TOWARDS UNDERSTANDING WHY FIXMATCH GENERALIZES BETTER THAN SUPERVISED LEARNING

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ABSTRACT

Semi-supervised learning (SSL), exemplified by FixMatch (Sohn et al., 2020), has shown significant generalization advantages over supervised learning (SL), particularly in the context of deep neural networks (DNNs). However, it is still unclear, from a theoretical standpoint, why FixMatch-like SSL algorithms generalize better than SL on DNNs. In this work, we present the first theoretical justification for the enhanced test accuracy observed in FixMatch-like SSL applied to DNNs by taking convolutional neural networks (CNNs) on classification tasks as an example. Our theoretical analysis reveals that the semantic feature learning processes in FixMatch and SL are rather different. In particular, FixMatch learns all the discriminative features of each semantic class, while SL only randomly captures a subset of features due to the well-known lottery ticket hypothesis. Furthermore, we show that our analysis framework can be applied to other FixMatch-like SSL methods, e.g., FlexMatch, FreeMatch, Dash, and SoftMatch. Inspired by our theoretical analysis, we develop an improved variant of FixMatch, termed Semantic-Aware FixMatch (SA-FixMatch). Experimental results corroborate our theoretical findings and the enhanced generalization capability of SA-FixMatch.

1 INTRODUCTION

Deep learning has made significant strides in various domains, showcasing applications in computer vision and natural language modeling (He et al., 2016; Vaswani et al., 2017; Radford et al., 2018; Dosovitskiy et al., 2020; Ho et al., 2020; Mildenhall et al., 2021; Ouyang et al., 2022; Schick et al., 2023). These advances stem from the scalable supervised learning where simultaneously scaling network size and labeled dataset size often enjoys better performance compared with small-scale network and dataset. Unfortunately, in real-world scenarios, labeled data are often scarce. Accordingly, the performance benefits given by a larger dataset can therefore come at a significant cost, since labeling data often requires human efforts and is very expensive, especially for the scenarios where experts are needed for labeling (Sohn et al., 2020; Ouali et al., 2020; Zhou et al., 2020; Zhang et al., 2021a; Pan et al., 2022).

To address this challenge, semi-supervised learning (SSL) (Berthelot et al., 2019b; Sohn et al., 2020; Zhang et al., 2021a) has emerged as a promising solution, demonstrating effectiveness across various tasks. The methodology of SSL involves training a network on both labeled and unlabeled data, where pseudo-labels for the unlabeled data are generated during training. As a leading SSL approach, FixMatch (Sohn et al., 2020) first generates a pseudo-label using the current model's prediction on a weakly augmented unlabeled image. It then selects the highly-confident pseudo-label as the training label of the strongly-augmented version of the same image, and trains the model together with the vanilla labeled data. By accessing large amount of cheap unlabeled data with minimal human effort, FixMatch has effortlessly and greatly improved supervised learning. Moreover, thanks to its effectiveness and simplicity, FixMatch has inspired many SoTA FixMatch-like SSL works, e.g., FlexMatch (Zhang et al., 2021a), FreeMatch (Wang et al., 2022b), Dash (Xu et al., 2021), and SoftMatch (Chen et al., 2023), and is seeing increasing applications across many deep learning tasks (Xie et al., 2020; Xu et al., 2021; Schmutz et al., 2022; Wang et al., 2022b; Chen et al., 2023).

Despite FixMatch's practical success, its theoretical foundations have not kept pace with its applications. Specifically, it remains unclear how FixMatch and its SL counterpart perform on deep neural networks, though heavily desired. Moreover, few theoretical studies explore the reasons for the practical superiority in test performance of SSL over SL on networks, let alone FixMatch. Most

existing theoretical works (He et al., 2022; Ţifrea et al., 2023) focus on analyzing the over-simplified models, e.g., linear learning models, which, however, differ significantly from the highly nonlinear and non-convex neural networks used in real-world SSL scenarios. Due to this gap, these works cannot well reveal the learning mechanism of SSL like FixMatch on networks. Some of other works (Rigollet, 2007; Van Engelen & Hoos, 2020; Guo et al., 2020) view the model as a black-box function under certain restrictive conditions, and their results do not reveal the dependence on the CNN models which is key for the superiority of FixMatch.

Contributions. To solve these issues, we theoretically justify the superior test performance of FixMatch-like SSL over SL in classification tasks, using FixMatch as a case study. We analyze the semantic learning processes in FixMatch and SL, elucidating their test performance differences and motivating the development of an enhanced FixMatch variant. Key contributions are summarized.

Firstly, we prove that on a three-layered CNN, FixMatch achieves better test accuracy than SL. Specifically, under the widely acknowledged multi-view data assumption (Allen-Zhu & Li, 2023), where multiple/single discriminative features exist in multi/single-view data, FixMatch consistently achieves zero training and test classification errors on both multi-view and single-view data. In contrast, while SL achieves zero test classification error on multi-view data, it suffers up to 50% test error on single-view data, showcasing FixMatch's superior generalization capacity compared to SL.

Secondly, our analysis highlights distinct feature learning processes between FixMatch and SL, directly affecting their test performance. We show that FixMatch comprehensively captures all semantic features within each class, virtually eliminating test classification errors. But SL learns only a partial set of these semantic features, and often fails on single-view samples due to the unlearned features, explaining its poor test classification accuracy on single-view data.

Finally, inspired by these insights, we introduce an improved version of FixMatch termed Semantic-Aware FixMatch (SA-FixMatch). This variant enhances FixMatch by masking learned semantics in unlabeled data, compelling the network to learn the remaining features missed by the current network. Our experimental evaluations confirm that SA-FixMatch achieves better generalization performance than FixMatch across various classification benchmarks.

2 Related Works

Modern Deep SSL Algorithms. Pseudo-labeling (Scudder, 1965; McLachlan, 1975) and consistency regularization (Bachman et al., 2014; Sajjadi et al., 2016; Laine & Aila, 2016) are the two important principles responsible for the success of modern deep SSL algorithms (Berthelot et al., 2019b;a; Xie et al., 2020; Zhang et al., 2021a; Xu et al., 2021; Wang et al., 2022b; Chen et al., 2023). FixMatch (Sohn et al., 2020), as a remarkable deep SSL algorithm, combines these principles with weak and strong data augmentations, achieving competitive results especially when labeled data is limited. Following FixMatch, several works, e.g., FlexMatch (Zhang et al., 2021a), Dash (Xu et al., 2021), FreeMatch (Wang et al., 2022b), and SoftMatch (Chen et al., 2023), try to improve FixMatch by adopting a flexible confidence threshold rather than the hard and fixed threshold adopted by FixMatch. These modern deep SSL algorithms can achieve remarkable test accuracy even trained with one labeled sample per semantic class (Sohn et al., 2020; Zhang et al., 2021a; Xu et al., 2021; Wang et al., 2022b; Chen et al., 2023).

SSL Generalization Error. Previous works on generalization capacity of SSL focus on a general machine learning setting (Rigollet, 2007; Singh et al., 2008; Van Engelen & Hoos, 2020; Wei et al., 2020; Guo et al., 2020; Mey & Loog, 2022). In particular, the authors here view the model as a black-box function under certain assumptions which does not reveal the dependence on model design. Some recent works (He et al., 2022; Ţifrea et al., 2023) analyze the generalization performance of SSL under the binary Gaussian mixture data distribution for linear learning models. The over-simplified model is significantly different from the highly nonlinear and non-convex neural networks.

Feature Learning Analysis Previous works on feature learning analysis have provided valuable insights into how neural networks learn and represent data (Wen & Li, 2021; 2022; Allen-Zhu & Li, 2022; 2023). For instance, Allen-Zhu & Li (2023) investigated the mechanisms through which ensemble method and knowledge distillation improve generalization performance, Wen & Li (2021) explained why contrastive learning can effectively capture true sparse features and avoid spurious dense features. Despite these advances, to the best of our knowledge, this work is the first to analyze the feature learning process of neural networks in the context of semi-supervised learning.

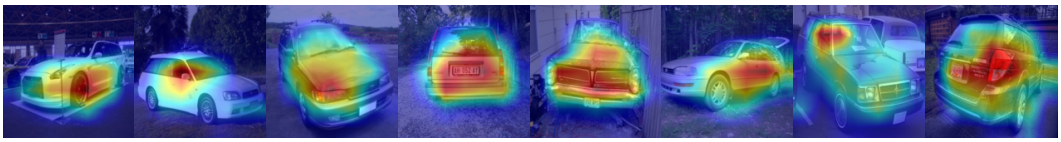

Figure 1: Visualization of pretrained ResNet-50 (He et al., 2016) using Grad-CAM. ResNet-50 locates different regions for different car images, e.g., wheel, rearview mirror, front light, and door.

3 Problem Setup

Here we first introduce the necessary multi-view data assumption used in this work, and then present FixMatch, a popular and classic SSL approach, to train a three-layered CNN on a k-class classification problem. For brevity, we use $O(\cdot), \Omega(\cdot), \Theta(\cdot)$ to hide constants w.r.t. k and use $\tilde{O}(\cdot), \tilde{\Omega}(\cdot), \tilde{\Theta}(\cdot)$ to hide polylogarithmic factors. Let $\mathrm{poly}(k)$ and $\mathrm{polylog}(k)$ respectively denote $\Theta(k^C)$ and $\Theta(\log^C k)$ with a constant $C > 0$. We use $[n]$ to denote the set of $\{1, 2, \ldots, n\}$.

3.1 Multi-View Data Distribution

Following Allen-Zhu & Li (2023), we employ the multi-view data assumption that suggests each semantic class possesses multiple distinct features—such as car lights and wheels—that can independently facilitate correct classification. To empirically validate this hypothesis, we utilize Grad-CAM (Selvaraju et al., 2017) to identify class-specific regions within images. As shown in Figure 1, Grad-CAM distinctly highlights separate and non-overlapping regions, such as different parts of a car, that contribute to its recognition. These results corroborate the findings of Allen-Zhu & Li (2023), confirming the presence of multiple independent discriminative features within each semantic class.

Now we introduce the multi-view data assumption in Allen-Zhu & Li (2023), which considers a dataset with k semantic classes. Let each sample pair (X, y) consists of the sample X, which is comprised of a set of P patches $\{x_p \in \mathbb{R}^d\}_{p=1}^P$, and $y \in [k]$ as the class label. We assume each class i has two discriminative features, $v_{i,1}$ and $v_{i,2}$ in $\mathbb{R}^d$, capable of independently ensuring correct classification. While this analysis focuses on two features per class, the methodology extends to multiple features. Below we define $\mathcal{V}$ as the set of all discriminative features across the k classes:

$$\mathcal{V} = \{v_{i,1}, v_{i,2} \mid \|v_{i,1}\|_2 = \|v_{i,2}\|_2 = 1, v_{i,l} \perp v_{i',l'} \text{ if } (i,l) \neq (i',l')\}_{i=1}^k, \tag{1}$$

where the conditions ensure the discrimination of each class and each feature in the data. Accordingly, we define the multi- and singe- view distribution $\mathcal{D}_m$ and $\mathcal{D}_s$, where data from $\mathcal{D}_m$ has two features, and data from $\mathcal{D}_s$ have one single feature. Set sparsity parameter $s = \mathrm{polylog}(k)$ and constant C_p.

Definition 1 (Informal, Data distribution (Allen-Zhu & Li, 2023))**.** *The data distribution $\mathcal{D}$ contains data from the multi-view data distribution $\mathcal{D}_m$ with probability $1 - \mu$, and data from the single-view data distribution $\mathcal{D}_s$ with probability $\mu = \frac{1}{\mathrm{poly}(k)}$. We define $(X, y) \sim \mathcal{D}$ by randomly uniformly selecting a label $y \in [k]$ and generate data X accordingly as follows.*

(a) *Sample a set of noisy features $\mathcal{V}'$ uniformly at random from $\{v_{i,1}, v_{i,2}\}_{i \neq y}$, each with probability s/k. Then the whole feature set of X is $\mathcal{V}(X) = \mathcal{V}' \cup \{v_{y,1}, v_{y,2}\}$, i.e., the noisy feature set $\mathcal{V}'$ plus the main features $\{v_{y,1}, v_{y,2}\}$.*

(b) *For each $v \in \mathcal{V}(X)$, pick C_p disjoint patches in $[P]$ and denote them as $\mathcal{P}_v(X)$. For a patch $p \in \mathcal{P}_v(X)$, we set $x_p = z_p v +$ "noises" $\in \mathbb{R}^d$, where the coefficients $z_p \geq 0$ satisfy:*
(b1) *For "multi-view" data $(X, y) \in \mathcal{D}_m$, $\sum_{p \in \mathcal{P}_v(X)} z_p \in [1, O(1)]$ when $v \in \{v_{y,1}, v_{y,2}\}$ and $\sum_{p \in \mathcal{P}_v(X)} z_p \in [\Omega(1), 0.4]$ when $v \in \mathcal{V}(X) \setminus \{v_{y,1}, v_{y,2}\}$.*
(b2) *For "single-view" data $(X, y) \in \mathcal{D}_s$, pick a value $\hat{l} \in [2]$ randomly uniformly as the index of the main feature. Then $\sum_{p \in \mathcal{P}_v(X)} z_p \in [1, O(1)]$ when $v = v_{y,\hat{l}}$, $\sum_{p \in \mathcal{P}_v(X)} z_p \in [\rho, O(\rho)]$ ($\rho = k^{-0.01}$) when $v = v_{y,3-\hat{l}}$, and $\sum_{p \in \mathcal{P}_v(X)} z_p = \frac{1}{\mathrm{polylog}(k)}$ when $v \in \mathcal{V}(X) \setminus \{v_{y,1}, v_{y,2}\}$.*
(c) *For each purely noisy patch $p \in [P] \setminus \cup_{v \in \mathcal{V}} \mathcal{P}_v(X)$, we set $x_p =$ "noises".*

For the details of Def. 1, please see Def. 7 in Appendix A. According to the definition, a multi-view sample $(X, y) \in \mathcal{D}_m$ has patches with two main features $v_{y,1}$ and $v_{y,2}$ plus some noises, while a single-view sample $(X, y) \in \mathcal{D}_s$ has patches with only one primary feature $v_{y,1}$ or $v_{y,2}$ plus noises.

3.2 FixMatch for Training Neural networks

Here we introduce the representative SSL approach, FixMatch and its variants, on a k-class classification problem, the most popular task in SSL.

Neural Network For the network, we assume it as a three-layer CNN which has mk convolutional kernels $\{w_{i,r}\}_{i\in[k],r\in[m]}$. Its classification probability $\mathbf{logit}_i(F, X)$ on class $i \in [k]$ is defined as

$$\mathbf{logit}_i(F, X) = \exp(F_i(X)) / \sum\nolimits_{j\in[k]} \exp(F_j(X)), \tag{2}$$

where $F(X) = (F_1(X), \cdots, F_k(X)) \in \mathbb{R}^d$ is defined as

$$F_i(X) = \sum\nolimits_{r\in[m]} \sum\nolimits_{p\in[P]} \overline{\mathrm{ReLU}}(\langle w_{i,r}, x_p\rangle), \quad (\forall i \in [k]). \tag{3}$$

Here $\overline{\mathrm{ReLU}}$ (Allen-Zhu & Li, 2023) is a smoothed ReLU that outputs zero for negative values, reduces small positive values to diminish noises, and maintains a linear relationship for larger inputs. This ensures $\overline{\mathrm{ReLU}}$ to focus on important features while filtering out noises. See details in Appendix A.

This three-layer network contains the essential components of neural networks, including linear mapping, activation, and a softmax layer, and thus its analysis provides valuable insights into understanding networks trained using SSL. Notably, many other theoretical works also ultilize shallow networks (e.g., two-layer models) to derive insights into deep networks, as seen in the analyses of Li & Yuan (2017); Arora et al. (2019); Zhang et al. (2021b). Additionally, this setup precisely matches the network architecture in Allen-Zhu & Li (2023), enabling direct comparisons between our FixMatch results and the SL findings in Allen-Zhu & Li (2023) in Sec. 4.2.

SSL Training For FixMatch-like SSLs, at t-th iteration, it has two types of losses: 1) a supervised one $L_s^{(t)}$ on labeled data, and 2) an unsupervised one $L_u^{(t)}$ on unlabeled data. For $L_s^{(t)}$, it is cross-entropy loss on labeled dataset $\mathcal{Z}_l$:

$$L_s^{(t)} = \mathbb{E}_{(X_l,y)\sim\mathcal{Z}_l} L_s^{(t)}(X_l, y) = \mathbb{E}_{(X_l,y)\sim\mathcal{Z}_l}[-\log \mathbf{logit}_y(F^{(t)}, \alpha(X_l))], \tag{4}$$

where $\alpha(X)$ is a weak augmentation applied to input X. In practice, $\alpha(X)$ includes a random horizontal flip and a random crop that retains most region of the image (Sohn et al., 2020; Zhang et al., 2021a) which often do not alter the semantic features. So we treat the weak augmentation as an identity map to simplify our analysis. Additionally, experiments in Appendix K.2 also verify that weak augmentation does not have significant effect on the training of SSL.

For the unsupervised loss $L_u^{(t)}(X_u)$, it feeds a weakly-augmented unlabeled sample $\alpha(X_u)$ into the network to get the model classification probability $\mathbf{logit}_i(F^{(t)}, \alpha(X_u))$ $(i \in [k])$. Next, if the maximal classification probability is highly-confident, i.e., $\max_i \mathbf{logit}_i(F^{(t)}, \alpha(X_u)) \geq \mathcal{T}_t$ with a confidence threshold $\mathcal{T}_t \in (0, 1]$, FixMatch-like SSLs use it as the pseudo-label to supervise the corresponding strongly-augmented image $\mathcal{A}(X_u)$:

$$L_u^{(t)} = \mathbb{E}_{X_u\sim\mathcal{Z}_u} L_u^{(t)}(X_u) = \mathbb{E}_{X_u\sim\mathcal{Z}_u}[-\mathbb{I}_{\{\mathbf{logit}_b(F^{(t)},\alpha(X_u))\geq\mathcal{T}_t\}} \log \mathbf{logit}_b(F^{(t)}, \mathcal{A}(X_u))], \tag{5}$$

where b is the pseudo-label $b = \arg\max_{i\in[k]}\{\mathbf{logit}_i(F^{(t)}, \alpha(X_u))\}$. Here, FixMatch-like SSLs use pseudo-labels generated from weakly-augmented samples to supervise the corresponding strongly-augmented ones, enforcing consistency regularization on model predictions, which we will show in Sec. 4.2 is crucial for the superior generalization performance of SSL compared to SL. For threshold $\mathcal{T}_t$, FixMatch (Sohn et al., 2020) sets it as a constant threshold $\mathcal{T}_t = \tau$ (e.g. 0.95) for high pseudo-label quality. Current SoTA SSLs, e.g., FlexMatch (Zhang et al., 2021a), FreeMatch (Wang et al., 2022b), Dash (Xu et al., 2021), and SoftMatch (Schick et al., 2023), follow FixMatch framework, and often design their own confidence threshold $\mathcal{T}_t$ in Eq. (5). This decides the applicability of our theoretical results on FixMatch in Sec. 4 to these FixMatch-like SSLs. See details in Appendix G.

For strong augmentation $\mathcal{A}(\cdot)$, it often uses CutOut (DeVries & Taylor, 2017) and RandAugment (Cubuk et al., 2020). CutOut randomly masks a large square region of the input image, potentially removing some semantic features. Experimental results in Appendix K.1 confirm the significant impact of CutOut on image semantics and model performance. RandAugment includes various transformations, e.g., rotation, translation, solarization. Appendix K.1 reveals that those augmentations that may remove data semantics also have a large impact on model performance. Based on these findings, we model the probabilistic feature removal effect of $\mathcal{A}(\cdot)$ for our analysis in Sec. 4.1.

Now given the training loss $L^{(t)} = L_s^{(t)} + \lambda L_u^{(t)}$ at the t-th iteration, we adopt the widely used gradient descent (GD) to update the model parameters $\{w_{i,r}\}_{i\in[k],r\in[m]}$ in the network:

$$w_{i,r}^{(t+1)} = w_{i,r}^{(t)} - \eta \nabla_{w_{i,r}} L_s^{(t)} - \lambda\eta \nabla_{w_{i,r}} L_u^{(t)}, \tag{6}$$

where $\eta \geq 0$ is a learning rate, and $\lambda > 0$ is the weight to balance the two losses. According to the common practice (Sohn et al., 2020; Zhang et al., 2021a; Xu et al., 2021; Wang et al., 2022b; Chen et al., 2023), we set $\lambda = 1$ in both our theoretical analysis and experiments.

4 Main Results

In this section, we first prove the superior generalization performance of FixMatch compared with SL. Next we analyze the intrinsic reasons for its superiority over SL via revealing and comparing the semantic feature learning process. Finally, inspired by our theoretical insights, we propose a Semantic-Aware FixMatch (SA-FixMatch) to better learn the semantic features.

4.1 Results on Test Performance

Here we analyze the performance of FixMatch, and compare it with its SL counterpart, whose implementation is simply setting the weight $\lambda = 0$ for the unsupervised loss in Eq. (6).

As discussed in Sec. 3.1, we assume that the training dataset $\mathcal{Z}$ follows the multi-view distribution $\mathcal{D}$ as defined in Def. 1, with multi-view and single-view sample ratios of $1-\mu$ and μ, respectively. Each class $i \in [k]$ in $\mathcal{Z}$ is associated with two i.i.d. semantic features $v_{i,1}$ and $v_{i,2}$, both of which are capable of predicting label i. Multi-view samples contain both semantics, while single-view samples contain only one. For clarity, we denote the labeled multi-view and single-view subsets of $\mathcal{Z}$ as $\mathcal{Z}_{l,m}$ and $\mathcal{Z}_{l,s}$, respectively, and the corresponding unlabeled subsets as $\mathcal{Z}_{u,m}$ and $\mathcal{Z}_{u,s}$. Below, we outline the necessary assumptions on the dataset and model initialization.

Assumption 2. ***(a)*** *The training dataset $\mathcal{Z}$ follows the distribution $\mathcal{D}$, and the size of the unlabeled data satisfies $N_c = |\mathcal{Z}_{u,m} \cup \mathcal{Z}_{u,s}| = |\mathcal{Z}_{l,m} \cup \mathcal{Z}_{l,s}| \cdot \mathrm{poly}(k)$.*
(b) *Each convolution kernel $w_{i,r}^{(0)}$ ($i \in [k]$, $r \in [m]$) is initialized by a Gaussian distribution $\mathcal{N}(0, \sigma_0^2\mathbf{I})$, where $\sigma_0^{q-2} = 1/k$ and $q \geq 3$ is given in the definition of $\overline{\mathrm{ReLU}}$.*

Assumption 2(a) indicates that number of unlabeled data significantly exceeds that of the labeled data, a common scenario given the lower cost of acquiring unlabeled versus labeled data. The Gaussian initialization in Assumption 2(b) accords with the standard initialization in practice, and is mild. Moreover, we also need assumptions on the strong augmentation $\mathcal{A}(\cdot)$ to formulate the effect of consistency regularization in unsupervised loss (5).

Assumption 3. *Suppose for a given image, strong augmentation $\mathcal{A}(\cdot)$ randomly removes its semantic patches and noisy patches with probabilities π_2 and $1-\pi_2$, respectively.*
(1) For a single-view image, the sole semantic feature is removed with probability π_2.
(2) For a multi-view image, either of the two features, $v_{i,1}$ or $v_{i,2}$, is removed with probabilities $\pi_1\pi_2$ and $(1-\pi_1)\pi_2$, respectively. We define strong augmentation $\mathcal{A}(\cdot)$ for multi-view data: for $p \in [P]$,

$$\mathcal{A}(x_p) = \begin{cases} \max(\epsilon_1, \epsilon_2)x_p, & \text{if } v_{y,1} \text{ is in the patch } x_p, \\ \max(1-\epsilon_1, \epsilon_2)x_p, & \text{if } v_{y,2} \text{ is in the patch } x_p, \\ (1-\epsilon_2)x_p, & \text{otherwise (noisy patch)}, \end{cases} \tag{7}$$

where ϵ_1 and ϵ_2 are i.i.d. Bernoulli variables, respectively equaling to 0 with probabilities π_1 and π_2.

As discussed in Sec. 3, for strong augmentation $\mathcal{A}(\cdot)$, we focus on its probabilistic feature removal effect on the input image, caused by techniques like CutOut and certain operations in RandAugment, such as solarization. The use of the $\max$ function ensures that ϵ_1 is active when $\epsilon_2 = 0$, indicating that $\mathcal{A}(\cdot)$ removes one feature at a time. Further details are provided in Appendix A.

Based on the above assumptions, we analyze the training and test performance of FixMatch, and summarize our main results in Theorem 4 with its proof in Appendix F.

Theorem 4. *Suppose Assumptions 2,3 holds. For sufficiently large k and $m = \mathrm{polylog}(k)$, by setting $\eta \leq 1/\mathrm{poly}(k)$, after running FixMatch for $T = \mathrm{poly}(k)/\eta$ iterations, we have:*

(a) Training performance is good. *For all training samples $(X, y) \in \mathcal{Z}$, with probability at least $1 - e^{-\Omega(\log^2 k)}$, we have*

$$F_y^{(T)}(X) \geq \max_{j \neq y} F_j^{(T)}(X) + \Omega(\log k).$$

(b) Test performance is good. *With probability at least $1 - e^{-\Omega(\log^2 k)}$ over the selection of any multi-view test sample $(X, y) \sim \mathcal{D}_m$ and single-view test sample $(X, y) \sim \mathcal{D}_s$, we have*

$$F_y^{(T)}(X) \geq \max_{j \neq y} F_j^{(T)}(X) + \Omega(\log k).$$

Theorem 4(a) shows that after $T = \text{poly}(k)/\eta$ training iterations, the network $F^{(T)}$ trained by FixMatch can well fit the training dataset $\mathcal{Z}$, and achieves zero classification error. This is because for any training sample (X, y), the predicted value $F_y(X)$ for the true label y consistently exceeds the predictions $F_j(X)$ $(j \neq y)$ for other class labels, ensuring correct classification. More importantly, Theorem 4(b) establishes that the trained network $F^{(T)}$ can also accurately classify test samples $(X, y) \sim \mathcal{D}_m \cup \mathcal{D}_s$, validating the generalization performance of FixMatch.

Now we compare FixMatch with SL (i.e. $\lambda = 0$ in Eq. (6)) under the same data distribution and the same network. According to Allen-Zhu & Li (2023), under the same assumption of Theorem 4, after running standard SL for $T = \text{poly}(k)/\eta$ iterations, SL can achieve good training performance as in Theorem 4(a). However, SL exhibits inferior test performance compared to FixMatch. Specifically, both methods achieve zero classification error on multi-view samples $(X, y) \sim \mathcal{D}_m$, while on single-view data $(X, y) \sim \mathcal{D}_s$, SL achieves only about 50% classification accuracy, significantly lower than FixMatch's nearly 100% accuracy. See Appendix B for more details on SL.

For other FixMatch-like SSLs such as FlexMatch (Zhang et al., 2021a), FreeMatch (Wang et al., 2022b), Dash (Xu et al., 2021), and SoftMatch (Chen et al., 2023), our theoretical results in Theorem 4 and the comparison with SL are also broadly applicable. Due to space limitations, we defer the discussions to Appendix G. These theoretical results justify the superiority of FixMatch-like SSLs over SL, aligning with empirical evidence from several studies (Sohn et al., 2020; Zhang et al., 2021a; Wang et al., 2022b; Xu et al., 2021; Chen et al., 2023).

4.2 Results on Feature Learning Process

Here we analyze the feature learning process in FixMatch and SL, and explain their rather different test performance as shown in Sec. 4.1. To monitor the feature learning process, we define

$$\Phi_{i,l}^{(t)} := \sum\nolimits_{r \in [m]} [\langle w_{i,r}^{(t)}, v_{i,l} \rangle]^+, \qquad (i \in [k], l \in [2])$$

as a feature learning indicator of feature $v_{i,l}$ in class i $(i \in [k], l \in [2])$, since it denotes the total positive correlation score between the l-th feature $v_{i,l}$ of class i and all the m convolution kernels $w_{i,r}$ $(r \in [m])$ at the t-th iteration. Larger $\Phi_{i,l}^{(t)}$ means the network can better capture the feature $v_{i,l}$, and thus can better use feature $v_{i,l}$ for classification. See more discussion in Appendix D.

Next, FixMatch uses a confidence threshold (τ) to govern the usage of unsupervised loss as in Eq. (5), delineating its feature learning process into Phase I and II. For Phase I, the network relies primarily on supervised loss due to its inability to generate highly confident pseudo-labels. As training continues, the network learns partial feature and becomes better at predicting highly confident pseudo-labels for unlabeled data. This marks the transition to Phase II, where unsupervised loss begins to contribute, driven by consistency regularization between weakly and strongly augmented samples.

Now we are ready to present the feature learning process of FixMatch and SL in Theorem 5.

Theorem 5. *Suppose Assumptions 2,3 holds. For sufficiently large k and $m = \text{polylog}(k)$, by setting $\eta \leq 1/\text{poly}(k)$ and $\tau = 1 - \tilde{O}(1/s^2)$, with probability at least $1 - e^{-\Omega(\log^2 k)}$:*

(a) FixMatch. *At the end of Phase I which continues for $T = \frac{\text{poly}(k)}{\eta}$ iterations, we have*

$$\Phi_{i,l}^{(T)} \geq \Omega(\log k), \quad \Phi_{i,3-l}^{(T)} \leq 1/\text{polylog}(k), \quad (\forall i \in [k], \exists l \in [2]). \tag{8}$$

At the end of its Phase II which continues another $T' = \frac{\text{poly}(k)}{\eta}$ iterations, we have

$$\Phi_{i,l}^{(T+T')} \geq \Omega(\log k), \quad (\forall i \in [k], \forall l \in [2]). \tag{9}$$

(b) Supervised Learning. *After running $T \geq \frac{\text{poly}(k)}{\eta}$ iterations, Eq. (8) always holds.*

See its proof in Appendix F. Theorem 5(a) indicates that Phase I in FixMatch continues for $T = \mathrm{poly}(k)/\eta$ iterations. During this phase, the network learns only one of the two semantic features per class. Specifically, in Eq. (8), for any class $i \in [k]$, there exists an index $l \in [2]$ so that the correlation score $\Phi_{i,l}^{(T)}$ exceeds $\Omega(\log k)$, showing feature $v_{i,l}$ is captured; and the score $\Phi_{i,3-l}^{(T)}$ remains low, indicating failure of learning $v_{i,3-l}$. Then we analyze classification performance when Eq. (8) holds.

Corollary 6. *Under the same conditions as Theorem 5. Assume Eq. (8) holds for the trained network $F^{(T)}$. For any sample X from class i containing the feature $v_{i,l}$, the network $F^{(T)}$ can correctly predict label i. Conversely, if X contains only the feature $v_{i,3-l}$, $F^{(T)}$ would misclassify X.*

See its proof in Appendix D. According to Corollary 6, after Phase I, the network can correctly classify the multi-view data, since each contains two features and the network has learned one of them. However, for single-view samples that possess only one of the features, the network's classification accuracy is only around 50% since it may not have learned the specific feature present in the sample. Then by running another T' iterations in Phase II, as shown in Theorem 5(a), FixMatch enables the network to capture both two features $v_{i,1}$ and $v_{i,2}$ in class i ($\forall i \in [k]$). As indicated in Eq. (9), all features have large correlation scores $\Phi_{i,l}^{(T+T')}$ ($\forall i \in [k], \forall l \in [2]$). By Corollary 6, for all training and test data, the network trained by FixMatch can correctly classify them with high probability. This explains the good classification performance of FixMatch in Theorem 4.

For Phase II of FixMatch, the reason for it to learn the semantics missed in Phase I is as follows. Having learned one feature per class in Phase I, the network is capable of generating highly confident pseudo-labels for weakly-augmented multi-view samples. As the confidence threshold $\tau = 1 - \tilde{O}(1/s^2)$ is close to 1 (e.g., $\tau = 0.95$), it ensures the correctness of these pseudo-labels. Then, FixMatch uses these correct pseudo-labels to supervise the corresponding strongly-augmented samples via consistency regularization. As shown in Eq. (7), strong augmentation $\mathcal{A}(\cdot)$ randomly removes the learned features in unlabeled multi-view samples with probabilities $\pi_1\pi_2$ or $(1-\pi_1)\pi_2$, effectively converting these samples into single-view data containing the unlearned feature. Given the large volume of unlabeled data as specified in Assumption 2, these transformed single-view samples are significant in their size. Accordingly, they dominate the unsupervised loss, since the rest samples containing the learned feature are already correctly classified by the network after Phase I and contribute minimally to the training loss. Consequently, the unsupervised loss enforces the network to learn the unlearned feature in Phase II.

For supervised learning (SL), Theorem 5(b) shows that with high probability, SL can only learn one of the two features for each class. This result accords with Phase I in FixMatch. Then according to Corollary 6, SL can correctly classify multi-view data using the single learned feature, but achieves only about 50% test accuracy on single-view data due to the unlearned feature, aligning with Sec. 4.1. By comparison, FixMatch achieves nearly 100% test accuracy on multi-view and single-view data, as it learns both semantic features for each class.

Comparison to Other SSL Analysis. This work differs from previous works from two key aspects. a) Our work provides the first analysis for FixMatch-like SSLs on CNNs. In contrast, many other works (He et al., 2022; Ţifrea et al., 2023) analyze over-simplified models, e.g., linear learning models, that differs substantially from the highly nonlinear and non-convex networks used in SSL. Some other works (Rigollet, 2007; Singh et al., 2008; Van Engelen & Hoos, 2020) view the model as a black-box function and do not reveal insights to model design. b) This work is also the first one to reveal the feature learning process of SSL, deepening the understanding to SSL and unveiling the intrinsic reasons of the superiority of SSL over its SL counterpart.

4.3 Semantic-Aware FixMatch

The analysis of feature learning Phase II in Sec. 4.2 shows the crucial role of strong augmentation $\mathcal{A}(\cdot)$ via consistency regularization in Eq. (5) to learn the features missed in Phase I. However, according to Eq. (7), $\mathcal{A}(\cdot)$ only removes the learned feature with probabilities $\pi_1\pi_2$ or $(1-\pi_1)\pi_2$. This means given $N_{u,m}$ unlabeled multi-view samples, $\mathcal{A}(\cdot)$ can generate at most $N_{\mathcal{A}} = \max(\pi_1\pi_2, (1-\pi_1)\pi_2)N_{u,m}$ samples containing only the missed features to enforce the network to learn them in Phase II. So FixMatch does not fully utilize unlabeled data in Phase II to learn comprehensive features, especially when π_2 is small, which usually happens when semantics only occupy a small portion of the image so that strong augmentation $\mathcal{A}(\cdot)$ like CutOut (DeVries & Taylor, 2017) and RandAugment has small probability to remove semantics (e.g., in ImageNet, see Appendix K.6).

Table 1: Comparison of Test accuracy (%) on CIFAR-100 and STL-10.

	CIFAR-100			STL-10		
Label Amount	400	2500	10000	40	250	1000
SL	11.45 ± 0.12	40.45 ± 0.50	63.77 ± 0.29	23.61 ± 1.62	38.83 ± 1.12	64.08 ± 0.47
FixMatch	55.16 ± 0.63	71.36 ± 0.44	77.25 ± 0.22	70.00 ± 4.02	88.73 ± 0.92	93.45 ± 0.19
SA-FixMatch	55.57 ± 0.43	72.12 ± 0.20	77.46 ± 0.16	71.81 ± 4.23	89.45 ± 1.19	94.04 ± 0.19

Motivated by this finding, we propose Semantic-Aware FixMatch (SA-FixMatch) to improve the probability of removing learned features by replacing random CutOut in FixMatch's strong augmentation $\mathcal{A}(\cdot)$ with Semantic-Aware CutOut (SA-CutOut). Specifically, if the unlabeled sample X has highly confident pseudo-label, SA-CutOut first performs Grad-CAM (Selvaraju et al., 2017) on the network F to localize the learned semantic regions which contribute to the network's class prediction and can be regarded as features. Then for each semantic region, SA-CutOut finds its region center, i.e., the point with highest attention score in the region, and then averages attention score within a $q \times q$ bounding box centered at this point (e.g., $q = 16$). Finally, SA-CutOut selects one semantic region with the highest average score for masking. Here masking semantic region with the highest score can enforce the network to learn the remaining features that are not well learned or missed in Phase I, as they will not be detected by Grad-CAM or detected with relatively low attention scores. In this way, SA-FixMatch can enhance vanilla FixMatch to better use unlabeled data to learn comprehensive semantic features. For analysis, see our formulation of $\mathcal{A}(\cdot)$ with SA-CutOut in Appendix E.

In Theorem 13 of Appendix A, we prove that SA-FixMatch enjoys the same good training and test accuracy in Theorem 4, but reduces the required number of unlabeled data samples N_c in vanilla FixMatch to $N_u = \max\{\pi_1\pi_2, (1-\pi_1)\pi_2\}N_c$, where N_c is given in Assumption 2. This data efficiency stems from SA-FixMatch's use of SA-CutOut, which selectively removes the well-learned features, thereby compelling the network to focus on learning previously missed or unlearned features. Detailed theoretical discussions and proofs are presented in Appendix E, illustrating how SA-FixMatch outperforms vanilla FixMatch in terms of data efficiency and better test performance.

As discussed in Sec. 3.2, SoTA deep SSLs, including FlexMatch (Zhang et al., 2021a), FreeMatch (Wang et al., 2022b), Dash (Xu et al., 2021), and SoftMatch (Chen et al., 2023), often build upon FixMatch, and only modify the confidence threshold $\mathcal{T}_t$ in Eq. (5). Hence, SA-CutOut is also applicable to these FixMatch-like SSLs to enhance performance. Experimental results in Sec. 5.3 validates the effectiveness and compatibility of SA-CutOut.

5 Experiments

To corroborate our theoretical results, we evaluate SL, FixMatch, and SA-FixMatch on several image classification benchmarks, including CIFAR-100 (Krizhevsky et al., 2009), STL-10 (Coates et al., 2011), Imagewoof (Howard & Gugger, 2020), and ImageNet (Deng et al., 2009). Following standard SSL evaluation protocols (Sohn et al., 2020; Zhang et al., 2021a; Wang et al., 2022a), we use WRN-28-8 (Zagoruyko & Komodakis, 2016) for CIFAR-100, WRN-37-2 (Zhou et al., 2020) for STL-10 and Imagewoof, and ResNet50 (He et al., 2016) for ImageNet. We also apply SA-CutOut to other FixMatch-like SSL methods and compare their performance with the original algorithms. All experiments are run three times, and we report the mean and standard deviation. Additional experimental details are provided in Appendix K.4 and K.5. Our code is included in the supplementary material and will be publicly released.

5.1 Classification Results

Here we evaluate SL, FixMatch, and SA-FixMatch by using different number of labeled data on CIFAR-100, STL-10, Imagewoof, and ImageNet. Table 1 shows that on STL-10, FixMatch and SA-FixMatch improve SL by a significant 28%+ of test accuracy under all three settings. From Tables 1 and 2, one can also observe very similar big improvement on other datasets, e.g., 13%+ on CIFAR-100 and Imagewoof, and 6%+ on ImageNet. These results verify the superiority of SSL methods over conventional SL methods, and are consistent with our theoretical findings in Sec. 4.1.

Meanwhile, from Tables 1 and 2, we find that our proposed SA-FixMatch outperforms vanilla FixMatch. For example, on Imagewoof, SA-FixMatch has a 1.5%+ average test accuracy improvement

Table 2: Comparison of Test accuracy (%) on Imagewoof and ImageNet.

Label Amount	Imagewoof 250	Imagewoof 1000	Imagewoof 2000	ImageNet 100K
SL	25.94 ± 1.54	42.04 ± 0.90	60.77 ± 1.04	44.62 ± 1.16
FixMatch	43.00 ± 1.46	64.91 ± 1.18	74.05 ± 0.15	50.80 ± 0.73
SA-FixMatch	46.73 ± 1.36	67.76 ± 1.29	75.62 ± 0.13	52.18 ± 0.32

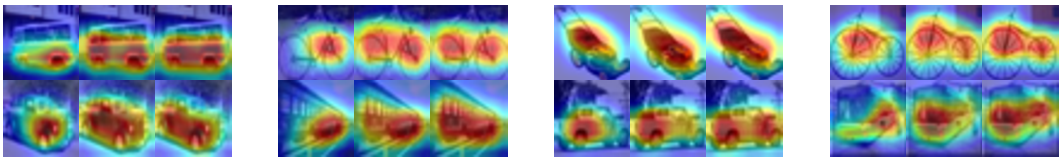

Figure 2: Visualization of WRN-28-8 via Grad-CAM on CIFAR-100. For each group of three images, the left, middle and right one are the visualization of the models trained with SL, FixMatch, and SA-FixMatch, respectively.

on FixMatch; on ImageNet, SA-FixMatch has a 1.38% higher average test accuracy than FixMatch; on CIFAR-100 and STL-10, SA-FixMatch also consistently outperforms FixMatch, albeit with a smaller performance gap. The reason behind this different improvement is that for samples in CIFAR-100 and STL-10, the semantic subject in the image occupies the majority of the image (see Appendix K.6). Accordingly, a random square mask in CutOut can well remove the semantic features with high probability, and thus has very similar masking effects as our SA-CutOut. Indeed, if we reduce the mask size in CutOut, random mask has less chance to well mask the semantic features and its performance degrades as observed in Table 4. For the Imagewoof and ImageNet datasets, most semantic subject only occupies less than a quarter of the image (see Appendix K.6). Therefore, a random square mask in CutOut only has small probability to remove the semantic features compared with SA-CutOut, and SA-FixMatch has much better test performance than FixMatch.

The superior test accuracy of SA-FixMatch compared to FixMatch is consistent with our theoretical analysis in Sec. 4.3. The reason behind this improvement is that to achieve good test performance in Theorem 4, the Phase II of SSL algorithms need to effectively remove well-learned features for enforcing the network to learn missed semantic features in Phase I. While FixMatch uses CutOut to randomly mask learned features in unlabeled data, SA-FixMatch always well masks the learned semantic feature because it adopts SA-CutOut as discussed in Sec. 4.3. Therefore, with a fixed number of images in unlabeled dataset, SA-FixMatch can more effectively use unlabeled data for feature learning, and thus achieve better test performance.

5.2 Semantic Feature Learning

To visualize the semantic features learned by networks trained by SL, FixMatch, and SA-FixMatch, we use Grad-CAM (Selvaraju et al., 2017) to highlight regions of input images that contribute to the model's class-specific predictions. For SL, FixMatch, and SA-FixMatch, we follow the default setting of Grad-CAM, and apply it to the last convolutional layer of the WRN-28-8 network on CIFAR-100.

Figure 2 shows that the network trained by SL often captures a single semantic feature since Grad-CAM only localizes one small image region, e.g., bicycle front wheel. Differently, networks trained by FixMatch can often grab multiple features for some classes, e.g., bicycle front and back wheels, but still misses some features for certain classes, e.g., bus compartment. By comparison, networks trained by SA-FixMatch reveals better semantic feature learning performance, since it often captures multiple semantic features, e.g., bicycle front and back wheels, bus front and compartment. The reason behind these phenomena is that as theoretically analyzed in Sec. 4.2, for classes which have multiple semantic features, SL can only learn a single semantic feature, while FixMatch and SA-FixMatch are capable of learning all the semantic features via the two-phase (supervised and unsupervised) learning process. Moreover, as shown in Sec. 4.3, compared with FixMatch, SA-FixMatch can more effectively use unlabeled data as it better removes well-learned features for enforcing network to learn missed features in data. Thus, SA-FixMatch is more likely to capture all semantic features of the data in practice with a fix number of unlabeled training data as observed in Figure 2.

5.3 SA-CutOut on FixMatch Variants

SA-CutOut is compatible with other deep SSL methods, such as FlexMatch (Zhang et al., 2021a), FreeMatch (Wang et al., 2022b), Dash (Xu et al., 2021), and SoftMatch (Chen et al., 2023), since as discussed in Sec. 3.2, the main difference between these deep SSL methods and FixMatch is their choice of confidence threshold $\mathcal{T}_t$. Here we apply SA-CutOut to these algorithms and compare their test accuracies with the original methods on STL-10 and CIFAR-100 dataset. From Table 3, one can observe that on STL-10, application of SA-CutOut increases the test accuracies of FlexMatch and FreeMatch by 2.6%+, and the test accuracies of Dash and SoftMatch by 5.4%+. On CIFAR-100, SA-CutOut increases the test accuracies of FreeMatch and Dash by 0.65%+, SoftMatch and FlexMatch by 0.5%+. This validates our analysis in Sec. 4.3 that SA-CutOut can more effectively use unlabeled data to learn comprehensive semantic features and thereby achieve higher test accuracy.

Table 3: Comparison of Test accuracy (%) of SSL algorithms with CutOut and SA-CutOut on STL-10 with 40 labeled data and CIFAR-100 with 400 labeled data.

Dataset	STL-10				CIFAR-100			
Algorithm	FlexMatch	FreeMatch	Dash	SoftMatch	FlexMatch	FreeMatch	Dash	SoftMatch
CutOut	72.13 ± 5.66	75.29 ± 1.29	67.51 ± 1.47	78.55 ± 2.90	59.65 ± 1.14	58.44 ± 1.92	48.56 ± 2.16	60.16 ± 2.22
SA-CutOut	75.91 ± 5.59	77.91 ± 2.01	78.41 ± 1.91	84.04 ± 4.67	60.16 ± 1.06	59.12 ± 1.69	50.24 ± 1.82	60.69 ± 1.95

5.4 Ablation Study

Here we investigate the effect of the mask size in (SA-)CutOut on the performance of (SA-)FixMatch. For CIFAR-100 whose image size is 32×32, we set the mask size in (SA-)CutOut as 4, 8, 12, and 16 to train the WRN-28-8 network. Table 4 shows that 1) as mask size grows, both the test accuracy of FixMatch and SA-FixMatch improves; 2) when mask size is small, SA-FixMatch makes significant improvement over FixMatch, e.g., 4%+ when using a mask size of 4; 3) as mask size grows, the improvement of SA-FixMatch over FixMatch becomes reduced, e.g., 0.55% when using a mask size of 16. For 1), as mask size in (SA-)CutOut increases, the learned features in the image are more likely to be removed, which is the key for (SA-)FixMatch to learn comprehensive semantics in Phase II as analyzed in Sec. 4.2. This explains the better performance of FixMatch and SA-FixMatch when their mask sizes increase. For 2), when using small masks, a random mask in CutOut has much lower probability to remove learned features compared with SA-CutOut. Thus, SA-FixMatch has much better performance than FixMatch. For 3), as mask size grows, a random mask in CutOut also has large probability to mask learned features in the image. This explains the reduced gap between SA-FixMatch and FixMatch.

Table 4: Effect of (SA-)CutOut mask size to test accuracy (%) on CIFAR-100 with 400 labeled data.

Mask Size	4	8	12	16
FixMatch	48.65	50.11	53.48	55.23
SA-FixMatch	52.71	52.95	55.37	55.78

6 Conclusion

By examining the classical FixMatch, we first provide theoretical justifications for the superior test performance of SSL over SL on neural networks. Then we uncover the differences in the feature learning processes between FixMatch and SL, explaining their distinct test performances. Inspired by theoretical insights, a practical enhancement called SA-FixMatch is proposed and validated through experiments, showcasing the potential for our newly developed theoretical understanding to inform improved SSL methodologies. Apart from FixMatch-like SSL, there are also other effective SSL frameworks whose analyses and comparisons are left as our future work.

Limitations. (a) Apart from FixMatch-like SSLs, we did not analyze other SSL frameworks, like MeanTeacher (Tarvainen & Valpola, 2017) and MixMatch (Berthelot et al., 2019b). However, current SoTA deep SSLs like FlexMatch, FreeMatch, Dash, and SoftMatch all follow the FixMatch framework, indicating the generalizability of our theoretical analysis on them. See details in Sec. 3.2 and Appendix G. (b) Due to limited GPU resources, we use small datasets, e.g. STL-10 and CIFAR-100, instead of large datasets like ImageNet to test SA-CutOut on other SoTA SSLs. Future work involves testing SA-CutOut on other SSLs methods (other than FixMatch) and on larger datasets.

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A THEOREM STATEMENT

In this section, we formally state the relevant data assumptions and theorems. Building on the proof framework of Allen-Zhu & Li (2023), our results extend their findings from supervised learning (SL) to semi-supervised learning (SSL). To maintain consistency, we adopt their notation throughout our proof. Specifically, we follow their data distribution assumptions and extend their analysis from SL to SSL through a two-phase learning process.

To formally define the data distribution, we set global constant C_p, sparsity parameter $s = \mathrm{polylog}(k)$, feature noise parameter $\gamma = \frac{1}{\mathrm{poly}(k)}$, and random noise parameter $\sigma_p = \frac{1}{\sqrt{d}\,\mathrm{polylog}(k)}$ to control noises in data. Here, feature noise implies that a sample from class i primarily exhibits feature $v_{i,l}$ (with $l \in [2]$), but also includes minor scaled features $v_{j,l}$ (with $j \neq i$) from other classes. Each sample pair (X, y) consists of the sample X, which is comprised of a set of $P = k^2$ patches $\{x_i \in \mathbb{R}^d\}_{i=1}^P$, and $y \in [k]$ as the class label. The following describes the data generation process.

Definition 7 (data distributions for single-view $\mathcal{D}_s$ and multi-view data $\mathcal{D}_m$ (Allen-Zhu & Li, 2023))**.** *Data distribution $\mathcal{D}$ consists of data from multi-view data $\mathcal{D}_m$ with probability $1-\mu$ and from single-view data $\mathcal{D}_s$ with probability $\mu = 1/\mathrm{poly}(k)$. We define $(X, y) \sim \mathcal{D}$ by randomly uniformly selecting a label $y \in [k]$ and generating data X as follows.*

1) *Sample a set of noisy features $\mathcal{V}'$ uniformly at random from $\{v_{i,1}, v_{i,2}\}_{i \neq y}$ each with probability s/k.*

2) *Denote $\mathcal{V}(X) = \mathcal{V}' \cup \{v_{y,1}, v_{y,2}\}$ as the set of feature vectors used in data X.*

3) *For each $v \in \mathcal{V}(X)$, pick C_p disjoint patches in $[P]$ and denote it as $\mathcal{P}_v(X)$ (the distribution of these patches can be arbitrary). We denote $\mathcal{P}(X) = \cup_{v \in \mathcal{V}(X)} \mathcal{P}_v(X)$.*

4) *If $\mathcal{D} = \mathcal{D}_s$ is the single-view distribution, pick a value $\hat{l} = \hat{l}(X) \in [2]$ uniformly at random.*

5) *For each $p \in \mathcal{P}_v(X)$ for some $v \in \mathcal{V}(X)$, given feature noise $\alpha_{p,v'} \in [0, \gamma]$, we set*
$$x_p = z_p v + \sum\nolimits_{v' \in \mathcal{V}} \alpha_{p,v'} v' + \xi_p,$$
where $\xi_p \in \mathcal{N}(0, \sigma_p^2 \mathbf{I})$ is an independent random Gaussian noise. The coefficients $z_p \geq 0$ satisfy
   - *For "multi-view" data $(X, y) \in \mathcal{D}_m$, when $v \in \{v_{y,1}, v_{y,2}\}$, $\sum_{p \in \mathcal{P}_v(X)} z_p \in [1, O(1)]$ and $\sum_{p \in \mathcal{P}_v(X)} z_p^q \in [1, O(1)]$ for an integer $q \geq 3$, and the marginal distribution of $\sum_{p \in \mathcal{P}_v(X)} z_p$ is left-close. When $v \in \mathcal{V}(X) \setminus \{v_{y,1}, v_{y,2}\}$, $\sum_{p \in \mathcal{P}_v(X)} z_p \in [\Omega(1), 0.4]$, and the marginal distribution of $\sum_{p \in \mathcal{P}_v(X)} z_p$ is right-close.*
   - *For "single-view" data $(X, y) \in \mathcal{D}_s$, when $v = v_{y,\hat{l}}$, $\sum_{p \in \mathcal{P}_v(X)} z_p \in [1, O(1)]$ for the integer $q \geq 3$. When $v = v_{y,3-\hat{l}}$, $\sum_{p \in \mathcal{P}_v(X)} z_p \in [\rho, O(\rho)]$ (we set $\rho = k^{-0.01}$ for simplicity). When $v \in \mathcal{V}(X) \setminus \{v_{y,1}, v_{y,2}\}$, $\sum_{p \in \mathcal{P}_v(X)} z_p \in [\Omega(\Gamma), \Gamma]$, where $\Gamma = 1/\mathrm{polylog}(k)$, and the marginal distribution of $\sum_{p \in \mathcal{P}_v(X)} z_p$ is right-close.*

6) *For each $p \in [P] \setminus \mathcal{P}(X)$, with an independent random Gaussian noise $\xi_p \sim \mathcal{N}(0, \frac{\gamma^2 k^2}{d} \mathbf{I})$,*
$$x_p = \sum\nolimits_{v' \in \mathcal{V}} \alpha_{p,v'} v' + \xi_p,$$
where each $\alpha_{p,v'} \in [0, \gamma]$ is the feature noise.

Based on the definition of data distribution $\mathcal{D}$, we define the training dataset $\mathcal{Z}$ as follows.

Definition 8. *Assume the distribution $\mathcal{D}$ consists of samples from $\mathcal{D}_m$* w.p. $1-\mu$ *and from $\mathcal{D}_s$* w.p. μ*. We are given N_l labeled training samples and N_u unlabeled training samples from $\mathcal{D}$, where typically $N_u \gg N_l$. The training dataset is denoted as $\mathcal{Z} = \mathcal{Z}_{l,m} \cup \mathcal{Z}_{l,s} \cup \mathcal{Z}_{u,m} \cup \mathcal{Z}_{u,s}$, where $\mathcal{Z}_{l,m}$ and $\mathcal{Z}_{l,s}$ represent the multi-view and single-view labeled data, respectively, and $\mathcal{Z}_{u,m}$ and $\mathcal{Z}_{u,s}$ represent the multi-view and single-view unlabeled data, respectively. We denote $(X, y) \sim \mathcal{Z}$ as a pair (X, y) sampled uniformly at random from the empirical training dataset $\mathcal{Z}$.*

Then, we introduce the smoothed ReLU function $\overline{\text{ReLU}}$ (Allen-Zhu & Li, 2023) in detail: for an integer $q \geq 2$ and a threshold $\varrho = \frac{1}{\text{polylog}(k)}$, $\overline{\text{ReLU}}(z) = 0$ if $z \leq 0$, $\overline{\text{ReLU}}(z) = \frac{z^q}{(q\varrho^{q-1})}$ if $z \in [0, \varrho]$ and $\overline{\text{ReLU}}(z) = z - (1 - \frac{1}{q})\varrho$ if $z \geq \varrho$. This configuration ensures a linear relationship for large z values while significantly reducing the impact of low-magnitude noises for small z values, thereby enhancing the separation of true features from noises.

We also introduce our assumption on FixMatch's strong augmentation $\mathcal{A}(\cdot)$, which is composed by CutOut (DeVries & Taylor, 2017) and RandAugment (Cubuk et al., 2020). As discussed in Sec. 3.2 and Appendix K.1, we focus on its probabilistic feature removal effect.

Assumption 9. *Suppose that for a given image, strong augmentation $\mathcal{A}(\cdot)$ randomly removes its semantic patches and noisy patches with probabilities π_2 and $1 - \pi_2$, respectively. For a single-view image, the sole semantic feature is removed with probability π_2. For a multi-view image, either of the two features, $v_{i,1}$ or $v_{i,2}$, is removed with probabilities $\pi_1\pi_2$ and $(1 - \pi_1)\pi_2$, respectively. We define the strong augmentation $\mathcal{A}(\cdot)$ for multi-view data as follows: for $p \in [P]$,*

$$\mathcal{A}(x_p) = \begin{cases} \max(\epsilon_1, \epsilon_2)x_p, & \text{if } v_{y,1} \text{ is in the patch } x_p, \\ \max(1-\epsilon_1, \epsilon_2)x_p, & \text{if } v_{y,2} \text{ is in the patch } x_p, \\ (1-\epsilon_2)x_p, & \text{otherwise (noisy patch)}, \end{cases} \tag{10}$$

where ϵ_1 and ϵ_2 are independent Bernoulli random variables, each equal to 0 with probabilities π_1 and π_2, respectively.

Here we use the "max" function to ensure ϵ_1 is active when $\epsilon_2 = 0$, which implies that $\mathcal{A}(\cdot)$ selects one feature to remove at a time. The reason behind this assumption is that as we can observe from Figure 1 and 2, different semantic features in a multi-view image are spatially distinct. Consequently, the likelihood of a square patch from random CutOut and transformations from RandAugment to remove both features is substantially lower than removing just one. To simplify our theoretical analysis, we therefore assume that $\mathcal{A}(\cdot)$ targets a single feature for removal in each instance.

Then we introduce the parameter assumption necessary to the proof. As we follow the proof framework of Allen-Zhu & Li (2023), the assumptions on most of the parameters are similar.

Parameter Assumption 10. *We assume that*

- *$q \geq 3$ and $\sigma_0^{q-2} = 1/k$, where σ_0 gives the initialization magnitude.*
- *$\gamma \leq \tilde{O}(\frac{\sigma_0}{k})$ and $\gamma^q \leq \tilde{\Theta}(\frac{1}{k^{q-1}mP})$, where γ controls the feature noise.*
- *The size of single-view labeled training data $N_{l,s} = \tilde{o}(k/\rho)$ and $N_{l,s} \leq \frac{k^2}{s}\rho^{q-1}$.*
- *$N_l \geq N_{l,s} \cdot \text{poly}(k)$, $\eta T \geq N_l \cdot \text{poly}(k)$, and $\sqrt{d} \geq \eta T \cdot \text{poly}(k)$.*
- *The weight for unsupervised loss $\lambda = 1$ and the confidence threshold $\tau = 1 - \tilde{O}(\frac{1}{s^2})$.*
- *The number of unlabeled data for FixMatch $N_c \geq \eta T' \cdot \text{poly}(k)$ with $\eta T' \geq \text{poly}(k)$, and the ratio of single-view unlabeled data $\frac{N_{c,s}}{N_c} \leq \frac{k^2}{\eta s T'}$.*

Here the first four parameter assumptions are followed from Allen-Zhu & Li (2023) for supervised learning Phase I, and the last two parameter assumptions are specific to the unsupervised loss Eq. (5) in learning Phase II. Define $\Phi_{i,l}^{(t)} := \sum_{r\in[m]}[\langle w_{i,r}^{(t)}, v_{i,l}\rangle]^+$ and $\Phi_i^{(t)} := \sum_{l\in[2]} \Phi_{i,l}^{(t)}$. We have the following theorem for vanilla FixMatch under CutOut:

Theorem 11 (Peformance on FixMatch)**.** *For sufficiently large $k > 0$, for every $m = \text{polylog}(k)$, $\eta \leq \frac{1}{\text{poly}(k)}$, setting $T = \frac{\text{poly}(k)}{\eta}$ and $T' = \frac{\text{poly}(k)}{\eta}$, when Parameter Assumption 10 is satisfied, with probability at least $1 - e^{-\Omega(\log^2 k)}$,*

- *(training accuracy is perfect) for every $(X, y) \in \mathcal{Z}$:*

$$\forall i \neq y : F_y^{(T+T')}(X) \geq F_i^{(T+T')}(X) + \Omega(\log k).$$

- *(multi-view testing is good) for every $i, j \in [k]$, we have $\tilde{O}(1) \geq \Phi_i^{(T+T')} \geq 0.4\Phi_j^{(T+T')} + \Omega(\log k)$, and thus*

$$\Pr_{(X,y)\in\mathcal{D}_m}\left[F_y^{(T+T')}(X) \geq \max_{j\neq y} F_j^{(T+T')}(X) + \Omega(\log k)\right] \geq 1 - e^{-\Omega(\log^2 k)}.$$

- *(single-view testing is good) for every $i \in [k]$ and $l \in [2]$, we have $\Phi_{i,l}^{(T+T')} \geq \Omega(\log k)$, and thus*

$$\Pr_{(X,y)\in\mathcal{D}_s}\left[F_y^{(T+T')}(X) \geq \max_{j\neq y} F_j^{(T+T')}(X) + \Omega(\log k)\right] \geq 1 - e^{-\Omega(\log^2 k)}.$$

For Semantic-Aware FixMatch (SA-FixMatch), we denote the number of unlabeled data in this case as N_u. Then we have the following assumption on N_u.

Parameter Assumption 12. $N_u = \max\{\pi_1\pi_2, (1-\pi_1)\pi_2\}N_c$.

Here $\pi_1 \in (0,1)$ and $\pi_2 \in (0,1)$ are the probabilities defined in Assumption 9, where π_2 is typically small $(1/\mathrm{poly}(k))$, as explained in Appendix H. From Parameter Assumption 12, we observe that the requirement for the number of unlabeled samples in SA-FixMatch is significantly smaller compared to that in FixMatch.

Under Parameter Assumptions 10 and 12, SA-FixMatch achieves the same performance results as Theorem 11, but with a reduced requirement for the number of unlabeled data, decreasing from N_c to N_u. Thus, we state the following theorem regarding the performance of SA-FixMatch.

Theorem 13 (Performance on SA-FixMatch)**.** *Under Parameter Assumption 10 and 12, we can achieve the same training and test performance as FixMatch in Theorem 11.*

Our main proof of Theorem 11 and Theorem 13 for FixMatch and SA-FixMatch includes analyses on a two-phase learning process. In Phase I, the network relies primarily on the supervised loss due to its inability to generate highly confident pseudo-labels and the large confidence threshold τ in Eq. (5). According to the results in Allen-Zhu & Li (2023), partial features are learned during the supervised learning Phase I. We review the results on supervised training in Appendix B.

Then in Phase II, the network predicts highly confident pseudo-labels for weakly-augmented samples and uses these correct pseudo-labels to supervise the corresponding strongly-augmented samples via consistency regularization. To theoretically analyze the learning process in Phase II, we build on the proof framework of Allen-Zhu & Li (2023) and demonstrate how the network learns the unlearned features while preserving the learned features during Phase II. Specifically, we present the induction hypothesis for Phase II in Appendix C, along with gradient calculations and function approximations for the unsupervised loss in Eq. (5) in Appendix D. We then provide a detailed proof of SA-FixMatch in Appendix E and extend the results to FixMatch in Appendix F. Finally, we generalize our proof to other FixMatch-like SSL methods in Appendix G.

B Results on Supervised Training

In this section, we first recall the results in supervised training that were derived in Allen-Zhu & Li (2023). Before showing their main results, we first introduce some necessary notations. For every $i \in [k]$, define $\Phi_{i,l}^{(t)} := \sum_{r\in[m]}[\langle w_{i,r}^{(t)}, v_{i,l}\rangle]^+$ and $\Phi_i^{(t)} := \sum_{l\in[2]}\Phi_{i,l}^{(t)}$. Define

$$\Lambda_i^{(t)} := \max_{r\in[m],l\in[2]}[\langle w_{i,r}^{(t)}, v_{i,l}\rangle]^+ \quad \text{and} \quad \Lambda_{i,l}^{(t)} := \max_{r\in[m]}[\langle w_{i,r}^{(t)}, v_{i,l}\rangle]^+,$$

where $\Lambda_{i,l}$ indicates the largest correlation between the feature vector $v_{i,l}$ and all neurons $w_{i,r}$ ($r \in [m]$) from class i. Then we define the "view lottery winning" set:

$$\mathcal{M}_F := \left\{(i,l^*) \in [k]\times[2] \middle| \Lambda_{i,l^*}^{(0)} \geq \Lambda_{i,3-l^*}^{(0)}\left(1 + \frac{2}{\log^2 m}\right)\right\}.$$

The intuition behind $\mathcal{M}_F$ is that if $(i,l) \in \mathcal{M}_F$, then the feature $v_{i,l}$ is likely to be learned by the model and the feature $v_{i,3-l}$ is likely to be missed due to model initialization and data distribution. $\mathcal{M}_F$ satisfies the following property (refer to the Proposition C.2. of Allen-Zhu & Li (2023)):

Proposition 14. *Suppose* $m \leq \text{poly}(k)$. *For every* $i \in [k]$, $\Pr[(i,1) \in \mathcal{M}_F$ *or* $(i,2) \in \mathcal{M}_F] \geq 1 - o(1)$.

Based on Theorem 1 of Allen-Zhu & Li (2023), after training for T iterations with the supervised training loss $L_s^{(t)}$

$$L_s^{(t)} = \mathbb{E}_{(X,y)\sim\mathcal{Z}_l}\left[-\log \mathbf{logit}_y(F^{(t)}, X)\right],$$

the training accuracy on labeled samples is perfect and $L_s^{(T)}$ approaches zero, i.e., for every $(X,y) \in \mathcal{Z}_l$,

$$\forall i \neq y : F_y^{(T)}(X) \geq F_i^{(T)}(X) + \Omega(\log k),$$

and we have $L_s^{(T)} \leq \frac{1}{\text{poly}(k)}$. Besides, it satisfies that $0.4\Phi_i^{(T)} - \Phi_j^{(T)} \leq -\Omega(\log k)$ for every pair $i,j \in [k]$. This means that at least one of $\Phi_{i,1}^{(T)}$ or $\Phi_{i,2}^{(T)}$ for all $i \in [k]$ increase to a large scale of $\Theta(\log(k))$, which means at least one of $v_{i,1}$ and $v_{i,2}$ for all $i \in [k]$ is learned after supervised training for T iterations. Thus, all multi-view training data are classified correctly. For single-view training data without the learned features, they are classified correctly by memorizing the noises in the data during the supervised training process. Then for the test accuracy, for the multi-view data point $(X,y) \sim \mathcal{D}_m$, with the probability at least $1 - e^{-\Omega(\log^2 k)}$, it has

$$\mathbf{logit}_y(F^{(T)}, X) \geq 1 - \tilde{O}\left(\frac{1}{s^2}\right),$$

and

$$\Pr_{(X,y)\sim\mathcal{D}_m}\left[F_y^{(T)}(X) \geq \max_{j\neq y} F_j^{(T)}(X) + \Omega(\log k)\right] \geq 1 - e^{-\Omega(\log^2 k)}.$$

This means that the test accuracy of multi-view data is good. However, for the single-view data $(X,y) \sim \mathcal{D}_s$, whenever $(i,l^*) \in \mathcal{M}_F$, we have $\Phi_{i,3-l^*}^{(T)} \ll \frac{1}{\text{polylog}(k)}$ and

$$\Pr_{(X,y)\sim\mathcal{D}_s}\left[F_y^{(T)}(X) \geq \max_{j\neq y} F_j^{(T)}(X) - \frac{1}{\text{polylog}(k)}\right] \leq \frac{1}{2}(1 + o(1)),$$

which means that the test accuracy on single-view data is nearly 50%.

The results in Allen-Zhu & Li (2023) fully indicate the feature learning process of supervised learning. The main reason for the imperfect performance of SL is that, due to "lottery winning", it only captures one of the two features for each semantic class during the supervised training process. Therefore for single-view data without this feature, it has low test accuracy.

In the following, we will consider the effect of loss $L_u^{(t)}$ on unlabeled data for training:

$$L_u^{(t)} = \mathbb{E}_{(X,y)\sim\mathcal{Z}_u}\left[\mathbb{I}_{\{\max_i \mathbf{logit}_i(F^{(t)},\alpha(X))\geq\tau\}} \cdot -\log \mathbf{logit}_b(F^{(t)}, \mathcal{A}(X))\right].$$

where $b = \arg\max_{i\in[k]} \mathbf{logit}_i(F^{(t)}, \alpha(X))$, τ is the confidence threshold and $\alpha, \mathcal{A}$ are the weak and strong augmentations, respectively. For the simplicity of proof, we set α to be identity mapping. In the following, we will prove Theorem 11. By setting $\tau = 1 - \tilde{O}(1/s^2)$, we will show that after we train the network $F^{(T)}$ combining the loss $L_u^{(t)}$ for another $T' = \frac{\text{poly}(k)}{\eta}$ epochs, the network can learn complete semantic features for all classes, resulting in perfect test performance on both multi-view and single-view data.

C Induction Hypothesis

In this section, to prove our theorem, similar to Allen-Zhu & Li (2023), we present an induction hypothesis for every training iteration t in learning Phase II. We first show the loss function in learning Phase II.

Loss Function. Recall $\mathbf{logit}_i(F, X) := \frac{e^{F_i(X)}}{\sum_{j\in[k]} e^{F_j(X)}}$. In learning Phase I, before the network learned partial features to make confident prediction, only the supervised loss $L_s^{(t)}$ takes effect

$$L_s^{(t)} = \mathbb{E}_{(X,y)\sim\mathcal{Z}_l}\left[-\log \mathbf{logit}_y(F^{(t)}, X)\right].$$

In Phase II, after we train the network F for $T = \frac{\mathrm{poly}(k)}{\eta}$ epochs using $L_s^{(t)}$ in the Phase I, according to the results in Appendix B, one of the features in each class is captured. Then we consider to optimize the network $F^{(T)}$ using the following combination of losses:

$$\begin{aligned} L^{(t)} =& \mathbb{E}_{(X,y)\sim\mathcal{Z}_l}\left[-\log \mathbf{logit}_y(F^{(t)}, X)\right] \\ &+ \lambda \mathbb{E}_{X\sim\mathcal{Z}_u}\left[\mathbb{I}_{\{\max_i \mathbf{logit}_i(F^{(t)}, \alpha(X))\geq\tau\}} \cdot -\log \mathbf{logit}_b(F^{(t)}, \mathcal{A}(X))\right], \end{aligned}$$

where $b = \arg\max_{i\in[k]} \mathbf{logit}_i(F^{(t)}, \alpha(X))$. Recall $\tau = 1 - \tilde{O}(1/s^2)$, when $t \geq T$ and we use $F^{(t)}$ to classify the unlabeled data $X \sim \mathcal{Z}_u$, we will get a correct pseudo-label with high probability, i.e., $b = y$, where y denotes the ground truth label of X. This means that for $X \sim \mathcal{Z}_{u,m}$, with probability at least $1 - e^{-\Omega(\log^2 k)}$, $\mathbf{logit}_y(F^{(t)}, X) \geq \tau$ and for $X \sim \mathcal{Z}_{u,s}$, when $(y, l^*) \in \mathcal{M}_F$ and $\hat{l}(X) = l^*$, with the probability at least $1 - e^{-\Omega(\log^2 k)}$, $\mathbf{logit}_y(F^{(t)}, X) \geq \tau$. We denote the samples in $\mathcal{Z}_u$ that satisfy $\mathbf{logit}_y(F^{(t)}, X) \geq \tau$ as $\tilde{\mathcal{Z}}_u$ and let $\tilde{N}_u = |\tilde{\mathcal{Z}}_u|$. In this way, we can further simplify the loss as

$$\begin{aligned} L^{(t)} =& L_s^{(t)} + \lambda L_u^{(t)} \\ =& \mathbb{E}_{(X,y)\sim\mathcal{Z}_l}\left[-\log \mathbf{logit}_y(F^{(t)}, X)\right] + \lambda \mathbb{E}_{X\sim\tilde{\mathcal{Z}}_u}\left[-\log \mathbf{logit}_b(F^{(t)}, \mathcal{A}(X))\right]. \end{aligned} \tag{11}$$

We introduce the following induction hypothesis:

Induction Hypothesis 15. *For every $l \in [2]$, for every $r \in [m]$, for every $X \in \tilde{\mathcal{Z}}_u$ and $i \in [k]$,*

(a) For every $p \in \mathcal{P}_{v_{i,l}}(X)$, we have: $\langle w_{i,r}^{(t)}, x_p\rangle = \langle w_{i,r}^{(t)}, v_{i,l}\rangle z_p \pm \tilde{o}(\sigma_0)$.

(b) For every $p \in \mathcal{P}(X) \setminus (\mathcal{P}_{v_{i,1}}(X) \cup \mathcal{P}_{v_{i,2}}(X))$, we have: $|\langle w_{i,r}^{(t)}, x_p\rangle| \leq \tilde{O}(\sigma_0)$.

(c) For every $p \in [P] \setminus \mathcal{P}(X)$, we have $|\langle w_{i,r}^{(t)}, x_p\rangle| \leq \tilde{O}(\sigma_0\gamma k)$.

Moreover, we have for every $i \in [k]$, every $l \in [2]$,

(d) $\Phi_{i,l}^{(t)} \geq \Omega(\sigma_0)$ and $\Phi_{i,l}^{(t)} \leq \tilde{O}(1)$.

(e) for every $r \in [m]$, it holds that $\langle w_{i,r}^{(t)}, v_{i,l}\rangle \geq -\tilde{O}(\sigma_0)$.

Recall that $\Phi_{i,l}^{(t)} := \sum_{r\in[m]}[\langle w_{i,r}^{(t)}, v_{i,l}\rangle]^+$ and $\Phi_i^{(t)} := \sum_{l\in[2]} \Phi_{i,l}^{(t)}$.

The intuition behind Induction Hypothesis 15 is that training with semi-supervised loss (11) filters out feature noises and background noises for both multi-view data and single-view data. This can be seen in comparison with Induction Hypothesis C.3 of Allen-Zhu & Li (2023). With the help of Induction Hypothesis 15, we can prove that the correlations between $w_{i,r}$ and learned features in Phase I are retained in Phase II, and the correlations between $w_{i,r}$ and unlearned features will increase to a large scale ($\log(k)$) in the end of learning Phase II.

D Gradient Calculations and Function Approximation

Gradient Calculation. We present the gradient calculations for the cross-entropy loss $L_u(F; X, y) = -\log \mathbf{logit}_y(F, \mathcal{A}(X))$ on unlabeled data X with correctly predicted pseudo-label y. With a slight abuse of notation, we use $(X, y) \sim \tilde{\mathcal{Z}}_u$ to denote unlabeled data $X \sim \tilde{\mathcal{Z}}_u$ along with its corresponding ground truth label y.

Fact 16. *Given data point $(X, y) \sim \tilde{\mathcal{Z}}_u$, for every $i \in [k], r \in [m]$,*

$$-\nabla_{w_{i,r}} L_u(F; X, y) = (1 - \mathbf{logit}_i(F, \mathcal{A}(X))) \sum_{p \in [P]} \overline{\mathrm{ReLU}}'(\langle w_{i,r}, \mathcal{A}(x_p)\rangle)\mathcal{A}(x_p), \quad \textit{when } i = y, \tag{12}$$

$$-\nabla_{w_{i,r}} L_u(F; X, y) = -\mathbf{logit}_i(F, \mathcal{A}(X)) \sum_{p \in [P]} \overline{\mathrm{ReLU}}'(\langle w_{i,r}, \mathcal{A}(x_p)\rangle)\mathcal{A}(x_p), \quad \textit{when } i \neq y. \tag{13}$$

Definition 17. *For each data point X, we define a value $V_{i,r,l}(X)$ as*

$$V_{i,r,l}(X) := \mathbb{I}_{v_{i,l} \in \mathcal{V}(X)} \sum_{p \in \mathcal{P}_{v_{i,l}}(X)} \overline{\mathrm{ReLU}}'(\langle w_{i,r}, \mathcal{A}(x_p)\rangle)\mathcal{A}(z_p).$$

Definition 18. *We also define small error terms which will be frequently used:*

$$\mathcal{E}_1 := \tilde{O}(\sigma_0^{q-1})\gamma s \qquad \mathcal{E}_{2,i,r}(X) := O(\gamma(V_{i,r,1}(X) + V_{i,r,2}(X)))$$
$$\mathcal{E}_3 := \tilde{O}(\sigma_0 \gamma k)^{q-1}\gamma P \qquad \mathcal{E}_{4,j,l}(X) := \tilde{O}(\sigma_0^{q-1})\mathbb{I}_{v_{j,l} \in \mathcal{V}(X)}.$$

Then we have the following bounds for positive gradients, i.e., when $i = y$:

Claim 19 (positive gradients)**.** *Suppose Induction Hypothesis 15 holds at iteration t. For every $(X, y) \in \tilde{\mathcal{Z}}_u$, every $r \in [m]$, every $l \in [2]$, and $i = y$, we have*

(a) $\langle -\nabla_{w_{i,r}} L_u(F^{(t)}; X, y), v_{i,l}\rangle \geq \left(V_{i,r,l}(X) - \tilde{O}(\sigma_p P)\right)\left(1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))\right).$

(b) $\langle -\nabla_{w_{i,r}} L_u(F^{(t)}; X, y), v_{i,l}\rangle \leq (V_{i,r,l}(X) + \mathcal{E}_1 + \mathcal{E}_3)\left(1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))\right).$

(c) For every $j \in [k] \setminus \{i\}$,
$|\langle -\nabla_{w_{i,r}} L_u(F^{(t)}; X, y), v_{j,l}\rangle| \leq (\mathcal{E}_1 + \mathcal{E}_{2,i,r}(X) + \mathcal{E}_3 + \mathcal{E}_{4,j,l}(X))\left(1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))\right).$

We also have the following claim about the negative gradients (i.e., $i \neq y$). The proof of positive and negative gradients is identical to the proof in Allen-Zhu & Li (2023), except that in our case, we have the augmentation operations on the data patches.

Claim 20 (negative gradients)**.** *Suppose Induction Hypothesis 15 holds at iteration t. For every $(X, y) \sim \tilde{\mathcal{Z}}_u$, every $r \in [m]$, every $l \in [2]$, and $i \in [k] \setminus \{y\}$, we have*

(a) $\langle -\nabla_{w_{i,r}} L_u(F^{(t)}; X, y), v_{i,l}\rangle \geq -\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))\left(\mathcal{E}_1 + \mathcal{E}_3 + V_{i,r,l}(X)\right).$

(b) For every $j \in [k]$: $\langle -\nabla_{w_{i,r}} L_u(F^{(t)}; X, y), v_{j,l}\rangle \leq \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))\tilde{O}(\sigma_p P).$

(c) For every $j \in [k] \setminus \{i\}$: $\langle -\nabla_{w_{i,r}} L_u(F^{(t)}; X, y), v_{j,l}\rangle \geq -\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))\left(\mathcal{E}_1 + \mathcal{E}_3 + \mathcal{E}_{4,j,l}(X)\right).$

Function Approximation. Let us denote $Z_{i,l}^{(t)}(X) := \mathbb{I}_{v_{i,l} \in \mathcal{V}(X)}\left(\sum_{p \in \mathcal{P}_{v_{i,l}}(X)} \mathcal{A}(z_p)\right)$, we can easily derive the following result on function approximation.

Claim 21 (function approximation)**.** *Suppose Induction Hypothesis 15 holds at iteration t and suppose $s \leq \tilde{O}(\frac{1}{\sigma_0^q m})$ and $\gamma \leq \tilde{O}(\frac{1}{\sigma_0 k (mP)^{1/q}})$, we have:*

- *for every t, every $(X, y) \in \tilde{\mathcal{Z}}_u$ and $i \in [k]$, we have*
$$F_i^{(t)}(X) = \sum_{l \in [2]} \left(\Phi_{i,l}^{(t)} \times Z_{i,l}^{(t)}(X)\right) \pm O(\frac{1}{\mathrm{polylog}(k)}).$$

- *for every $(X, y) \sim \mathcal{D}$, with probability at least $1 - e^{-\Omega(\log^2 k)}$, it satisfies for every $i \in [k]$,*
$$F_i^{(t)}(X) = \sum_{l \in [2]} \left(\Phi_{i,l}^{(t)} \times Z_{i,l}^{(t)}(X)\right) \pm O(\frac{1}{\mathrm{polylog}(k)}).$$

Claim 22 (classification test performance)**.** *Suppose Parameter Assumption 10 holds. Assume for* $\forall i \in [k], \exists l \in [2]$ *such that* $\Phi_{i,l} \geq \Omega(\log k)$ *and* $\Phi_{i,3-l} \leq \frac{1}{\text{polylog}(k)}$ *in the trained network* F*. Then the following statements hold with probability at least* $1 - e^{-\Omega(\log^2 k)}$*:*

- *For any* $(X, y) \sim \mathcal{D}$ *which contains* $v_{y,l}$ *as the main semantic feature, network* F *can correctly predict the label* y *of* X*.*
- *For any* $(X, y) \sim \mathcal{D}$ *only with* $v_{y,3-l}$ *as the main semantic feature, the network* F *would mistakenly predict the label of* X*.*

Proof. Based on our definition of multi-view and single-view data, for any multi-view data $(X, y) \sim \mathcal{D}_m$, when we have $\Phi_i \geq \Omega(\log k)$ ($\forall i \in [k]$), according to Claim 21 and Claim D.16 in Allen-Zhu & Li (2023), we have $0.4\Phi_i - \Phi_j \leq -\Omega(\log k)$, which means $F_y(X) \geq \max_{j \neq y} F_j(X) + \Omega(\log k)$. For any single-view data $(X, y) \sim \mathcal{D}_s$ with $v_{y,l}$ as the main semantic feature, according to Claim 21, $F_y(X) \geq \Omega(\log k)$ and for $i \neq y$, $F_i(X) \leq O(\Gamma)$. Thus, we have $F_y(X) \geq \max_{j \neq y} F_j(X) + \Omega(\log k)$. In the above two cases, the network F can correctly predict the label y of X.

For any single-view data $(X, y) \sim \mathcal{D}_s$ with $v_{y,3-l}$ as the main semantic feature, according to Claim 21, $F_y(X) \leq \tilde{O}(\rho) + \frac{1}{\text{polylog}(k)}$ and with probability at least $1 - e^{-\Omega(\log^2 k)}$ there exists $i \in [k]$ and $i \neq y$ such that $F_i(X) \geq \tilde{\Omega}(\Gamma)$. This means that $F_y(X) \leq \max_{i \neq y} F_i(X) - \frac{1}{\text{polylog}(k)}$. In this case, the network F will mistakenly predict the label of X. □

E Proof for Semantic-Aware FixMatch

Here we consider to prove the SA-FixMatch case first. SA-FixMatch replaces CutOut operation in strong augmentation of FixMatch with SA-CutOut, which deterministically removes the learned features in Phase I. This helps to reduce the number of unlabeled samples needed during the Phase II training as shown in Assumption 12. Since the learned features of Phase I are deterministically removed in SA-FixMatch, for the simplicity of theoretical analysis, we first prove the results under SA-FixMatch and then we can easily generalize the results to FixMatch.

For theoretical proof, we assume that Grad-CAM in SA-CutOut can correctly identify the learned feature after the first stage. In this case, the formulation of strong augmentation $\mathcal{A}(\cdot)$ with SA-CutOut for $X \sim \tilde{\mathcal{Z}}_u$ and $(i, l^*) \in \mathcal{M}_F \cap \mathcal{V}(X)$ (l^* varies depending on i) is

$$\mathcal{A}(x_p) = \begin{cases} 0, & \text{if } p \in \mathcal{P}_{v_{i,l^*}}(X), \\ x_p, & \text{otherwise.} \end{cases} \tag{14}$$

In the following, we will begin to prove Theorem 13. We first introduce some useful claims as consequences of the Induction Hypothesis 15.

E.1 Useful Claims

Based on the results from Allen-Zhu & Li (2023), at the end of learning Phase I, for $(i, l^*) \in \mathcal{M}_F$, we have $\Phi_{i,l^*}^{(T)} \geq \Omega(\log k)$ while $\Phi_{i,3-l^*}^{(T)} \leq 1/\text{polylog}(k)$. Below the first claim addresses the initial growth of the correlations between $w_{i,r}$ and the unlearned feature ($\Phi_{i,3-l^*}^{(t)}$) in learning Phase II, and the second claim asserts that the correlations between $w_{i,r}$ and the learned feature ($\Phi_{i,l^*}^{(t)}$) are preserved during learning Phase II. Here we first give a naive bound on the **logit** function based on function approximation result Claim 21.

Claim 23 (approximation of logits)**.** *Suppose Induction Hypothesis 15 holds at iteration* t*, and suppose* $s \leq \tilde{O}(\frac{1}{\sigma_0^q m})$ *and* $\gamma \leq \tilde{O}(\frac{1}{\sigma_0 k (mP)^{1/q}})$*, then*

- *for every* $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$ *and* $(i, l^*) \in \mathcal{M}_F$*:* $\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)) = O\left(\frac{e^{O(\Phi_{i,3-l^*})}}{e^{O(\Phi_{i,3-l^*})} + k}\right)$.
- *for every* $(X, y) \sim \tilde{\mathcal{Z}}_{u,s}$ *and every* $i \in [k]$*:* $\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)) = O\left(\frac{1}{k}\right)$.

Proof. Recall $F_i^{(t)}(\mathcal{A}(X)) = \sum_{r\in[m]}\sum_{p\in[P]} \overline{\mathrm{ReLU}}(\langle w_{i,r}, \mathcal{A}(x_p)\rangle)$. According to Claim 21, data assumption 7 and data augmentation defined in (14), we have that for $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$ and $(i, l^*) \in \mathcal{M}_F$ (l^* varies depending on i),

$$0 \le F_y^{(t)}(\mathcal{A}(X)) \le \Phi_{y,3-l^*}^{(t)} \cdot O(1) + O(\frac{1}{\mathrm{polylog}(k)}),$$

and for $i \in [k] \setminus \{y\}$,

$$0 \le F_i^{(t)}(\mathcal{A}(X)) \le \Phi_{i,3-l^*}^{(t)} \cdot 0.4 + O(\frac{1}{\mathrm{polylog}(k)}).$$

Thus, combining the above results, for every $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$ and $(i, l^*) \in \mathcal{M}_F$, we have for every $i \in [k]$,

$$\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)) = O\left(\frac{e^{O(\Phi_{i,3-l^*}^{(t)})}}{e^{O(\Phi_{i,3-l^*}^{(t)})} + k}\right).$$

On the other hand, for the single-view data in $\tilde{\mathcal{Z}}_{u,s}$, as the only class-specific semantic feature is masked after we conduct strong augmentation, only noisy unlearned features and background noises remain. Thus, for $(X, y) \sim \tilde{\mathcal{Z}}_{u,s}$ and $(i, l^*) \in \mathcal{M}_F$, we have for $i \neq y$,

$$0 \le F_y^{(t)}(\mathcal{A}(X)) \le O(1) \quad \text{and} \quad 0 \le F_i^{(t)}(\mathcal{A}(X)) \le \Phi_{i,3-l^*}^{(t)} \cdot O(\Gamma) + O(\frac{1}{\mathrm{polylog}(k)}) \le O(1),$$

and thus we have for every $i \in [k]$,

$$\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)) = O\left(\frac{1}{k}\right).$$

□

Now we are ready to prove the following claim on the initial growth of $\Phi_{i,3-l^*}^{(t)}$ with $(i, l^*) \in \mathcal{M}_F$.

Claim 24 (initial growth)**.** *Suppose Induction Hypothesis 15 holds at iteration t, then for every $i \in [k]$ with $(i, l^*) \in \mathcal{M}_F$, suppose $\Phi_{i,3-l^*}^{(t)} \le O(1)$, then it satisfies*

$$\Phi_{i,3-l^*}^{(t+1)} = \Phi_{i,3-l^*}^{(t)} + \tilde{\Theta}\left(\frac{\eta}{k}\right) \overline{\mathrm{ReLU}}'(\Phi_{i,3-l^*}^{(t)}).$$

Proof. For any $w_{i,r}$ and $v_{i,3-l^*}$ ($i \in [k], r \in [m]$), we have

$$\begin{aligned}\langle w_{i,r}^{(t+1)}, v_{i,3-l^*}\rangle = \langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle &- \eta\mathbb{E}_{(X,y)\sim\mathcal{Z}_l}[\langle \nabla_{w_{i,r}} L_s(F^{(t)}; X, y), v_{i,3-l^*}\rangle] \\ &- \eta\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[\langle \nabla_{w_{i,r}} L_u(F^{(t)}; X, y), v_{i,3-l^*}\rangle].\end{aligned}$$

For the loss term on $\mathcal{Z}_l$, we have

$$\begin{aligned}&-\mathbb{E}_{(X,y)\sim\mathcal{Z}_l}[\langle \nabla_{w_{i,r}} L_s(F^{(t)}; X, y), v_{i,3-l^*}\rangle] \\ =&\mathbb{E}_{(X,y)\sim\mathcal{Z}_l}\big[\mathbb{I}_{i=y}(1 - \mathbf{logit}_i(F, X)) \sum\nolimits_{p\in[P]} \overline{\mathrm{ReLU}}'(\langle w_{i,r}, x_p\rangle)\langle x_p, v_{i,3-l^*}\rangle - \\ &\mathbb{I}_{i\neq y}\mathbf{logit}_i(F, X) \sum\nolimits_{p\in[P]} \overline{\mathrm{ReLU}}'(\langle w_{i,r}, x_p\rangle)\langle x_p, v_{i,3-l^*}\rangle\big].\end{aligned}$$

Based on the results from Allen-Zhu & Li (2023), when $t \ge T$, we have

$$\mathbb{E}_{(X,y)\sim\mathcal{Z}_l}\big[(1 - \mathbf{logit}_y(F, X))\big] \le \frac{1}{\mathrm{poly}(k)} \quad \text{and} \quad \mathbb{E}_{(X,y)\sim\mathcal{Z}_l}\big[\mathbb{I}_{i\neq y}\mathbf{logit}_i(F, X)\big] \le \frac{1}{\mathrm{poly}(k)},$$

which means

$$-\mathbb{E}_{(X,y)\sim\mathcal{Z}_l}[\langle \nabla_{w_{i,r}} L_s(F^{(t)}; X, y), v_{i,3-l^*}\rangle] \le \frac{1}{\mathrm{poly}(k)},$$

i.e., the supervised loss is fully minimized in the first stage and contributes little in the second stage.

Then, from Claim 19 and Claim 20, we know

$$\langle w_{i,r}^{(t+1)}, v_{i,3-l^*}\rangle \geq \langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle + \eta \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[\mathbb{I}_{y=i}(V_{i,r,3-l^*}(X) - \tilde{O}(\sigma_p P))(1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))) - \mathbb{I}_{y\neq i}(\mathcal{E}_1 + \mathcal{E}_3 + \mathbb{I}_{v_{i,3-l^*}\in\mathcal{P}(X)} V_{i,r,3-l^*}(X))\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))].$$

Consider $r = \arg\max_{r\in[m]}\{\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle\}$, then as $m = \text{polylog}(k)$, we know $\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle \geq \tilde{\Omega}(\Phi_{i,3-l^*}^{(t)})$. Recall $V_{i,r,3-l^*}(X) := \mathbb{I}_{v_{i,3-l^*}\in\mathcal{V}(X)} \sum_{p\in\mathcal{P}_{v_{i,3-l^*}}(X)} \overline{\text{ReLU}}'(\langle w_{i,r}^{(t)}, \mathcal{A}(x_p)\rangle)\mathcal{A}(z_p)$, according to Induction Hypothesis 15(a) and definition in (14), we have

$$V_{i,r,3-l^*}(X) = \mathbb{I}_{v_{i,3-l^*}\in\mathcal{V}(X)} \sum_{p\in\mathcal{P}_{v_{i,3-l^*}}(X)} \overline{\text{ReLU}}'(\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle z_p + \tilde{o}(\sigma_0))z_p.$$

- When $i = y$, at least for $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$, we have $\sum_{p\in\mathcal{P}_{v_{i,3-l^*}}(X)} z_p \geq 1$, and together with $|\mathcal{P}_{v_{i,3-l^*}}| \leq C_p$, we know $V_{i,r,3-l^*} \geq \Omega(1)\cdot\overline{\text{ReLU}}'(\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle)$.
- When $i \neq y$ and when $v_{i,3-l^*} \in \mathcal{P}(X)$, we can use $\sum_{p\in\mathcal{P}_{v_{i,3-l^*}}(X)} z_p \leq 0.4$ to derive that $V_{i,r,3-l^*} \leq 0.4\cdot\overline{\text{ReLU}}'(\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle)$.

Moreover, when $\Phi_{i,3-l^*}^{(t)} \leq O(1)$, by Claim 23, we have $\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)) \leq O(\frac{1}{k})$. Then we can derive that

$$\langle w_{i,r}^{(t+1)}, v_{i,3-l^*}\rangle \geq \langle w_{i,r}^{(t)}, v_{i,l}\rangle + \eta \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[\mathbb{I}_{y=i}\cdot\Omega(1) - O(1)\cdot\mathbb{I}_{y\neq i}\mathbb{I}_{v_{i,3-l^*}\in\mathcal{P}(X)}\cdot\frac{1}{k}] \cdot\overline{\text{ReLU}}'\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle - \eta\tilde{O}(\frac{\sigma_p P + \mathcal{E}_1 + \mathcal{E}_3}{k}).$$

Finally, recall that $\Pr(v_{i,3-l^*} \in \mathcal{P}(X)|i \neq y) = \frac{s}{k} \ll o(1)$, we have that

$$\langle w_{i,r}^{(t+1)}, v_{i,3-l^*}\rangle \geq \langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle + \tilde{\Omega}\left(\frac{\eta}{k}\right)\overline{\text{ReLU}}'(\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle).$$

Similarly, using Claim 19 and 20, we can derive:

$$\langle w_{i,r}^{(t+1)}, v_{i,3-l^*}\rangle \leq \langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle + \eta \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}\left[\mathbb{I}_{y=i}(V_{i,r,3-l^*}(X) + \mathcal{E}_1 + \mathcal{E}_3)(1 - \mathbf{logit}_i(F^{(t)}, X)) - \mathbb{I}_{y\neq i}\tilde{O}(\sigma_p P)\mathbf{logit}_i(F^{(t)}, X)\right].$$

With similar analyses to the upper bound, we can derive the lower bound

$$\langle w_{i,r}^{(t+1)}, v_{i,3-l^*}\rangle \leq \langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle + \tilde{O}\left(\frac{\eta}{k}\right)\overline{\text{ReLU}}'(\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle).$$

□

With initial growth analysis in Claim 24, similar to Claim D.11 in Allen-Zhu & Li (2023), we can obtain the following result:

Claim 25. *Define iteration threshold* $T_0 := \tilde{\Theta}\left(\frac{k}{\eta\sigma_0^{q-2}}\right)$*, then for every* $i \in [k], (i, l^*) \in \mathcal{M}_F$ *and* $t \geq T + T_0$*, it satisfies that* $\Phi_{i,3-l^*}^{(t)} = \Theta(1)$.

As we stated in Claim 23, model prediction for the augmented single-view data in $\tilde{\mathcal{Z}}_{u,s}$ are kept to the scale of $O\left(\frac{1}{k}\right)$, since after strong augmentation there remains only noises. Now we present the convergence of multi-view data in $\tilde{\mathcal{Z}}_{u,m}$ from $T + T_0$ till the end.

Claim 26 (multi-view error till the end)**.** *Suppose that the Induction Hypothesis 15 holds for every iteration* $T < t \leq T + T'$*, and suppose* $\frac{\tilde{N}_{u,s}}{\tilde{N}_u} \leq \frac{k^2}{\eta s T'}$*, then*

$$\sum_{t=T+T_0}^{T+T'} \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}[1 - \mathbf{logit}_y(F^{(t)}, \mathcal{A}(X))] \leq \tilde{O}\left(\frac{k}{\eta}\right).$$

Proof. For any $w_{i,r}$ and $v_{i,3-l^*}$ ($i \in [k], r \in [m]$), we have

$$\langle w_{i,r}^{(t+1)}, v_{i,3-l^*}\rangle = \langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle - \eta\mathbb{E}_{(X,y)\sim\mathcal{Z}_l}[\langle \nabla_{w_{i,r}} L_s(F^{(t)}; X, y), v_{i,3-l^*}\rangle] - \eta\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[\langle \nabla_{w_{i,r}} L_u(F^{(t)}; X, y), v_{i,3-l^*}\rangle].$$

For the loss term on $\mathcal{Z}_l$, as discussed above, we have

$$-\mathbb{E}_{(X,y)\sim\mathcal{Z}_l}[\langle \nabla_{w_{i,r}} L_s(F^{(t)}; X, y), v_{i,3-l^*}\rangle] \le \frac{1}{\mathrm{poly}(k)}.$$

Again, by Claim 19 and Claim 20, we know

$$\langle w_{i,r}^{(t+1)}, v_{i,3-l^*}\rangle \ge \langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle + \eta\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[\mathbb{I}_{y=i}(V_{i,r,3-l^*}(X) - \tilde{O}(\sigma_p P))(1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))) - \mathbb{I}_{y\neq i}(\mathcal{E}_1 + \mathcal{E}_3 + \mathbb{I}_{v_{i,3-l^*}\in\mathcal{P}(X)} V_{i,r,3-l^*}(X))\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))].$$

Take $r = \arg\max_{r\in[m]}\{\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle\}$, then by $m = \mathrm{polylog}(k)$ we know $\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle \ge \tilde{\Omega}(\Phi_{i,3-l^*}^{(t)}) = \tilde{\Omega}(1)$ for $t \ge T + T_0$.

Recall $V_{i,r,3-l^*}(X) := \mathbb{I}_{v_{i,3-l^*}\in\mathcal{V}(X)} \sum_{p\in\mathcal{P}_{v_{i,3-l^*}}(X)} \overline{\mathrm{ReLU}}'(\langle w_{i,r}^{(t)}, \mathcal{A}(x_p)\rangle)\mathcal{A}(z_p)$ and our definition of $\mathcal{A}$, using the Induction Hypothesis 15, we have that for $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$, it satisfies

$$V_{i,r,3-l^*}(X) = \sum\nolimits_{p\in\mathcal{P}_{v_{i,3-l^*}}(X)} \overline{\mathrm{ReLU}}'(\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle z_p \pm \tilde{o}(\sigma_0))z_p.$$

Since we have $\langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle \ge \tilde{\Omega}(1) \gg \varrho$ and $|\mathcal{P}_{v_{i,3-l^*}}(X)| \le O(1)$, for most of $p \in \mathcal{P}_{v_{i,3-l^*}}$, we have already in the linear regime of $\overline{\mathrm{ReLU}}$ so

$$0.9\sum\nolimits_{p\in\mathcal{P}_{v_{i,3-l^*}}(X)} z_p \le V_{i,r,3-l^*}(X) \le \sum\nolimits_{p\in\mathcal{P}_{v_{i,3-l^*}}(X)} z_p.$$

Thus, when $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$ and $y = i$, we have $V_{i,r,3-l^*}(X) \ge 0.9$; when $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$, $y \neq i$ and $v_{i,3-l^*} \in \mathcal{P}(X)$, we have $V_{i,r,3-l^*}(X) \le 0.4$. When $(X, y) \sim \tilde{\mathcal{Z}}_{u,s}$ and $y = i$, we have $V_{i,r,3-l^*}(X) \ge 0$; when $(X, y) \sim \tilde{\mathcal{Z}}_{u,s}$, $y \neq i$ and $v_{i,3-l^*} \in \mathcal{P}(X)$, we have $V_{i,r,3-l^*}(X) \le O(\Gamma) \ll o(1)$. Then we can derive that

$$\begin{aligned}
&\langle w_{i,r}^{(t+1)}, v_{i,3-l^*}\rangle \\
&\ge \langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle + \eta\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[0.89\cdot\mathbb{I}_{y=i}(1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)))\right] \\
&\quad - \eta\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[\mathbb{I}_{y\neq i}(\mathcal{E}_1 + \mathcal{E}_3 + 0.4\mathbb{I}_{v_{i,3-l^*}\in\mathcal{P}(X)})\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))\right] \\
&\quad - O\left(\frac{\eta\tilde{N}_{u,s}}{\tilde{N}_u}\right)\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,s}}\left[\tilde{O}(\sigma_p P)\mathbb{I}_{y=i}(1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)))\right] \\
&\quad - O\left(\frac{\eta\tilde{N}_{u,s}}{\tilde{N}_u}\right)\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,s}}\left[\mathbb{I}_{y\neq i}(\mathcal{E}_1 + \mathcal{E}_3 + \mathbb{I}_{v_{i,3-l^*}\in\mathcal{P}(X)})\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))\right] \\
&\ge \langle w_{i,r}^{(t)}, v_{i,3-l^*}\rangle + \Omega\left(\frac{\eta}{k}\right)\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[(1 - \mathbf{logit}_y(F^{(t)}, \mathcal{A}(X)))\right] - O\left(\frac{\eta s\tilde{N}_{u,s}}{k^2\tilde{N}_u}\right),
\end{aligned}$$

where the last step is based on Claim 23 and the fact that $\Pr(v_{i,l} \in \mathcal{P}(X)|i \neq y) = \frac{s}{k} \ll o(1)$. Thus, when summing up all $r \in [m]$, and telescoping from $T + T_0$ to $T + T'$, we have

$$\Phi_{i,3-l^*}^{(T'+T)} \ge \Phi_{i,3-l^*}^{(T+T_0)} + \tilde{\Omega}\left(\frac{\eta}{k}\right)\sum_{t=T+T_0}^{T+T'}\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[(1 - \mathbf{logit}_y(F^{(t)}, \mathcal{A}(X)))\right] - \tilde{O}\left(\frac{T'\eta s\tilde{N}_{u,s}}{k^2\tilde{N}_u}\right).$$

Then combining that $\Phi_{i,3-l^*}^{(t)} \le \tilde{O}(1)$ from the Induction Hypothesis 15(d), we have:

$$\sum_{t=T+T_0}^{T+T'}\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[(1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)))\right] \le \tilde{O}\left(\frac{k}{\eta}\right) + \tilde{O}\left(\frac{T's\tilde{N}_{u,s}}{k\tilde{N}_u}\right) \le \tilde{O}\left(\frac{k}{\eta}\right).$$

□

Now we are ready to prove the following claim on the correlations between model kernels and the learned feature $\Phi_{i,l^*}^{(t)}$ is retained during learning Phase II.

Claim 27 (learned is retained)**.** *Suppose that the Induction Hypothesis 15 holds for every iteration $T < t \leq T+T'$, under Parameter Assumption 10 and 12, we have for every iteration $T < t \leq T+T'$:*

$$\forall (i, l^*) \in \mathcal{M}_F, \quad \Phi_{i,l^*}^{(t)} \geq \Omega(\log(k).$$

Proof. For any $w_{i,r}$ and v_{i,l^*} ($i \in [k], r \in [m]$), we have

$$\begin{aligned}\langle w_{i,r}^{(t+1)}, v_{i,l^*} \rangle = \langle w_{i,r}^{(t)}, v_{i,l^*} \rangle &- \eta \mathbb{E}_{(X,y)\sim\mathcal{Z}_l}[\langle \nabla_{w_{i,r}} L_s(F^{(t)}; X, y), v_{i,l^*} \rangle] \\ &- \eta \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[\langle \nabla_{w_{i,r}} L_u(F^{(t)}; X, y), v_{i,l^*} \rangle].\end{aligned}$$

For the loss term on $\mathcal{Z}_l$, as discussed in Claim 24, we have

$$-\mathbb{E}_{(X,y)\sim\mathcal{Z}_l}[\langle \nabla_{w_{i,r}} L_s(F^{(t)}; X, y), v_{i,l^*} \rangle] \leq \frac{1}{\mathrm{poly}(k)}.$$

Again, by Claim 19 and Claim 20, we know

$$\begin{aligned}\langle w_{i,r}^{(t+1)}, v_{i,l^*} \rangle \geq &\langle w_{i,r}^{(t)}, v_{i,l^*} \rangle + \eta \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[\mathbb{I}_{y=i}(V_{i,r,l^*}(X) - \tilde{O}(\sigma_p P))(1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))) \\ &- \mathbb{I}_{y\neq i}(\mathcal{E}_1 + \mathcal{E}_3 + \mathbb{I}_{v_{i,l^*}\in\mathcal{P}(X)} V_{i,r,l^*}(X))\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))].\end{aligned}$$

Recall $V_{i,r,l^*}(X) := \mathbb{I}_{v_{i,l^*}\in\mathcal{V}(X)} \sum_{p\in\mathcal{P}_{v_{i,l^*}}(X)} \overline{\mathrm{ReLU}}'(\langle w_{i,r}^{(t)}, \mathcal{A}(x_p)\rangle)\mathcal{A}(z_p)$ and our definition of strong augmentation in (14), we have $V_{i,r,l^*}(X) = 0$, so we have by Claim 23 that

$$\langle w_{i,r}^{(t+1)}, v_{i,l^*} \rangle \geq \langle w_{i,r}^{(t)}, v_{i,l^*} \rangle - \tilde{O}\left(\frac{\eta\sigma_p P}{k}\right) \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))] - O\left(\frac{\eta(\mathcal{E}_1 + \mathcal{E}_3)}{k}\right).$$

Summing up all $r \in [m]$ and using $m = \mathrm{polylog}(k)$, we have

$$\Phi_{i,l^*}^{(t+1)} \geq \Phi_{i,l^*}^{(t-1)} - \tilde{O}\left(\frac{\eta\sigma_p P}{k}\right) \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[1 - \mathbf{logit}_i(F^{(t)}, \mathcal{A}(X))] - \tilde{O}\left(\frac{\eta\gamma(\sigma_0^{q-1}s + (\sigma_0\gamma k)^{q-1}P)}{k}\right).$$

In the following, we separate the process into $T \leq t \leq T + T_0$ and $t \geq T_0 + T$.

When $T < t \leq T + T_0$. Recall at the end of learning Phase I, we have $\Phi_{i,l^*}^{(T)} \geq \Omega(\log(k)$. Using $T_0 = \tilde{\Theta}\left(\frac{k}{\eta\sigma_0^{q-2}}\right)$ and our parameter assumption 10, we have $\Phi_{i,l^*}^{(t)} \geq \Omega(\log(k)$ for every iteration of $T < t \leq T + T_0$.

When $T + T_0 < t \leq T + T'$. By the upper bound on multi-view error in Claim 26, we know $\Phi_{i,l^*}^{(t)} \geq \Omega(\log(k)$ for every iteration of $T + T_0 < t \leq T + T'$. □

Next, we present our last claim on individual error similar to Claim D.16 in Allen-Zhu & Li (2023). It states that when training error on $\tilde{\mathcal{Z}}_{u,m}$ is small enough, the model has high probability to correctly classify any individual data.

Claim 28 (individual error)**.** *When $\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[1 - \mathbf{logit}_y\left(F^{(t)}, X\right)\right] \leq \frac{1}{k^4}$ is sufficiently small, we have for any $(i, 3-l), (j, 3-l') \notin \mathcal{M}_F$,*

$$0.4\Phi_{i,3-l}^{(t)} - \Phi_{j,3-l'}^{(t)} \leq -\Omega(\log(k)), \quad \Phi_{i,3-l}^{(t)}, \Phi_{j,3-l'}^{(t)} \geq \Omega(\log(k)),$$

and therefore for every $(X, y) \in \mathcal{Z}$ (and every $(X, y) \in \mathcal{D}$ w.p. $1 - e^{-\Omega(\log^2(k))}$),

$$F_y^{(t)}(X) \geq \max_{j\neq y} F_j^{(t)}(X) + \Omega(\log k).$$

Proof. Denote by $\tilde{\mathcal{Z}}^*_{u,m}$ for the sample $(X,y) \in \tilde{\mathcal{Z}}_{u,m}$ such that $\sum_{p \in P_{v_{y,3-l^*}}(X)} z_p \leq 1 + \frac{1}{100\log(k)}$ where $(y, l^*) \in \mathcal{M}_F$. For a sample $(X,y) \in \tilde{\mathcal{Z}}^*_{u,m}$, denote by $\mathcal{H}(X)$ as the set of all $i \in [k] \setminus \{y\}$ such that $\sum_{p \in P_{v_{i,3-l}}(X)} z_p \geq 0.4 - \frac{1}{100\log(k)}$ where $(i,l) \in \mathcal{M}_F$.

Now, suppose $1 - \mathbf{logit}_y(F^{(t)}, X) = \mathcal{E}(X)$, with $\min(1,\beta) \leq 2(1 - \frac{1}{1+\beta})$, we have

$$\min(1, \sum\nolimits_{i \in [k]\setminus\{y\}} e^{F_i^{(t)}(X) - F_y^{(t)}(X)}) \leq 2\mathcal{E}(X)$$

By Claim 21 and our definition of $\mathcal{H}(X)$, this implies that

$$\min(1, \sum\nolimits_{i \in \mathcal{H}(X)} e^{0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{y,3-l^*}}) \leq 4\mathcal{E}(X).$$

If we denote by $\psi = \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}[1 - \mathbf{logit}_y\left(F^{(t)}, X\right)]$, then

$$\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[\min(1, \sum\nolimits_{i \in \mathcal{H}(X)} e^{0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{y,3-l^*}})\right] \leq O(\psi),$$
$$\implies \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[\sum\nolimits_{i \in \mathcal{H}(X)} \min(\frac{1}{k}, e^{0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{y,3-l^*}})\right] \leq O(\psi).$$

Notice that we can rewrite the LHS so that

$$\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[\sum\nolimits_{j \in [k]} \mathbb{I}_{j=y} \sum\nolimits_{i \in [k]} \mathbb{I}_{i \in \mathcal{H}(X)} \min(\frac{1}{k}, e^{0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{j,3-l'}})\right] \leq O(\psi),$$
$$\implies \sum\nolimits_{j \in [k]} \sum\nolimits_{i \in [k]} \mathbb{I}_{i \neq y} \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[\mathbb{I}_{j=y}\mathbb{I}_{i \in \mathcal{H}(X)}\right] \min(\frac{1}{k}, e^{0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{j,3-l'}}) \leq O(\psi),$$

where $(j, l') \in \mathcal{M}_F$. Note for every the probability for every $i \neq j \in [k]$, the probability of generating a sample $(X,y) \in \tilde{\mathcal{Z}}^*_{u,m}$ with $y = j$ and $i \in \mathcal{H}(X)$ is at least $\tilde{\Omega}(\frac{1}{k} \cdot \frac{s^2}{k^2})$. This implies

$$\sum\nolimits_{i \in [k]\setminus\{j\}} \min(\frac{1}{k}, e^{0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{j,3-l'}}) \leq \tilde{O}\left(\frac{k^3}{s^2}\psi\right).$$

Then, with $1 - \frac{1}{1+\beta} \leq \min(1,\beta)$, we have for every $(X,y) \in \tilde{\mathcal{Z}}_{u,m}$,

$$\begin{aligned} 1 - \mathbf{logit}_y(F^{(t)}, X) \leq & \min(1, \sum\nolimits_{i \in [k]\setminus\{y\}} 2e^{0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{y,3-l^*}}) \\ \leq & k \cdot \sum\nolimits_{i \in [k]\setminus\{y\}} \min(\frac{1}{k}, e^{0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{y,3-l^*}}) \leq \tilde{O}\left(\frac{k^4}{s^2}\psi\right). \end{aligned} \tag{15}$$

Thus, we can see that when $\psi \leq \frac{1}{k^4}$ is sufficiently small, we have for any $i \in [k] \setminus \{y\}$

$$e^{0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{y,3-l^*}} \leq \frac{1}{k} \implies 0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{y,3-l^*} \leq -\Omega(\log(k)).$$

By symmetry and non-negativity of $\Phi^{(t)}_{i,3-l}$, we know for any $(i, 3-l), (j, 3-l') \notin \mathcal{M}_F$, we have:

$$0.4\Phi^{(t)}_{i,3-l} - \Phi^{(t)}_{j,3-l'} \leq -\Omega(\log(k)), \quad \Phi^{(t)}_{i,3-l}, \Phi^{(t)}_{j,3-l'} \geq \Omega(\log(k)). \tag{16}$$

Since (16) holds for any $(i, 3-l), (j, 3-l') \notin \mathcal{M}_F$ at iteration t such that $\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_m}\left[1 - \mathbf{logit}_y\left(F^{(t)}, X\right)\right] \leq \frac{1}{k^4}$, and from Claim D.16 in Allen-Zhu & Li (2023) we know (16) also holds for $\Phi_{i,l}, \Phi_{j,l'}$ for any $(i,l), (j,l') \in \mathcal{M}_F$ during learning Phase II, so we have

- for every $(X,y) \sim \mathcal{Z}_m$, by Claim 21 we have

$$F_y^{(t)}(X) \geq 1 \cdot \Phi_y - O(\frac{1}{\mathrm{polylog}(k)}) \geq 0.4 \max_{j \neq y} \Phi_j + \Omega(\log(k)) \geq \max_{j \neq y} F_j^{(t)}(X) + \Omega(\log k).$$

- for every $(X, y) \sim \mathcal{Z}_s$, suppose $v_{y,l}$ is its only semantic feature, by Claim 21 we have

$$F_y^{(t)}(X) \geq 1 \cdot \Phi_{y,l} - O(\frac{1}{\text{polylog}(k)}) \geq \Omega(\log(k)),$$
$$F_j^{(t)}(X) \leq O(\Gamma) \cdot \Phi_{j,l} + O(\frac{1}{\text{polylog}(k)}) \leq O(1) \text{ for } j \neq y.$$

Therefore, we have

$$F_y^{(t)}(X) \geq \max_{j \neq y} F_j^{(t)}(X) + \Omega(\log k).$$

□

Let $T + T_1$ be the first iteration that $\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[1 - \textbf{logit}_y\left(F^{(t)}, X\right)\right] \leq \frac{1}{k^4}$, then we know for $t \geq T + T_1$ (16) always holds, since the objective $L^{(t)} = L_s^{(t)} + \lambda L_u^{(t)}$ ($\lambda = 1$) is $O(1)$-Lipschitz smooth and we are using full gradient descent, which means the objective value is monotonically non-increasing. Since in Phase II, $L_s^{(t)}$ is kept at a small value, $L_u^{(t)}$ is monotonically non-increasing.

E.2 Main lemmas to prove the Induction Hypothesis 15

In this section, we show lemmas that when combined together, shall prove the Induction Hypothesis 15 holds for every iteration.

E.2.1 Correlation Growth

Lemma 29. *Suppose Parameter 10 holds and suppose Induction Hypothesis 15 holds for all iteration $< t$ starting from T. Then, letting $\Phi_{i,l}^{(t)} := \sum_{r\in[m]}[\langle w_{i,r}^{(t)}, v_{i,l}\rangle]^+$, we have for every $i \in [k], l \in [2]$,*

$$\Phi_{i,l}^{(t)} \leq \tilde{O}(1).$$

Proof. For every $i \in [k]$ and every $(i, l) \in \mathcal{M}_F$, after the first stage, we have $\Phi_{i,l}^{(T)} \leq \tilde{O}(1)$. In the second stage, as in Semantic-Aware CutOut, the learned features (i, l) are masked and so the correlations between gradients and learned features are kept small. This means that $\Phi_{i,l}^{(t)} \leq \tilde{O}(1)$ holds true in learning Phase II for $T < t \leq T + T'$.

Then for the unlearned feature $(i, 3 - l)$, we suppose $t > T + T_1$ is some iteration so that $\Phi_{i,3-l}^{(t)} \geq \text{polylog}(k)$. We will prove that if we continue from iteration t for at most T' iterations, we still have $\Phi_{i,3-l}^{(t)} \leq \tilde{O}(1)$. Based on Claim 19, we have that

$$\begin{aligned}
&\langle w_{i,r}^{(t+1)}, v_{i,3-l}\rangle \\
&\quad \leq \langle w_{i,r}^{(t)}, v_{i,3-l}\rangle + \eta\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}\left[\mathbb{I}_{i=y}(\mathcal{E}_1 + \mathcal{E}_3 + V_{i,r,3-l})(1 - \textbf{logit}_i(F^{(t)}, \mathcal{A}(X)))\right] \\
&\quad \leq \langle w_{i,r}^{(t)}, v_{i,3-l}\rangle + O(\eta)\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_{u,m}}\left[\mathbb{I}_{i=y}(1 - \textbf{logit}_i(F^{(t)}, \mathcal{A}(X)))\right] + O\left(\frac{\eta\rho\tilde{N}_{u,s}}{k\tilde{N}_u}\right).
\end{aligned}$$

This is because that when $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$, we have $V_{i,r,3-l} \leq O(1)$ and when $(X, y) \sim \tilde{\mathcal{Z}}_{u,s}$, we have $V_{i,r,3-l} \leq O(\rho)$. For every $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$, when $y = i$, we have

$$F_i^{(t)}(\mathcal{A}(X)) \geq \Phi_{i,3-l}^{(t)} \cdot \sum\nolimits_{p\in\mathcal{P}_{v_{i,3-l}}} z_p - O(\frac{1}{\text{polylog}(k)}) \geq \Phi_{i,3-l}^{(t)} - O(\frac{1}{\text{polylog}(k)}).$$

Then when $j \neq y$ and $(j, l') \in \mathcal{M}_F$, we have

$$F_j^{(t)}(\mathcal{A}(X)) \leq \Phi_{j,3-l'}^{(t)} \cdot \sum\nolimits_{p\in\mathcal{P}_{v_{j,3-l'}}} z_p + O(\frac{1}{\text{polylog}(k)}) \leq 0.4\Phi_{j,3-l'}^{(t)} + O(\frac{1}{\text{polylog}(k)}).$$

So by (16), we have

$$1 - \mathbf{logit}_y(F; \mathcal{A}(X), y) \leq \frac{1}{k^{\Omega(\log k)}}.$$

Summing up over all $r \in [m]$, we have

$$\Phi_{i,3-l}^{(t+1)} \leq \Phi_{i,3-l}^{(t)} + \frac{\eta m}{k^{\Omega(\log k)}} + \tilde{O}\left(\frac{\eta \rho \tilde{N}_{u,s}}{k \tilde{N}_u}\right).$$

Therefore, if we continue for T' iterations, we still have $\Phi_{i,3-l^*}^{(T+T')} \leq \tilde{O}(1)$. □

E.2.2 Off-Diagonal Correlations are Small

Lemma 30. *Suppose Parameter 10 holds and suppose Induction Hypothesis 15 holds for all iteration $< t$ starting from T. Then,*

$$\forall i \in [k], \forall r \in [m], \forall j \in [k] \setminus \{i\}, \quad |\langle w_{i,r}^{(t)}, v_{j,l} \rangle| \leq \tilde{O}(\sigma_0).$$

Proof. In Phase I when $t \leq T$, from Lemma D.22 in Allen-Zhu & Li (2023), we have $|\langle w_{i,r}^{(t)}, v_{j,l} \rangle| \leq \tilde{O}(\sigma_0)$. Now we consider Phase II when $t > T$, and denote by $R_i^{(t)} := \max_{r \in [m], j \in [k] \setminus \{i\}} |\langle w_{i,r}^{(t)}, v_{j,l} \rangle|$. According to Claim 19 and Claim 20, we have

$$\begin{aligned} R_i^{(t+1)} \leq & R_i^{(t)} + \eta \mathbb{E}_{(X,y) \sim \tilde{\mathcal{Z}}_u} \left[\mathbb{I}_{y=i} (\mathcal{E}_{2,i,r}(X) + \mathcal{E}_1 + \mathcal{E}_3 + \mathcal{E}_{4,j,l}(X))(1 - \mathbf{logit}_i(F^{(t)}, X)) \right] \\ & + \eta \mathbb{E}_{(X,y) \sim \tilde{\mathcal{Z}}_u} \left[\mathbb{I}_{y \neq i} \left(\mathcal{E}_1 + \mathcal{E}_3 + \mathcal{E}_{4,j,l}(X) \right) \mathbf{logit}_i(F^{(t)}, X) \right]. \end{aligned}$$

For single-view data $(X, y) \sim \tilde{\mathcal{Z}}_{u,s}$, by Claim 23, we have $\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)) = O\left(\frac{1}{k}\right)$ for every $i \in [k]$. In the following, we separate the process into $T < t \leq T + T_0$ and $T + T_0 < t \leq T + T'$.

When $T < t \leq T + T_0$. During this stage, by Claim 23 we know $\mathbf{logit}_i(F^{(t)}, X) = O(\frac{1}{k})$ ($\forall i \in [k]$) for any $(X, y) \sim \tilde{\mathcal{Z}}_u$. We also have $\mathcal{E}_{2,i,r}(X) \leq \tilde{O}(\gamma(\Phi_{i,3-l^*}^{(t)})^{q-1})$ with $(i, l^*) \in \mathcal{M}_F$, and have $\mathcal{E}_{4,j,l}(X) \leq \tilde{O}(\sigma_0)^{q-1} \mathbb{I}_{v_{j,l} \in \mathcal{V}(X)}$ by definition. Recall when $T < t \leq T + T_0$, by Claim 24, we have $\Phi_{i,3-l^*}^{(t+1)} = \Phi_{i,3-l^*}^{(t)} + \tilde{\Theta}\left(\frac{\eta}{k}\right) \overline{\mathrm{ReLU}}'(\Phi_{i,3-l^*}^{(t)})$, so $\sum_{T < t \leq T + T_0} \eta (\Phi_{i,3-l^*}^{(t)})^{q-1} \leq \tilde{O}(k)$. Also, $\Pr(v_{i,3-l^*} \in \mathcal{P}(X) | i \neq y) = \frac{s}{k}$. Therefore, for every $T < t \leq T + T_0$ with $T_0 = \tilde{\Theta}(\frac{k}{\eta \sigma_0^{q-2}})$, we have

$$R_i^{(t)} \leq R_i^{(T)} + \tilde{O}(\sigma_0) + \tilde{O}\left(\frac{\eta}{k} T_0\right) \left((\sigma_0^{q-1}) \gamma s + (\sigma_0 \gamma k)^{q-1} \gamma P + (\sigma_0)^{q-1} \frac{s}{k} \right) \leq \tilde{O}(\sigma_0).$$

When $T + T_0 < t \leq T + T'$. During this stage, we have the naive bound on $\mathcal{E}_{2,i,r}(X) \leq \gamma$, so again by Claim 19 and Claim 20, we have

$$R_i^{(t+1)} \leq R_i^{(t)} + \frac{\eta}{k} \mathbb{E}_{(X,y) \sim \tilde{\mathcal{Z}}_u} \left[(\gamma + (\sigma_0^{q-1}) \gamma s + (\sigma_0 \gamma k)^{q-1} \gamma P + (\sigma_0)^{q-1} \frac{s}{k})(1 - \mathbf{logit}_i(F^{(t)}, X)) \right].$$

Therefore, by the upper bound on multi-view error in Claim 26 and $\frac{\tilde{N}_{u,s}}{\tilde{N}_u} \leq \frac{k^2}{\eta s T'}$, we know $R_i^{(t)} \leq \tilde{O}(\sigma_0)$ for $T + T_0 < t \leq T + T'$. □

E.2.3 Noise Correlation is Small

Lemma 31. *Suppose Parameter 10 holds and suppose Induction Hypothesis 15 holds for all iteration $< t$ starting from T. For every $l \in [2]$, for every $r \in [m]$, for every $(X, y) \in \tilde{\mathcal{Z}}_u$ and $i \in [k]$:*

(a) For every $p \in \mathcal{P}_{v_{i,l}}(X)$, we have: $|\langle w_{i,r}^{(t)}, \xi_p \rangle| \leq \tilde{o}(\sigma_0)$.

(b) For every $p \in \mathcal{P}(X) \setminus (\mathcal{P}_{v_{i,1}}(X) \cup \mathcal{P}_{v_{i,2}}(X))$, we have: $|\langle w_{i,r}^{(t)}, \xi_p \rangle| \leq \tilde{O}(\sigma_0)$.

(c) For every $p \in [P] \setminus \mathcal{P}(X)$, we have: $|\langle w_{i,r}^{(t)}, \xi_p \rangle| \leq \tilde{O}(\sigma_0 \gamma k)$.

Proof. Based on gradient calculation Fact 16 and $|\langle x'_{p'}, \xi_p \rangle| \leq \tilde{O}(\sigma_p) \leq o(\frac{1}{\sqrt{d}})$ if $X' \neq X$ or $p' \neq p$, we have that for every $(X, y) \sim \tilde{\mathcal{Z}}_u$ and $p \in [P]$, if $i = y$

$$\langle w_{i,r}^{(t+1)}, \xi_p \rangle = \langle w_{i,r}^{(t)}, \xi_p \rangle + \tilde{\Theta}(\frac{\eta}{\tilde{N}_u}) \overline{\mathrm{ReLU}}'(\langle w_{i,r}^{(t)}, x_p \rangle)(1 - \mathbf{logit}_i(F^{(t)}, X)) \pm \frac{\eta}{\sqrt{d}}.$$

Else if $i \neq y$,

$$\langle w_{i,r}^{(t+1)}, \xi_p \rangle = \langle w_{i,r}^{(t)}, \xi_p \rangle - \tilde{\Theta}(\frac{\eta}{\tilde{N}_u}) \overline{\mathrm{ReLU}}'(\langle w_{i,r}^{(t)}, x_p \rangle) \mathbf{logit}_i(F^{(t)}, X) \pm \frac{\eta}{\sqrt{d}}.$$

Suppose that it satisfies that $|\langle w_{i,r}^{(t)}, x_p \rangle| \leq A$ for every $t < t_0$ where t_0 is any iteration $T \leq t_0 \leq T + T'$. When $T \leq t \leq T + T_0$, we have that

$$\begin{aligned} \langle w_{i,r}^{(t)}, \xi_p \rangle &\leq \langle w_{i,r}^{(T)}, \xi_p \rangle + \tilde{O}\left(\frac{T_0 \eta A^{q-1}}{\tilde{N}_u}\right) + \frac{T_0 \eta}{\sqrt{d}} \\ &\leq \tilde{o}(\sigma_0) + \tilde{O}\left(\frac{k A^{q-1}}{\tilde{N}_u \sigma_0^{q-2}}\right) + \frac{T_0 \eta}{\sqrt{d}}, \end{aligned}$$

where the last step is because $T_0 = \tilde{\Theta}(\frac{k}{\eta \sigma_0^{q-2}})$. When $T + T_0 \leq t \leq T + T'$, for multi-view data $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$, based on (15) in Claim 28, we can obtain that

$$\begin{aligned} \langle w_{i,r}^{(t)}, \xi_p \rangle &\leq \langle w_{i,r}^{(T+T_0)}, \xi_p \rangle + \tilde{O}\left(\frac{k^5 A^{q-1}}{s^2 \tilde{N}_u}\right) + \frac{(T' - T_0)\eta}{\sqrt{d}} \\ &\leq \tilde{O}\left(\frac{k A^{q-1}}{\tilde{N}_u \sigma_0^{q-2}} + \frac{k^5 A^{q-1}}{s^2 \tilde{N}_u}\right) + \frac{T' \eta}{\sqrt{d}}. \end{aligned}$$

For single-view data $(X, y) \sim \tilde{\mathcal{Z}}_{u,s}$, we have that

$$\begin{aligned} \langle w_{i,r}^{(t)}, \xi_p \rangle &\leq \langle w_{i,r}^{(T+T_0)}, \xi_p \rangle + \tilde{O}\left(\frac{T' \eta A^{q-1}}{\tilde{N}_u}\right) + \frac{(T' - T_0)\eta}{\sqrt{d}} \\ &\leq \tilde{O}\left(\frac{k A^{q-1}}{\tilde{N}_u \sigma_0^{q-2}} + \frac{T' \eta A^{q-1}}{\tilde{N}_u}\right) + \frac{T' \eta}{\sqrt{d}}. \end{aligned}$$

When $p \in \mathcal{P}_{v_{i,l}}(X)$, we have $|\langle w_{i,r}^{(t)}, x_p \rangle| \leq \tilde{O}(1)$ from Induction Hypothesis 15. Then plugging in $A = \tilde{O}(1), \tilde{N}_u \geq \tilde{\Omega}\left(\frac{k}{\sigma_0^{q-1}}\right)$, $\tilde{N}_u \geq \tilde{\Omega}\left(\frac{k^5}{\sigma_0}\right)$ and $\tilde{N}_u \geq \eta T' \mathrm{poly}(k)$, we can obtain that $|\langle w_{i,r}^{(t)}, \xi_p \rangle| \leq \tilde{o}(\sigma_0)$.

When $p \in \mathcal{P}(X) \setminus (\mathcal{P}_{v_{i,1}}(X) \cup \mathcal{P}_{v_{i,2}}(X))$, we have $|\langle w_{i,r}^{(t)}, x_p \rangle| \leq \tilde{O}(\sigma_0)$ from the Induction Hypothesis 15. Then plugging in $A = \tilde{O}(\sigma_0), \tilde{N}_u \geq k^5$ and $\tilde{N}_u \geq \eta T' \mathrm{poly}(k)$, we can obtain that $|\langle w_{i,r}^{(t)}, \xi_p \rangle| \leq \tilde{O}(\sigma_0)$.

When $p \in [P] \setminus \mathcal{P}(X)$, we have $|\langle w_{i,r}^{(t)}, x_p \rangle| \leq \tilde{O}(\sigma_0 \gamma k)$ from Induction Hypothesis 15. Then plugging in $A = \tilde{O}(\sigma_0 \gamma k), \tilde{N}_u \geq k^5$ and $\tilde{N}_u \geq \eta T' \mathrm{poly}(k)$, we can obtain that $|\langle w_{i,r}^{(t)}, \xi_p \rangle| \leq \tilde{O}(\sigma_0 \gamma k)$.

□

E.2.4 Diagonal Correlations are Nearly Non-Negative

Lemma 32. *Suppose Parameter 10 holds and suppose Induction Hypothesis 15 holds for all iteration $< t$ starting from T. Then,*

$$\forall i \in [k], \quad \forall r \in [m], \quad \forall l \in [2], \quad \langle w_{i,r}^{(t)}, v_{i,l} \rangle \geq -\tilde{O}(\sigma_0).$$

Proof. From Lemma D.27 in Allen-Zhu & Li (2023), we know $\langle w_{i,r}^{(t)}, v_{i,l}\rangle \geq -\tilde{O}(\sigma_0)$ for every iteration $t \leq T$. Now we consider any iteration $t > T$ so that $\langle w_{i,r}^{(t)}, v_{i,l}\rangle \leq -\widetilde{\Omega}(\sigma_0)$. We start from this iteration to see how negative the next iterations can be. Without loss of generality, we consider the case when $\langle w_{i,r}^{(t')}, v_{i,l}\rangle \leq -\widetilde{\Omega}(\sigma_0)$ holds for every $t' \geq t$. By Claim 19 and Claim 20,

$$\begin{aligned}\langle w_{i,r}^{(t+1)}, v_{i,l}\rangle \geq & \langle w_{i,r}^{(t)}, v_{i,l}\rangle + \eta \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}\Big[\mathbb{I}_{y=i}(V_{i,r,l}(X) - \tilde{O}(\sigma_p P))(1 - \mathbf{logit}_i(F^{(t)}, X)) \\ & - \mathbb{I}_{y\neq i}\left(\mathcal{E}_1 + \mathcal{E}_3 + \mathbb{I}_{v_{i,l}\in\mathcal{P}(X)} V_{i,r,l}(X)\right)\mathbf{logit}_i(F^{(t)}, X)\Big]\end{aligned}$$

Recall by Induction Hypothesis 15(a),

$$V_{i,r,l}(X) = \sum\nolimits_{p\in P_{v_{i,l}}(X)} \overline{\mathrm{ReLU}}'(\langle w_{i,r}^{(t)}, x_p\rangle) z_p = \sum\nolimits_{p\in P_{v_{i,l}}(X)} \overline{\mathrm{ReLU}}'\left(\langle w_{i,r}, v_{i,l}\rangle z_p \pm \tilde{o}(\sigma_0)\right) z_p.$$

Since we have assumed $\langle w_{i,r}^{(t)}, v_{i,l}\rangle \leq -\widetilde{\Omega}(\sigma_0)$, so $V_{i,r,l}(X) = 0$, and we have

$$\begin{aligned}\langle w_{i,r}^{(t+1)}, v_{i,l}\rangle \geq & \langle w_{i,r}^{(t)}, v_{i,l}\rangle - \eta \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}\Big[\mathbb{I}_{y=i}\tilde{O}(\sigma_p P)(1 - \mathbf{logit}_i(F^{(t)}, X)) \\ & + \mathbb{I}_{y\neq i}\left(\mathcal{E}_1 + \mathcal{E}_3\right)\mathbf{logit}_i(F^{(t)}, X)\Big].\end{aligned} \tag{17}$$

We first consider every $t \leq T + T_0$. Using Claim 23 we have $\mathbf{logit}_i(F^{(t)}, X) = O\left(\frac{1}{k}\right)$, which implies

$$\langle w_{i,r}^{(t)}, v_{i,l}\rangle \geq -\tilde{O}(\sigma_0) - O\left(\frac{\eta T_0}{k}\right)(\mathcal{E}_1 + \mathcal{E}_3) \geq -\tilde{O}(\sigma_0).$$

As for $t > T + T_0$, combining with Claim 26 and the fact that $\mathbf{logit}_i(F^{(t)}, X) \leq 1 - \mathbf{logit}_y(F^{(t)}, X)$ for $i \neq y$, we have

$$\langle w_{i,r}^{(t)}, v_{i,l}\rangle \geq \langle w_{i,r}^{(T_0)}, v_{i,l}\rangle - \tilde{O}(k)(\mathcal{E}_1 + \mathcal{E}_3) \geq \langle w_{i,r}^{(T_0)}, v_{i,l}\rangle - \tilde{O}(\sigma_0) \geq -\tilde{O}(\sigma_0).$$

□

E.2.5 Proof of Induction Hypothesis 15

Now we are ready to prove our Induction Induction Hypothesis 15, the proof is similar to Theorem D.2 in Allen-Zhu & Li (2023).

Lemma 33. *Under Parameter Assumption 10, for any $m = \mathrm{polylog}(k)$ and sufficiently small $\eta \leq \frac{1}{\mathrm{poly}(k)}$, our Induction Hypothesis 15 holds for all iterations $t = T, T+1, \ldots, T+T'$.*

Proof. At iteration t, we first calculate

$$\forall p \in P_{v_{j,l}}(X): \quad \langle w_{i,r}^{(t)}, x_p\rangle = \langle w_{i,r}^{(t)}, v_{j,l}\rangle z_p + \sum_{v'\in\mathcal{V}} \alpha_{p,v'}\langle w_{i,r}^{(t)}, v'\rangle + \langle w_{i,r}^{(t)}, \xi_p\rangle, \tag{18}$$

$$\forall p \in [P] \setminus P(X): \quad \langle w_{i,r}^{(t)}, x_p\rangle = \sum_{v'\in\mathcal{V}} \alpha_{p,v'}\langle w_{i,r}^{(t)}, v'\rangle + \langle w_{i,r}^{(t)}, \xi_p\rangle. \tag{19}$$

By Allen-Zhu & Li (2023) we already know Induction Hypothesis 15 holds at iteration $t = T$. Suppose Induction Hypothesis C.3 holds for all iterations $< t$ starting from T. We have established several lemmas:

$$\text{Lemma 29} \implies \forall i \in [k], \forall r \in [m], \forall l \in [2]: \langle w_{i,r}^{(t)}, v_{i,l}\rangle \leq \tilde{O}(1), \tag{20}$$

$$\text{Lemma 30} \implies \forall i \in [k], \forall r \in [m], \forall j \in [k]\setminus\{i\}: |\langle w_{i,r}^{(t)}, v_{j,l}\rangle| \leq \tilde{O}(\sigma_0), \tag{21}$$

$$\text{Lemma 32} \implies \forall i \in [k], \forall r \in [m], \forall l \in [2]: \langle w_{i,r}^{(t)}, v_{i,l}\rangle \geq -\tilde{O}(\sigma_0). \tag{22}$$

- To prove 15(a), it suffices to plug (21), (22) into (18), use $\alpha_{p,v'} \in [0, \gamma]$, use $|\mathcal{V}| = 2k$, and use $|\langle w_{i,r}^{(t)}, \xi_p\rangle| \leq \tilde{o}(\sigma_0)$ from Lemma 31.

- To prove 15(b), it suffices to plug (20), (21) into (18), use $\alpha_{p,v'} \in [0, \gamma]$, use $|\mathcal{V}| = 2k$, and use $|\langle w_{i,r}^{(t)}, \xi_p \rangle| \leq \tilde{O}(\sigma_0)$ from Lemma 31.
- To prove 15(c), it suffices to plug (20), (21) into (19), use $\alpha_{p,v'} \in [0, \gamma]$, use $|\mathcal{V}| = 2k$, and use $|\langle w_{i,r}^{(t)}, \xi_p \rangle| \leq \tilde{O}(\sigma_0 \gamma k)$ from Lemma 31.
- To prove 15(d), it suffices to note that (20) implies $\Phi_{i,l}^{(t)} \leq \tilde{O}(1)$, and note that Claim 24 implies $\Phi_{i,l}^{(t)} \geq \Omega(\Phi_{i,l}^{(0)}) \geq \tilde{\Omega}(\sigma_0)$.
- To prove15(e), it suffices to invoke (22).

□

E.3 Proof of Theorem 13

During the proof of Induction Hypothesis 15, i.e., the proofs of Lemma 29 to Lemma 32, we need the size of $\tilde{N}_u = |\tilde{\mathcal{Z}}_u|$ larger than $\eta T' \cdot \mathrm{poly}(k)$. As the probability that a sample $X \sim \mathcal{Z}_u$ after SA-CutOut belongs to $\tilde{\mathcal{Z}}_u$ is $1 - \frac{1}{\mathrm{poly}(k)}$ (based on our definition of SA-CutOut and threshold τ), we set the size of unlabeled dataset $N_u \geq \eta T' \cdot \mathrm{poly}(k)$ in Parameter Assumption 10. Then recall our training objective is

$$L^{(t)} = L_s^{(t)} + \lambda L_u^{(t)} = \mathbb{E}_{(X,y)\sim\mathcal{Z}_l}[-\log \mathbf{logit}_y(F^{(t)}, X)] + \mathbb{E}_{X\sim\tilde{\mathcal{Z}}_u}[-\log \mathbf{logit}_b(F^{(t)}, \mathcal{A}(X))].$$

From Allen-Zhu & Li (2023) we know $\mathbb{E}_{(X,y)\sim\mathcal{Z}_l}[-\log \mathbf{logit}_y(F^{(t)}, X)] \leq \frac{1}{\mathrm{poly}(k)}$ at the end of learning Phase I, and according to Claim 27 we now this continues to hold true during learning Phase II. For $\mathbb{E}_{X\sim\tilde{\mathcal{Z}}_u}[-\log \mathbf{logit}_b(F^{(t)}, \mathcal{A}(X))]$, since we have for every data $(X, y) \sim \tilde{\mathcal{Z}}_u$ $(y = b)$:

- if $\mathbf{logit}_y(F^{(t)}, \mathcal{A}(X)) \geq \frac{1}{2}$, then we know $-\log \mathbf{logit}_y(F^{(t)}, \mathcal{A}(X)) \leq O\left(1 - \mathbf{logit}_y(F^{(t)}, \mathcal{A}(X))\right)$;
- if $\mathbf{logit}_y(F^{(t)}, \mathcal{A}(X)) \leq \frac{1}{2}$, this cannot happen for too many tuples (X, y, t) thanks to Claim 26, and when this happens we have a naive bound $-\log \mathbf{logit}_y(F^{(t)}, \mathcal{A}(X)) \in [0, \tilde{O}(1)]$ using Claim 23.

Therefore, by Claim 26, we know when $T' \geq \frac{\mathrm{poly}(k)}{\eta}$,

$$\frac{1}{T'} \sum_{t=T+T_0}^{T+T'} \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u} \left[-\log \mathbf{logit}_y(F^{(t)}, X)\right] \leq \frac{1}{\mathrm{poly}(k)}.$$

Moreover, since we are using full gradient descent and the objective function is $O(1)$-Lipschitz continuous, the objective value decreases monotonically. Specifically, this implies that

$$\mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[1-\mathbf{logit}_y(F^{(T+T')}, \mathcal{A}(X))] \leq \mathbb{E}_{(X,y)\sim\tilde{\mathcal{Z}}_u}[-\log \mathbf{logit}_y(F^{(T+T')}, \mathcal{A}(X))] \leq \frac{1}{\mathrm{poly}(k)}.$$

for the last iteration $T + T'$, which directly implies that the training accuracy is perfect.

As for the test accuracy, from Claim 28 and Claim D.16 in Allen-Zhu & Li (2023), we have for every $i, j \in [k]$,

$$\Phi_i^{(T+T')} - 0.4\Phi_j^{(T+T')} \geq \Omega(\log(k)), \quad \Phi_{i,1}^{(T+T')}, \Phi_{i,2}^{(T+T')}, \Phi_{j,1}^{(T+T')}, \Phi_{j,2}^{(T+T')} \geq \Omega(\log(k)).$$

This combined with the function approximation Claim 21 shows that with high probability $F_y^{(T)}(X) \geq \max_{j\neq y} F_j^{(T)}(X) + \Omega(\log k)$ for every $(X, y) \in \mathcal{D}_m, \mathcal{D}_s$, which implies that the test accuracy on both multi-view data and single-view data is perfect.

F PROOF FOR FIXMATCH

In this section, we consider proving Theorem 11 on FixMatch. In this case, the formulation of strong augmentation $\mathcal{A}(\cdot)$ is defined in (10). For $(X, y) \in \tilde{Z}_{u,s}$ with $\hat{l}(X) = l^*$, the feature v_{y,l^*} is masked with the probability π_2. When the patches of learned feature are masked, the left part is pure noise. In this way, same as Claim 23, for every $i \in [k]$, $\mathbf{logit}_i(F^{(t)}, \mathcal{A}(X)) = O(\frac{1}{k})$, and $V_{i,r,l} = \mathbb{I}_{v_{i,l} \in \mathcal{V}(X)} \sum_{p \in \mathcal{P}_{v_{i,l}}(X)} \overline{\mathrm{ReLU}}'(\langle w_{i,r}, x_p \rangle) z_p = o(\frac{1}{\mathrm{polylog}(k)})$. When the patches of noises are masked, the left part is semantic patches of feature v_{y,l^*}. Since we have already captured this feature in learning Phase I, we have $\mathbf{logit}_y(F^{(t)}, \mathcal{A}(X)) \geq 1 - \tilde{O}(\frac{1}{s^2})$. In both above cases, by Claim 19 and Claim 20, the training samples $(X, y) \in \tilde{\mathcal{Z}}_{u,s}$ contributes little to the weight update process.

For multi-view data $(X, y) \in \tilde{Z}_{u,m}$, when the patches of noises are masked with probability $1 - \pi_2$, since the learned feature v_{y,l^*} of Phase I is still in the data, we have $\mathbf{logit}_y(F^{(t)}, \mathcal{A}(X)) \geq 1 - \tilde{O}(\frac{1}{s^2})$. When the patches of unlearned feature $v_{y,3-l^*}$ are masked with probability $\pi_1\pi_2$ or $(1-\pi_1)\pi_2$ (depending on the value of $3 - l^*$), the learned feature of Phase I is also still in the data. Thus we also have $\mathbf{logit}_y(F^{(t)}, \mathcal{A}(X)) \geq 1 - \tilde{O}(\frac{1}{s^2})$. In this way, the loss on all data points $(X, y) \in \tilde{\mathcal{Z}}_{u,m}$ that belongs to the above two cases keeps small ($\leq \frac{1}{\mathrm{poly}(k)}$) and contributes negligible to the learning of unlearned features in Phase II. Finally, when the patches of learned feature v_{y,l^*} are masked with probability $\pi_1\pi_2$ or $(1-\pi_1)\pi_2$ (depending on the value of l^*), the remaining patches of feature $v_{y,3-l^*}$ are unlearned and the approximation of initial loss on this part of samples is the same as Claim 23. The loss on samples $(X, y) \sim \tilde{\mathcal{Z}}_{u,m}$ with learned features masked dominates the training objective in learning Phase II, and the rest proof schedule is the same as the proof of SA-FixMatch. However, now the size of data with learned features masked for class $i \in [k]$ is either $\pi_1\pi_2 \cdot \tilde{N}_u^i$ or $(1-\pi_1)\pi_2 \cdot \tilde{N}_u^i$. Thus, similar to the proof of Theorem 13 and for the simplicity of notation, the requirement on the size of unlabeled data for FixMatch should be $\tilde{N}_c \geq \eta T' \cdot \mathrm{poly}(k) / \min\{\pi_1\pi_2, (1-\pi_1)\pi_2\}$. Accordingly, we can derive that the relationship between the size of the unlabeled data in SA-FixMatch N_u and FixMatch N_c is given by $N_u = \max\{\pi_1\pi_2, (1-\pi_1)\pi_2\} N_c$.

G PROOF FOR FLEXMATCH, FREEMATCH, DASH, AND SOFTMATCH

Our analysis framework and theoretical results are also applicable to other FixMatch-like SSL, e.g., FlexMatch (Zhang et al., 2021a), FreeMatch (Wang et al., 2022b), Dash (Xu et al., 2021), and SoftMatch (Chen et al., 2023), since the main difference is the choice of confidence threshold $\mathcal{T}_t$ in unsupervised loss Eq. (5). Here we first introduce their choice of $\mathcal{T}_t$ and then explain how our theoretical results in Sec. 4 can be generalized to their case.

FlexMatch (Zhang et al., 2021a) designs an adaptive class-specific threshold $\mathcal{T}_t = \beta_t(b)\tau$ at iteration t, where $\beta_t(b) \in [0, 1]$ is the model's prediction confidence for class b (L1 normalized). FreeMatch (Wang et al., 2022b) replaces τ in FlexMatch with an adaptive τ_t, which is the average prediction confidence of the model on unlabeled data and increases as the training progresses. SoftMatch uses the average prediction confidence τ_t of the model as the threshold and sets the sample weight as 1.0 if $\mathbf{logit}_b(F^{(t)}, \alpha(X_u)) \geq \tau_t$, otherwise a smaller constant according to a Gaussian function. Dash adopts the cross-entropy loss to design the indicator function $\mathbb{I}_{\{-\log \mathbf{logit}_b(F^{(t)}, \alpha(X_u)) < \rho_t\}}$, where ρ_t decreases as training processes. This is equivalent to a dynamically increasing threshold $\mathcal{T}_t$ in Eq. (5). Below we detail how our theoretical findings apply to each of these SSL algorithms.

FlexMatch (Zhang et al., 2021a) differentiates itself from FixMatch by modifying the constant threshold τ to include an adaptive class-specific threshold $\beta_t(b)$ for each class b. Under our multi-view data assumption as defined in Definition 7, the data distribution for each class is the same. Consequently, as suggested by Claim 24 and Claim D.10 in Allen-Zhu & Li (2023), all classes progress at a similar rate during training. This uniformity over all classes allows us to standardize $\beta_t(b) = 1, \forall b \in [k]$, thereby aligning the proof for FlexMatch with that of FixMatch.

For FreeMatch (Wang et al., 2022b) and SoftMatch (Chen et al., 2023), instead of applying a large constant threshold τ during the training process, they use an adaptive τ_t to involve more unlabeled data with correctly-predicted pseudo-label in the training of the network. Under our multi-view

data assumption 7, the majority of the data in training dataset is of multi-view (with probability $1-\frac{1}{\mathrm{poly}(k)}$), so we only consider the network's prediction confidence for multi-view data to determine τ_t. We set the adaptive threshold τ_t as follows:

$$\tau_t = \begin{cases} \max_{X\in\mathcal{Z}_{u,m}}[\mathbf{logit}_b(F^{(t)},X)], & t=T_0, \\ \beta\tau_{t-1}+(1-\beta)\max_{X\in\mathcal{Z}_{u,m}}[\mathbf{logit}_b(F^{(t)},X)], & t>T_0, \end{cases} \tag{23}$$

where β is the momentum parameter, $b=\arg\max_i \mathbf{logit}_i(F^{(t)},X)$, and $T_0=\Theta(\frac{k}{\eta\sigma_0^{q-2}})$. Here we do not consider the unsupervised loss term Eq. (5) before T_0-th iteration in our analysis, since the model is bad at generating correct pseudo-label at the initial phase of training. We use $\max$ function here to ensure the high quality of unlabeled data involved at each training step. After T_0-th iteration, according to Claim D.11 and Lemma D.22 in Allen-Zhu & Li (2023), the feature correlations increase to $\Lambda_i^{(t)}=\tilde{\Theta}(1)$ for $t\geq T_0$, while the off-diagonal correlations $\langle w_{i,r},v_{j,l}\rangle$ $(i\neq j)$ keep small at the scale of $\tilde{O}(\sigma_0)$. Denote $\Phi^{(t)}=\max_{i\in[k],l\in[2]}\Phi_{i,l}^{(t)}$, recall from Claim D.9 in Allen-Zhu & Li (2023), for every $X\in\arg\max_{X\in\mathcal{Z}_{u,m}}[\mathbf{logit}_b(F^{(t)},X)]$ with ground truth label y, we have $F_j^{(t)}(X)\leq 0.8001\Phi^{(t)}$ for $j\neq y$ and $F_y^{(t)}(X)\geq 0.9999\Phi^{(t)}$ with probability at least $1-e^{-\Omega(\log^2 k)}$. Accordingly, we have $F_y^{(t)}(X)\geq\max_{j\neq y}F_j^{(t)}(X)+\tilde{\Theta}(1)$, which means that $F^{(t)}$ can correctly classify the unlabeled data with high probability (i.e., $b=y$). Therefore, when $t\geq T_0$, both the supervised loss Eq. (4) and unsupervised loss Eq. (5) take effect. Same as in Sec. 4, we use $\Phi_{i,l}^{(t)}$ here to monitor the feature learning process. For $(i,l)\in\mathcal{M}_F$, feature $v_{i,l}$ is partially learned during the first T_0 iterations in that $\Phi_{i,l}^{(T_0)}=\tilde{\Theta}(1)<\Omega(\log(k))$, while feature $v_{i,3-l}$ is missed in that $\Phi_{i,3-l}^{(T_0)}=\tilde{O}(\sigma_0)\ll\tilde{\Theta}(1)$. Start from T_0, feature $v_{i,l}$ is continued to be better learned with the help of supervised loss and unsupervised loss until $\Phi_{i,l}^{(t)}\geq\Omega(\log k)$, and feature $v_{i,3-l}$ start to be learned with the help of unsupervised loss. We can analyze this feature learning process using a similar approach as in Sec. E. The key intuition for the extension of the proof of FixMatch to FreeMatch and SoftMatch is that by setting an adaptive confidence threshold, the learning process of unlearned features begin at T_0 instead of $T=O(\mathrm{poly}(k)/\eta)>T_0$ in FixMatch.

For Dash, it uses cross-entropy loss as the threshold indicator function rather than prediction confidence $\mathbb{I}_{\{-\log\mathbf{logit}_b(F^{(t)},\alpha(X_u))<\rho_t\}}$, where ρ_t decreases as the training progresses. Since we have

$$-\log\mathbf{logit}_b(F^{(t)},\alpha(X_u))<\rho_t \iff \mathbf{logit}_b(F^{(t)},\alpha(X_u))>e^{-\rho_t},$$

we can set $\rho_t=-\log\tau_t$ and the rest of the analysis is the same as in SoftMatch and FreeMatch.

H Effect of Strong Augmentation on Supervised Learning

In this section, we show why using strong augmentation with probabilistic feature removal effect, such as CutOut, in supervised learning (SL) has minimal alternation to the feature learning process. In SL, strong augmentation $\mathcal{A}(\cdot)$ is utilized at the start of training, before any feature has been effectively learned, corresponding to Phase I of SSL. According to Assumption 9, $\mathcal{A}(\cdot)$ randomly removes its semantic patches and noisy patches with probabilities of π_2 and $1-\pi_2$, respectively. Then for a single-view image, its only semantic feature is masked with probability π_2. For a multi-view image, one of the two features, $v_{i,1}$ or $v_{i,2}$ is masked with probabilities $\pi_1\pi_2$ and $(1-\pi_1)\pi_2$, respectively. Thus, the size of single-view data in training dataset $\mathcal{Z}_l$ is increased, as $\mathcal{A}(\cdot)$ transfers $\pi_2 N_{l,m}$ multi-view samples to single-view.

However, $\pi_2\in(0,1)$ is small, since based on our data assumption in Def. 7, the number of patches associated with certain semantic feature is constant C_p while the total number of patches is $P=k^2$. Therefore, when we do random masking in $\mathcal{A}(\cdot)$ (usually masks $1/4$ of all patches), we can approximate π_2 as $(C_p/P)^{C_p}$, which is $O(1/k^{C_p})$ based on our definition of $\mathcal{A}(\cdot)$ in Eq. (10).

Consequently, strong augmentation $\mathcal{A}(\cdot)$ only slightly increases the proportion of single-view data, and the majority of the training dataset remains multi-view, which dominates the supervised training loss Eq. (4) since no feature has been learned. The assumptions on the number of labeled single-view data $N_{l,s}\leq\tilde{o}(k/\rho)$ and $N_l\geq N_{l,s}\cdot\mathrm{poly}(k)$ still hold after strong augmentation $\mathcal{A}(\cdot)$. Thus, according to Allen-Zhu & Li (2023) and Appendix B, the network learns one feature per class to

correctly classify the majority multi-view data due to "view lottery winning", and memorizes the single-view data without learned feature during the training process of SL. We also validate the limited effect of CutOut on SL through experimental results in Appendix K.3.

I Comparison with Pioneering Work

While this work follows the data assumption and proof framework of Allen-Zhu & Li (2023), analysis of the feature learning process is significantly different. Firstly, this work focuses on SSL, where supervised loss on labeled data and unsupervised loss on unlabeled data result in rather different feature learning processes compared with supervised distillation loss on only labeled data in Allen-Zhu & Li (2023). Secondly, SSL uses the on-training model as an online teacher which varies along training iterations, while the SL setting in Allen-Zhu & Li (2023) uses a well-trained and fixed model as an offline teacher. Indeed, the online teacher in SSL setting is more challenging to analyze, as the evolution of its performance is harder to characterize, and has a rather different learning process.

J (SA-)FixMatch Algorithm

In this section, we present the detailed algorithm framework for FixMatch (Sohn et al., 2020) and SA-FixMatch. At iteration t, we first sample a batch of B labeled data $\mathcal{X}^{(t)}$ from labeled dataset $\mathcal{Z}_l$, and a batch of μB unlabeled data $\mathcal{U}^{(t)}$ from unlabeled dataset $\mathcal{Z}_u$. Then, according to Algorithm 1, we calculate the loss for current iteration, and use it for the update of the neural network model $F^{(t)}$. The only difference between FixMatch and SA-FixMatch is in line 6, where FixMatch adopts CutOut in its strong augmentation of unlabeled data $\mathcal{A}$, while SA-FixMatch adopts SA-CutOut.

Algorithm 1 (SA-)FixMatch algorithm.

1: **Input:** Labeled batch $\mathcal{X}^{(t)} = \{(X_i, y_i) : i \in (1, \ldots, B)\}$, unlabeled batch $\mathcal{U}^{(t)} = \{U_i : i \in (1, \ldots, \mu B)\}$, confidence threshold τ, unlabeled data ratio μ, unlabeled loss weight λ.
2: $L_s^{(t)} = \frac{1}{B}\sum_{i=1}^{B}\left(-\log \mathbf{logit}_{y_i}(F^{(t)}, \alpha(X_i))\right)$ {*Cross-entropy loss for labeled data*}
3: **for** $i = 1$ **to** μB **do**
4: $\quad v_i = \arg\max_j \{\mathbf{logit}_j(F^{(t)}, \alpha(U_i))\}$ {*Compute prediction after applying weak data augmentation of* U_i}
5: **end for**
6: $L_u^{(t)} = \frac{1}{\mu B}\sum_{i=1}^{\mu B}\left(-\mathbb{I}_{\{\mathbf{logit}_{v_i}(F^{(t)}, \alpha(U_i)) \geq \tau\}} \log \mathbf{logit}_{v_i}(F^{(t)}, \mathcal{A}(U_i))\right)$ {*Cross-entropy loss with pseudo-label and confidence for unlabeled data*}
7: **return:** $L_s^{(t)} + \lambda L_u^{(t)}$

K Experimental Details

K.1 Effect of Strong Augmentation

In this section, we conduct experiments to evaluate the impact of different strong augmentation operations employed in FixMatch (Sohn et al., 2020). We assess their effects by applying these strong augmentations to test images and observing the resulting changes in test accuracy. To ensure a fair comparison, we train neural networks using weakly-augmented labeled data, where the weak augmentation consists of a random horizontal flip and a slight extension of the image around its edges before cropping the main portion. Subsequently, we apply a single strong augmentation operation at a time to the test dataset and record the corresponding test accuracy on the pretrained model. The pool of strong augmentation operations from RandAugment (Cubuk et al., 2020) includes: Colorization, Equalize, Posterize, Solarize, Rotate, Sharpness, ShearX, ShearY, TranslateX, and TranslateY. The experimental results are summarized in Tables 5 and 6.

From Tables 5 and 6, we observe that CutOut is the strong augmentation operation with the most significant impact on model performance. Additionally, transformations such as Solarize and Equalize from RandAugment also have a noticeable effect on model performance. To better understand the influence of these transformations on input images, we visualize the effects of CutOut, Solarize,

Original	CutOut	ShearX	Solarize	TranslationX
80.95	38.67	78.38	52.70	80.69
Sharpness	Posterize	Equalize	Rotate	Color
72.99	76.17	60.14	67.97	69.71

Table 5: Pretrained model test accuracies (%) with different strong augmentation operations for test images on CIFAR-100.

Original	CutOut	ShearX	Solarize	TranslationX
86.44	62.94	85.01	78.94	84.44
Sharpness	Posterize	Equalize	Rotate	Color
82.17	86.19	80.74	82.29	84.34

Table 6: Pretrained model test accuracies (%) with different strong augmentation operations for test images on STL-10.

and Equalize on CIFAR-100 images in Figure 3. From the first and second rows of Figure 3, we can see that both CutOut and Solarize have the potential to remove semantic features by masking parts of the images. From the third row of Figure 3, we observe that Equalize tends to remove color features of images while retaining shape features. In all cases, these effective strong augmentation operations have the potential to remove partial semantic features. Therefore, in Assumption 3 for strong augmentation $\mathcal{A}(\cdot)$, we focus on its probabilistic feature removal effect.

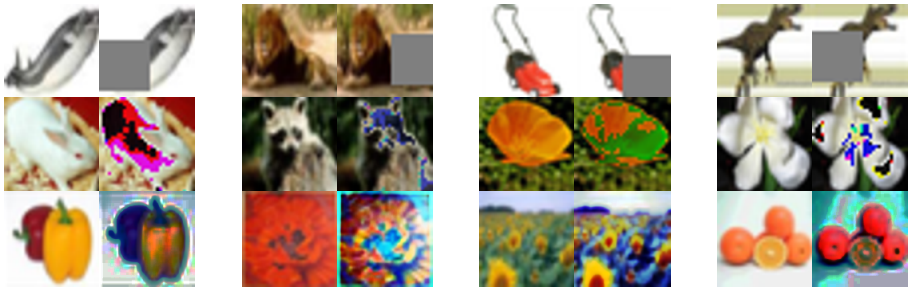

Figure 3: Visualization of the effects of CutOut (first row), Solarize (second row), and Equalize (third row) on CIFAR-100 images.

K.2 Effect of Weak Augmentation

Since weak augmentation consists only of a random horizontal flip and a random crop with a small padding of 4 pixels, followed by cropping the padded image back to the original size, it minimally alters the semantic features of the image. This allows us to treat weak augmentation $\alpha(\cdot)$ as an identity mapping for our theoretical analysis in Sec. 4. In this section, we conduct experiments by training FixMatch without weak augmentation on CIFAR-100 with 10000 labeled samples and STL-10 with 1000 labeled samples, comparing the test performance to that of the original FixMatch. As shown in Table 7, weak augmentation does not significantly impact the model's performance.

K.3 Comparison of CutOut in SL and FixMatch

Data augmentation operations like CutOut can help supervised learning (SL), but cannot improve as much as in deep SSL with limited labeled data. On STL-10 dataset with 40 labeled data, when we remove CutOut from SL, the test accuracy (%) does not drop a lot as shown in Table 8. In contrast, removing CutOut from the strong augmentation $\mathcal{A}(\cdot)$ in FixMatch's unsupervised loss $L_u^{(t)}$ leads to a severe performance degradation.

Dataset	STL-10	CIFAR-100
Weak Augmentation	92.65	77.27
No Weak Augmentation	91.83	77.19

Table 7: Comparison of test accuracies (%) of FixMatch with and without weak augmentation.

Method	SL	FixMatch
CutOut	23.98	68.30
No CutOut	22.88	53.64

Table 8: Comparison of test accuracies (%) of SL and FixMatch with and without CutOut.

K.4 Dataset Statistics

For each experiment in Sec. 5, following Sohn et al. (2020); Zhang et al. (2021a); Xu et al. (2021); Wang et al. (2022b); Chen et al. (2023), we randomly select image-label pairs from the entire training dataset according to labeled data amount, set images from the whole training dataset without labels as unlabeled dataset, and we use the standard test dataset. The table below details data statistics across different datasets.

Dataset	Total Training Data	Total Labeled Data in Training Data	Test Data
STL-10	105000	5000	8000
CIFAR-100	50000	50000	10000
ImageWoof	9025	9025	3929
ImageNet	1281167	1281167	50000

Table 9: Summary of Datasets.

K.5 Training Setting and Hyper-parameters

All the experiments are conducted on four RTX 3090 GPU (24G memory). Due to limited resources, we did not train the models for 1024 epochs with 1024 iterations per epoch (in total 2^{20} iterations) as in Sohn et al. (2020), but run 150 epochs with 2048 iterations per epoch (in total 307200 iterations). According to our experimental results in Sec. 5, the test accuracy results of our training setting approximates the results obtained by Sohn et al. (2020). For the experiments on FixMatch, our code is based on Kim (2020); for all other experiments, our code is based on Wang et al. (2022a). Each individual SSL experiment requires 48 to 120 hours to complete on a single RTX 3090 GPU, depending on the model and dataset.

For CIFAR-100, STL-10, Imagewoof, and ImageNet, their input image size are respectively 32×32, 96×96, 96×96, 224×224 and their mask size in CutOut are respectively 16×16, 48×48, 48×48, 112×112. For the application of SA-CutOut, according to our theoretical analysis in Sec. 4 and Appendix G, we only need it after partial feature already been learned to learn comprehensive features in the dataset. Therefore, in practice, we only apply SA-CutOut to deep SSL methods in the last 32 epochs of training, and the total running time of SA-FixMatch is roughly 1.15 times of FixMatch.

For hyper-parameters, we use the same setting following FixMatch (Sohn et al., 2020). Concretely, the optimizer for all experiments is standard stochastic gradient descent (SGD) with a momentum of 0.9 (Sutskever et al., 2013). For all datasets, we use an initial learning rate of 0.03 with a cosine learning rate decay schedule (Loshchilov & Hutter, 2016) as $\eta = \eta_0 \cos\left(\frac{7\pi k}{16K}\right)$, where η_0 is the initial learning rate, k is the current training step and K is the total training step that is set to 307200. We also perform an exponential moving average with the momentum of 0.999. The hyper-parameter settings are summarized in Table 10.

Dataset	CIFAR-100	STL-10	Imagewoof	ImageNet
Model	WRN-28-8	WRN-37-2	WRN-37-2	ResNet-50
Weight Decay	1e-3	5e-4	5e-4	3e-4
Batch Size	64			128
Unlabeled Data Raion μ	7			1
Threshold τ	0.95			0.7
Learning Rate η	0.03			
SGD Momentum	0.9			
EMA Momentum	0.999			
Unsupervised Loss Weight λ	1			

Table 10: Complete hyperparameter setting.

K.6 Samples in CIFAR-100, STL-10, Imagewoof, and ImageNet

As we can observe from Figure 4, for images in CIFAR-100 and STL-10, the semantic subject in the image occupies the majority of the image. On the other hand, for images in Imagewoof and ImageNet dataset, most semantic subject only occupies less than a quarter of the image.

Figure 4: Samples from CIFAR-100, STL-10, Imagewoof, and ImageNet datasets. Samples in the first row are from CIFAR-100, samples in the second row are from STL-10, samples in the third row are from Imagewoof, and samples in the last row are from ImageNet.

K.7 Same Training Dataset for SL and SA-FixMatch

With the same labeled training dataset $\mathcal{D}$, SSL still outperforms SL both theoretically and empirically. In this setting, SL uses $\mathcal{D}$ for supervised training, while SSL uses $\mathcal{D}$ as its labeled dataset and simultaneously treats the label-ignored $\mathcal{D}$ as its unlabeled dataset.

Theoretically, our analysis for SA-FixMatch can be extended to this scenario where SL and SSL share the same data. This is because SA-FixMatch assumes that the strong augmentation $\mathcal{A}_{SA}(\cdot)$ deterministically removes semantic features learned during Phase I from the unlabeled images (see Appendix E). As a result, even with the same labeled and unlabeled dataset, SA-FixMatch can still exploit the two-phase feature learning process to learn a more comprehensive set of semantic features compared to SL, ultimately achieving better generalization performance. This conclusion is rigorously supported by our proof in Appendix E.

To validate this theory empirically, we conducted experiments comparing SA-FixMatch with SL under controlled settings. Following the experimental protocols of our manuscript and FixMatch, we trained WRN-28-8 on CIFAR-100 with 10,000 labeled samples and WRN-37-2 on STL-10 with 1,000 labeled samples. In both cases, SL and SA-FixMatch shared the same labeled dataset $\mathcal{D}$, with SA-FixMatch treating the label-ignored $\mathcal{D}$ as unlabeled dataset.

The test accuracy (%) results in Table 11 demonstrate that SA-FixMatch significantly outperforms SL even when both using the same training dataset. This not only highlights the superiority of SSL over SL but also further validates our theoretical insights.

	CIFAR-100	STL-10
SL	63.48	67.29
SA-FixMatch	68.30	79.74

Table 11: Test accuracy (%) of SL and SA-FixMatch with same training dataset.