\,. \tag{G.57}
$$

Proof. We have

$$
\int_{z_0}^{z_1}\frac{1}{(1-z-\Delta)z}dz \geq \int_0^T dt\,, \tag{G.58}
$$

thus

$$
T \leq \frac{1}{1-\Delta}\left(\log\frac{1-z_0-\Delta}{1-z_1-\Delta} + \log\frac{z_1}{z_0}\right) \leq 2\left(\log\frac{1}{1-z_1-\Delta} + \log\frac{1}{z_0}\right)\,. \tag{G.59}
$$

□

Lemma 16 (Restated)**.** *Condition on good event $\mathcal{E}_{good}$, we have*

$$
\sum_{j\in\mathcal{N}_c}\|\boldsymbol{w}_j(t)\|^2 = \tilde{o}(\alpha^2)\,,\ \forall t \leq T^*\,. \tag{G.60}
$$

Proof. We deal with neurons with $\text{sign}(v_j) = +1$, the other case has a similar proof.

If $j \in \mathcal{N}_c$, it means $\boldsymbol{w}_{j0}$ is initialized into the void region with $c_{kj}(0) < 0$ and $|c_{kj}(t)| = \Theta(1)$, for $1 \le k \le K_1$. Therefore, the inner product between $\boldsymbol{w}_j(0)$ and a data point x_i from the k-th cluster is always negative, and this holds continuously as long as $c_{kj}(t) < 0$ and $|c_{kj}(t)| = \Theta(1)$.

We will show that

1. Until $t \le t^*$, we still have $c_{kj}(t) < 0$ and $|c_{kj}(t)| = \Theta(1)$, thus none of the data in positive clusters activates $\boldsymbol{w}_j$.
2. Then $c_{kj}(t) < 0$ and $|c_{kj}(t)| = \Theta(1)$ suggests that, $\sum_{j\in\mathcal{N}_c} \|\boldsymbol{w}_j\|^2$ has an at most $\mathcal{O}(\alpha^2)$ growth rate. And during $[t^*, T^*]$, with a slightly different argument, $\sum_{j\in\mathcal{N}_c} \|\boldsymbol{w}_j\|^2$ still has an at most $\mathcal{O}(\alpha^2)$ growth rate, thus continually stays at $\tilde{o}(\alpha^2)$.

The a more formal proof requires proof by contradiction, with previous lemmas we have proved, but the provided argument should easily be translated into a proof by contradiction.

First step: Given a $j \in \mathcal{N}_c \cup \mathcal{N}_+$ and $1 \le k \le K_1$, we have during $t \le t^*$,

$$\begin{aligned}
\frac{d}{dt}c_{kj} &= -\frac{1}{N}\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \; p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i\rangle - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right) \\
&= -\frac{1}{N}\sum_{K_1+1\le l\le K}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \; p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p-1}\left(\underbrace{\langle \boldsymbol{\mu}_k, \boldsymbol{x}_i\rangle}_{=\mathcal{O}(\frac{\alpha}{\sqrt{D}})} - \left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle c_{kj}\right) \\
&= -\frac{1}{N}\sum_{K_1+1\le l\le K}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i \; p\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p}\underbrace{c_{kj}}_{<0} + \mathcal{O}\left(\frac{\alpha}{\sqrt{D}}\right).
\end{aligned}$$

Since $\nabla_{\hat{y}}\ell_i$ is either < 0 (during alignment phase) or $= \mathcal{O}(\alpha^2)$ (after norm growth). Then we always have $\frac{d}{dt}c_{kj} = \mathcal{O}(\alpha^2)$. Therefore, $\forall t \le t^*$

$$c_{kj}(t) \le c_{kj}(0) + t\cdot\mathcal{O}(\alpha^2) \le c_{kj}(0) + t^*\mathcal{O}(\alpha^2) = c_{kj}(0) + \mathcal{O}\left(\alpha^2\log\frac{1}{\alpha}\right), \tag{G.61}$$

thus, we still have $c_{kj}(t) < 0$ and $|c_{kj}(t)| = \Theta(1)$.

Second step: During $[0, t^*]$, since none of the data in positive clusters activates $\boldsymbol{w}_j$, we have

$$\begin{aligned}
\frac{d}{dt}\|\boldsymbol{w}_j\|^2 &= -2\,\frac{1}{N}\left(\sum_{i:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i\;\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p}\right)\|\boldsymbol{w}_j\|^2 \\
&= -2\,\frac{1}{N}\left(\sum_{K_1+1\le l\le K}\sum_{i\in\mathcal{I}_l:\langle \boldsymbol{x}_i, \boldsymbol{w}_j\rangle > 0} \nabla_{\hat{y}}\ell_i\;\left(\left\langle \boldsymbol{x}_i, \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}\right\rangle\right)^{p}\right)\|\boldsymbol{w}_j\|^2.
\end{aligned}$$

Since $\nabla_{\hat{y}}\ell_i$ is either < 0 (during alignment phase) or $= \mathcal{O}(\alpha^2)$ (after norm growth). We have $\frac{d}{dt}\|\boldsymbol{w}_j\|^2 = \mathcal{O}(\alpha^2)\cdot\|\boldsymbol{w}_j\|^2$.

During $[t^*, T^*]$, we have $\nabla_{\hat{y}}\ell_i = \mathcal{O}(\alpha^2)$ for all i (as the consequence of $\left|1 - \sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\right| = \mathcal{O}(\alpha^2)$ and Lemma 11). Therefore we still have $\frac{d}{dt}\|\boldsymbol{w}_j\|^2 = \mathcal{O}(\alpha^2)\cdot\|\boldsymbol{w}_j\|^2$.

Then we have $\forall t \le T^*$,

$$\frac{d}{dt}\sum_{j\in\mathcal{N}_c}\|\boldsymbol{w}_j(t)\|^2 \le \mathcal{O}\left(\exp(\alpha^2 T^*)\right)\sum_{j\in\mathcal{N}_c}\|\boldsymbol{w}_j(0)\|^2 \le \mathcal{O}(1)\sum_{j\in\mathcal{N}_c}\|\boldsymbol{w}_j(0)\|^2 \le \mathcal{O}(\epsilon^2) = \tilde{o}(\alpha^2). \tag{G.62}$$

□

Lemma 17 (Restated). *If the neurons $\{\boldsymbol{w}_j\}_{j=1}^h$ satisfies the following for some $0 \le \delta \le 1$ and $\nu, \zeta > 0$:*

- $\max_k \max_{j \in \mathcal{N}_k} c_{kj}(t) \ge 1 - \delta$;
- $\left|1 - \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2\right| \le \nu$;
- $\sum_{j \in \mathcal{N}^c} \|\boldsymbol{w}_j\|^2 \le \zeta$,

then $\sup_{\boldsymbol{x} \in \mathbb{S}^{D-1}} \left|f^{(p)}(\boldsymbol{x}; \boldsymbol{\theta}) - F^{(p)}(\boldsymbol{x})\right| \le K(1+\nu)(2^p - 1)2\delta + K\nu + \zeta$

Proof.

$$
\begin{aligned}
& f^{(p)}(\boldsymbol{x}; \boldsymbol{\theta}) && \text{(G.63)} \\
&= \sum_{j=1}^h v_j \frac{\sigma^p(\langle \boldsymbol{w}_j, \boldsymbol{x}\rangle)}{\|\boldsymbol{w}_j\|^{p-1}} \\
&= \sum_{j=1}^h \operatorname{sign}(v_j)\|\boldsymbol{w}_j\|^2 \frac{\sigma^p(\langle \boldsymbol{w}_j, \boldsymbol{x}\rangle)}{\|\boldsymbol{w}_j\|^{p}} \\
&= \sum_{j=1}^h \operatorname{sign}(v_j)\|\boldsymbol{w}_j\|^2 \sigma^p\left(\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{x}\right\rangle\right) \\
&= \sum_{1 \le k \le K_1} \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \sigma^p\left(\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{x}\right\rangle\right) - \sum_{K_1+1 \le k \le K} \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \sigma^p\left(\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{x}\right\rangle\right) \\
&\qquad + \sum_{j \in \mathcal{N}^c} \operatorname{sign}(v_j)\|\boldsymbol{w}_j\|^2 \sigma^p\left(\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{x}\right\rangle\right) && \text{(G.64)}
\end{aligned}
$$

For the first term, we have $\forall \boldsymbol{x} \in \mathbb{S}^{D-1}$

$$
\begin{aligned}
& \left| \sum_{1 \le k \le K_1} \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \sigma^p\left(\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|}, \boldsymbol{x}\right\rangle\right) - \sum_{1 \le k \le K_1} \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) \right| \\
&\le \sum_{1 \le k \le K_1} \left| \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \sigma^p\left(\left\langle \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} - \boldsymbol{\mu}_k + \boldsymbol{\mu}_k, \boldsymbol{x}\right\rangle\right) - \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) \right| \\
&\le \sum_{1 \le k \le K_1} \left| \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \sigma^p\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle + \left\| \frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|} - \boldsymbol{\mu}_k \right\|\right) - \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) \right| \\
&= \sum_{1 \le k \le K_1} \left| \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \sigma^p\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle + 2(1 - c_{kj})\right) - \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) \right| \\
&\le \sum_{1 \le k \le K_1} \left| \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \sigma^p\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle + 2(1 - c_{kj})\right) - \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) \right| \\
&\qquad + \sum_{1 \le k \le K_1} \left| \sum_{j \in \mathcal{N}_k} \|\boldsymbol{w}_j\|^2 \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) - \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) \right| \\
&\le \sum_{1 \le k \le K_1} (1+\nu) \left| \sigma^p\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle + 2(1 - c_{kj})\right) - \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) \right| + \sum_{1 \le k \le K_1} \nu \left| \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) \right| \\
&\le \sum_{1 \le k \le K_1} (1+\nu) \left| \sigma^p\left(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle + 2(1 - c_{kj})\right) - \sigma^p(\langle \boldsymbol{\mu}_k, \boldsymbol{x}\rangle) \right| + K_1 \nu
\end{aligned}
$$

$$\leq\ K_1(1+\nu)(2^p-1)2\delta + K_1\nu\,,$$

where the last inequality is due to the following derivation (notice that ReLU $\sigma(z)$ is non-decreasing in z, and polynomial z^p is non-decreasing for $z>0$)

$$\begin{aligned}&|\sigma^p\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}\rangle+2(1-c_{kj})\right)-\sigma^p(\langle\boldsymbol{\mu}_k,\boldsymbol{x}\rangle)|\\ =&\sigma^p\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}\rangle+2(1-c_{kj})\right)-\left(\langle\boldsymbol{\mu}_k,\boldsymbol{x}\rangle\right)\\ \leq&(1+2\delta)^p-1\leq(2^p-1)2\delta\,.\end{aligned}$$

Similarly, for the second term, we have $\forall\boldsymbol{x}\in\mathbb{S}^{D-1}$

$$\begin{aligned}&\left|\sum_{K_1+1\leq k\leq K}\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\sigma^p\left(\left\langle\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|},\boldsymbol{x}\right\rangle\right)-\sum_{K_1+1\leq k\leq K}\sigma^p(\langle\boldsymbol{\mu}_k,\boldsymbol{x}\rangle)\right|\\ \leq&K_2(1+\nu)(2^p-1)2\delta+K_2\nu\end{aligned}$$

Lastly, for the third term, we have

$$\left|\sum_{j\in\mathcal{N}^c}\operatorname{sign}(v_j)\|\boldsymbol{w}_j\|^2\sigma^p\left(\left\langle\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|},\boldsymbol{x}\right\rangle\right)\right|\leq\sum_{j\in\mathcal{N}^c}\|\boldsymbol{w}_j\|^2\leq\zeta$$

Therefore, for any $\boldsymbol{x}\in\mathbb{S}^{D-1}$, we have

$$\begin{aligned}&\left|f^{(p)}(\boldsymbol{x};\boldsymbol{\theta})-F^{(p)}(\boldsymbol{x})\right|\\ \leq&\left|\sum_{1\leq k\leq K_1}\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\sigma^p\left(\left\langle\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|},\boldsymbol{x}\right\rangle\right)-\sum_{1\leq k\leq K_1}\sigma^p(\langle\boldsymbol{\mu}_k,\boldsymbol{x}\rangle)\right|\\ &\qquad+\left|\sum_{K_1+1\leq k\leq K}\sum_{j\in\mathcal{N}_k}\|\boldsymbol{w}_j\|^2\sigma^p\left(\left\langle\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|},\boldsymbol{x}\right\rangle\right)-\sum_{K_1+1\leq k\leq K}\sigma^p(\langle\boldsymbol{\mu}_k,\boldsymbol{x}\rangle)\right|\\ &\qquad+\left|\sum_{j\in\mathcal{N}^c}\operatorname{sign}(v_j)\|\boldsymbol{w}_j\|^2\sigma^p\left(\left\langle\frac{\boldsymbol{w}_j}{\|\boldsymbol{w}_j\|},\boldsymbol{x}\right\rangle\right)\right|\\ \leq&K(1+\nu)(2^p-1)2\delta+K\nu+\zeta\end{aligned}$$

□