Enhancing Semi-supervised Learning with Zero-shot Pseudolabels

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Abstract

The high cost of data labeling presents a major barrier to deploying machine learning systems at scale. Semi-supervised learning (SSL) mitigates this challenge by utilizing unlabeled data alongside limited labeled examples, while the emergence of foundation models (FMs) offers powerful zero-shot capabilities that can further reduce labeling cost. However, directly fine-tuning large FMs is often impractical in resource-constrained settings, and naïvely using their pseudo-labels for unlabeled data can degrade performance due to its unreliablity or domain mismatch with target task. In this work, we introduce ZeroMatch, a novel SSL framework that integrates knowledge distillation with consistency-based learning to jointly leverage labeled data, unlabeled data, and pseudo-labels from FMs. ZeroMatch trains a compact student model and access FMs only through inference services, making it suitable for low-resource environments such as personal devices with limited compute. Experiments on six vision and language classification benchmarks show that ZeroMatch consistently outperforms standard SSL and zero-shot augmented methods, demonstrating its effectiveness and robustness across a range of foundation model qualities.

1 Introduction

The growing scale of machine learning applications has made data labeling costs a critical bottleneck in deploying ML systems (Northcutt et al., 2021; Sun et al., 2017; Shen et al., 2024). Semi-supervised learning (SSL) addresses this challenge by leveraging unlabeled data alongside limited labeled examples (Tarvainen & Valpola, 2017). Traditional SSL approaches like pseudo-labeling and consistency regularization have demonstrated strong performance across domains, particularly in computer vision and natural language processing (Sohn et al., 2020; Laine & Aila, 2022; Tarvainen & Valpola, 2017).

In parallel, the emergence of foundation models (FMs) has opened new opportunities for reducing reliance on labeled data. These large-scale pre-trained models exhibit strong zero-shot capabilities, enabling them to generalize to novel tasks without requiring task-specific fine-tuning (Brown et al., 2020; Liang et al., 2022). To this end, recent efforts have explored integrating foundation models into the SSL pipeline. Proposed strategies include fine-tuning foundation models with labeled and unlabeled data (Shi et al., 2023; Zhang et al., 2024; Gan & Wei, 2024), using zero-shot predictions as pseudo-labels (Hegselmann et al., 2023; Nam et al., 2023), and distilling knowledge from foundation models into smaller student models (Yang et al., 2025; Shi et al.; Vemulapalli et al., 2023; Zhao et al., 2023; Jiang et al., 2023).

We motivate our problem setting with a practical on-device training scenario: a user with a personal modest-sized dataset and limited computational resources (e.g., a single GPU), with access to foundation model inference services. In such settings, direct fine-tuning of large foundation models (including parameter-efficient fine-tuning (Houlsby et al., 2019; Hu et al., 2022) and test-time adaptation (Sun et al., 2020)) is infeasible due to large parameter size and high computational costs for backpropagation. Furthermore, naively using pseudo-labels from foundation models to supervise unlabeled data can degrade performance — particularly when pseudo-labels are inaccurate (Zhu et al., 2024) — which can be common when the foundation model has not encountered data similar to the user's personal data. Among existing approaches, knowledge distillation-based methods (Zhao et al., 2023; Vemulapalli et al., 2023; Jiang et al., 2023) offers a promising solution for such

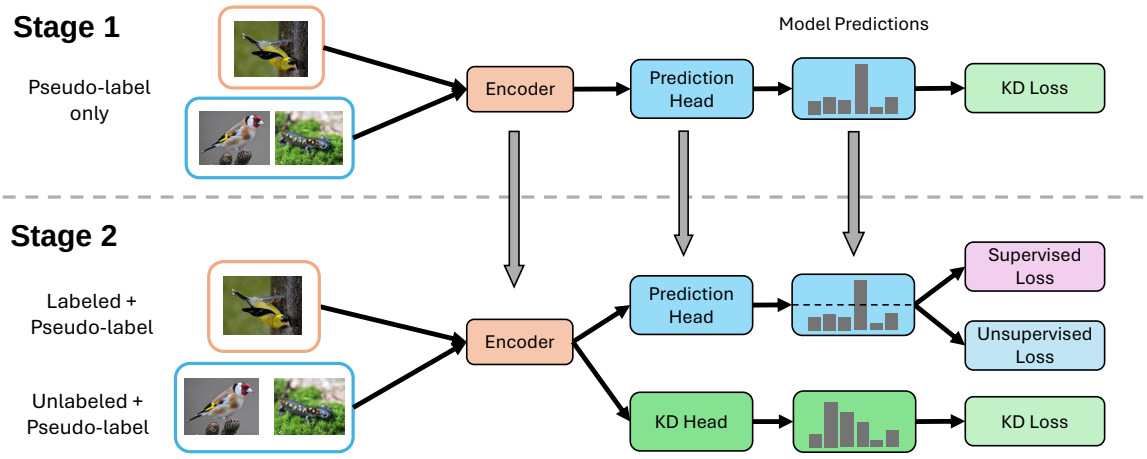

Figure 1: Illustration of our 2-stage ZeroMatch algorithm. Both labeled and unlabeled input data receive pseudo-labels from foundation models. In stage 1, knowledge distillation is performed with pseudo-labels from teacher foundation model. In stage 2, the model is trained with supervised and unsupervised loss of SSL algorithm, with weights and initial confident prediction learned from the previous stage. We add an auxiliary classifier head (green box) that runs knowledge distillation task, to reduce potential catastrophic forgetting that may occur during runing SSL.

resource-constrained settings. However, current methods typically leverage either the teacher's predictions or the labeled data independently, missing opportunities to combine these complementary supervision sources. Thus, fully leveraging labels, unlabeled data, and pseudo-labels from foundation models in a unified framework remains an underexplored direction.

In this paper, we introduce **ZeroMatch**, a method that integrates knowledge distillation and semi-supervised learning to jointly supervise a student model using both pseudo-labels from a foundation model and a confidence-based SSL objective. Our approach is based on the insight that the student model can iteratively refine its predictions on unlabeled data by drawing from the strengths of both the teacher (via distillation) and labeled data (via SSL). We conduct extensive experiments across six datasets in vision and language classification, evaluating ZeroMatch using pseudo-labels generated by both high- and low-quality foundation models. Our results show that ZeroMatch consistently outperforms standard SSL baselines, zero-shot classification, and other zero-shot augmented approaches, highlighting its robustness and practical applicability in low-resource scenarios.

In summary, our key contributions are as follows:

1. We propose ZeroMatch: a novel knowledge distillation-based semi-supervised learning approach that effectively leverages labels, unlabeled data, and teacher pseudo-labels from foundation models.

2. Our framework trains small models while directly leveraging zero-shot predictions from foundation models as pseudo-labels, enabling training on modest hardware, and eliminating the need for teacher model to be present. This addresses a practical setting where users have limited computational resources but access to foundation model inference services.

3. We provide extensive experiments on 6 datasets across vision and language domains which demonstrate that ZeroMatch outperforms both standard SSL methods and zero-shot augmented approaches.

2 Related Work

2.1 Semi-supervised Learning

Semi-supervised learning (SSL) has evolved from foundational consistency regularization methods to sophisticated deep learning approaches. The Π-Model (Laine & Aila, 2022) and Mean Teacher (Tarvainen & Valpola, 2017) established core principles by enforcing consistent predictions across different model states. FixMatch (Sohn et al., 2020) later unified these ideas by combining weak and strong augmentations with pseudo-labeling. Subsequent work focused on reliability: UPS (Rizve et al., 2021) introduced confidence-based filtering while FlexMatch (Zhang et al., 2021) developed adaptive thresholding for pseudo-label selection. Recent approaches like SimMatch (Zheng et al., 2022) have further advanced the field by incorporating contrastive learning principles.

2.2 Foundation Models in SSL

The integration of foundation models into SSL frameworks is an emerging direction. One of main emerging approaches is to fine-tune foundation models with SSL or unsupervised algorithms (Shi et al., 2023; You et al., 2024; Hegselmann et al., 2023; Menghini et al., 2023; Zhang et al., 2024; Gan & Wei, 2024). These methods provides a strong and robust learner in general, but are not often applied to state-of-the-art foundaton models due to building upon model-specific features like cosine similarity of embeddings, and requiring significant compute for the fine-tuning step involved in tuning large foundation models. In contrast, our setup leverage foundation models as a pseudo-label generator. Researchers have also proposed theoretical guarantees to accommodate potentially noisy pseudo-labels (Zhu et al., 2024). Our work builds on this goal to develop a practical method for incorporating unreliable pseudo-labels.

2.3 Knowledge Distillation in SSL

Knowledge distillation (KD) has been widely used to transfer knowledge from large teacher models to smaller student models (Buciluǎ et al., 2006; Hinton et al., 2015; West et al., 2021; Beyer et al., 2022; Hsieh et al., 2023; Vöge et al., 2024), allowing the benefits of large models on low compute device. Many KD approaches applied in the semi-supervised learning (SSL) setting rely on pre-training a large teacher model—either via supervised or self-supervised objectives (Chen et al., 2020; He et al., 2021; Yang et al., 2025; Xie et al., 2022; Shi et al.; Vemulapalli et al., 2023) which often makes impractical to apply to recent large foundation models like LLaMA-70B due to its large compute requirement for tuning. Recent alternative KD attempts avoids explicitly training a teacher by optimizing the student models on teacher's zero-shot outputs, but trains the student model on either one of teacher model outputs (Zhao et al., 2023; Jiang et al., 2023) or labeled data (Vemulapalli et al., 2023), missing synergic opportunity of using both. To the best of our knowledge, there is no existing KD approach that satisfies our goal to fully leverage labels, unlabeled data and teacher outputs simulataneously.

3 Preliminaries

3.1 Problem Setup

We consider an on-device training setup with compute-limited device (e.g. single GPU, or edge device with memory less than 8GB), semi-supervised training data, and read-only access to a foundation model $\hat{f}$ through inference service. The training data consists of a labeled set $\mathcal{D}_L = (x_i, y_i) : i \in [N_L]$ and an unlabeled set $\mathcal{D}_U = (u_i) : i \in [N_U]$, where inputs of both sets comes from the same distribution. $\mathcal{D} = \mathcal{D}_L \cup \mathcal{D}_U$ represents the full dataset where $[N]$ denotes integers $1, 2, ..., N$. The foundation model $\hat{f}$ generates pseudo-label distributions $\hat{y}_i^L = \hat{f}(x_i)$ for labeled data and $\hat{y}_i^U = \hat{f}(u_i)$ for unlabeled data. The goal is to train a classifier f that outputs class distributions $\mathbf{p}(y|x)$ using $\mathcal{D}_L$, $\mathcal{D}_U$, and pseudo-labels $\hat{y}_i^L, \hat{y}_i^U$. [1] We assume $\hat{f}$ was not

[1] Our usage of "pseudo-labels" differs from traditional SSL literature, where they typically refer to predictions on $\mathcal{D}_U$ from a model partially trained on $\mathcal{D}_L$. Here, they represent foundation model predictions without any task-specific training.

trained on $\mathcal{D}_L$ or $\mathcal{D}_U$. The pseudo-label quality depends on the model's capabilities and prompt design, with potential failure modes including hallucinations and out-of-domain responses.

Our main objective is to develop a SSL method that maximally leverages labels, unlabeled data, and pseudo-labels from foundation model. This implies that the algorithm should fully utilze pseudo-labels when they are high quaility, and gracefully degrades to standard SSL performance when pseudo-labels are unreliable.

3.2 Semi-supervised learning methods

Recent advancements in SSL have led to the development of methods that jointly train a classifier from both supervision with labeled set, and unsupervised feature learning on unlabeled data. The training objective is typically expressed as $\mathcal{L} = \mathcal{L}_s + \mathcal{L}_u$ where $\mathcal{L}_s$ is the supervised loss, often the cross-entropy loss computed on the labeled data:

$$\mathcal{L}_s = \frac{1}{B_L} \sum_{i=1}^{B_L} \mathcal{H}(y_i, \mathbf{p}(y|x_i)).$$

where B_L is the size of data batch sampled from labeled set $\mathcal{D}_L$.

On the other hand, $\mathcal{L}_u$ represents the unsupervised loss, which leverages different strategies to incorporate unlabeled data into the training process. Some notable strategies include the following:

- **Self-training**: This strategy involves using the model trained on labeled data to generate temporary predictions for the unlabeled samples. These predictions are then incorporated into the model's supervision objective (Lee, 2013).
- **Confidence-based sample selection**: Unlabeled samples with less confidence or potentially incorrect pseudo-labels are filtered out based on predefined thresholds. This ensures that only samples with reliable predictions contribute to the training process (Xie et al., 2020).
- **Strong augmentation**: To further enhance feature learning, the model is optimized so that its predictions on weakly augmented and strongly augmented versions of the same sample agree, to encourage the model to learn robust features (Xie et al., 2020).
- **Distribution alignment**: This technique adjusts the output probability distribution of each class based on the input data distribution (Berthelot et al., 2020).

With strong augmentation $\mathcal{A}_s(u_i)$ and weak augmentation $\mathcal{A}_w(u_i)$ of unlabeled samples u_i, we denote predictions from classifier f of these augmented samples by $p_i^s = \mathbf{p}(y|\mathcal{A}_s(u_i))$ and $p_i^w = \mathbf{p}(y|\mathcal{A}_w(u_i))$, respectively.

When a data batch of size B_U is sampled from $\mathcal{D}_U$, the unsupervised training objective in typical SSL methods takes the following form:

$$\mathcal{L}_u = \frac{1}{B_U} \sum_{i=1}^{B_U} \mathbb{1}(\max(\hat{p}_i^w) > \tau) \mathcal{H}(y_i, \mathbf{p}(y|u_i))$$

where $\hat{p}_i^w = DA(p_i^w)$ is the label prediction for input $\mathcal{A}_w(u_i)$ and DA represents the distribution alignment process.

4 The ZeroMatch Framework

In order to develop a SSL method that effectively leverages labeled data, unlabeled data, and pseudo-labels generated by a foundation model, we propose a hybrid approach that combines the strengths of knowledge distillation and SSL techniques.

The two key intuitions behind our approach are:

1. **Knowledge distillation methods utilizes teacher model's prediction** to improve student model's prediction output on unlabeled data.
2. **Semi-supervised learning algorithms utilize labeled data** to refine model's predictions on unlabeled data.

These imply that the both methods can be used to improve predictions on unlabeled data from different supervision sources in a complementary manner. To this end, we propose following two-stage algorithm that integrates both paradigms to maximize the utility of all available supervision signals.

Stage 1: Knowledge Distillation (KD) We start by following standard knowledge distillation procedure with teacher's output. A student model is trained using available unlabeled data (including the unlabeled input in labeled data) with the pseudo-labels $\hat{y}_i^L, \hat{y}_i^U$ generated from teacher foundation model $\hat{f}$ with following objective:

$$\mathcal{L}_{KD} = \frac{1}{N}\left(\sum_{i=1}^{N_L} \mathcal{H}(\hat{y}_i^L, \mathbf{p}(y|x_i)) + \sum_{i=1}^{N_U} \mathcal{H}(\hat{y}_i^U, \mathbf{p}(y|u_i))\right).$$

where $N = N_L + N_U$. The resulting student model obtains high-confidence predictions for unlabeled data that matches the teacher's pseudo-labels.

Stage 2: Semi-supervised learning with auxiliary KD loss The objective of second stage is to train the student model with SSL objective. The key component is that, unlike running SSL from scratch, predictions obtained from the previous stage can be utilized as initial high-confidence samples in SSL algorithm, allowing more unlabeled samples to be utilized since the beginning stage of SSL learning, achieving faster convergence as result.

One possible failure mode of running a SSL algorithm in stage 2 is catastrophic forgetting (Goodfellow et al., 2013), where learned knowledge from teacher's pseudo-label can be forgotten during training for downstream task (SSL in this case). This can happen frequently in low-label setting, where SSL algorithm can develop inaccurate predictions on unlabeled data due to inherently low information in labels, leading to inaccurate pseudo-label that overwrites the knowledge learned. To address this issue, we include knowledge distillation as an auxiliary objective alongside the main SSL objective, motivated by Kar et al. (2022). When the student classifier f consists of a non-linear projector head $h(\cdot)$ and a feature encoder $g(\cdot)$, such that $f = h \circ g$, we introduce an additional linear projector head $h_p(\cdot)$, which learns a knowledge distillation task, while sharing the encoder g with the main classification task. Given a batch of labeled and unlabeled data of size B_L and B_U, stage 2 optimizes $h_p \circ g$ with following loss:

$$\mathcal{L}_{KD_2} = \frac{1}{B}\left(\sum_{i=1}^{B_L} \mathcal{H}(\hat{y}_i^L, \mathbf{q}(y|x_i)) + \sum_{i=1}^{B_U} \mathcal{H}(\hat{y}_i^U, \mathbf{q}(y|u_i))\right).$$

where $B = B_L + B_U$ and $\mathbf{q}(y|x)$ indicates predicted class distribution of $h_p(g(x))$. Together with the SSL objective, the overall loss function of stage 2 is:

$$\mathcal{L}_{KD-SSL} = \mathcal{L}_s + \mathcal{L}_u + \alpha_t \cdot \lambda_p \mathcal{L}_{KD_2}$$

where α_t is an annealing parameter that linearly increases value from 0 to 1 during training based on training step t, and λ_p is a fixed scalar hyperparameter indicating relative weight of pseudo-label prediction task. We

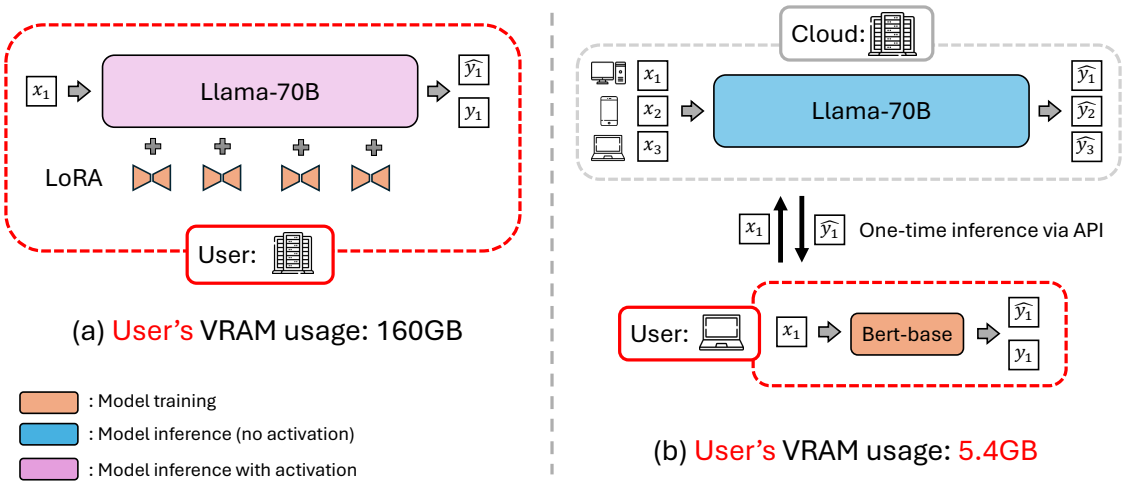

Figure 2: Comparing training setup and memory usage of (a) LoRA fine-tuning and (b) ZeroMatch using Llama-70B foundation model (with 16 bit quantization). (a) While LoRA offers parameter-efficient adaptation, it still requires loading the entire Llama-70B model and storing intermediate activations for backpropagation, leading to a large memory footprint (approximately 160 GB), requiring users to have access to data center-level GPUs. (b) In contrast, ZeroMatch trains a lightweight student model (e.g., BERT-base) locally while delegating heavy LLM inference to cloud servers via one-time API calls, and cloud servers effectively hide the computation cost by batch processing requests from multiple users. This design offloads both computation and memory from user, enabling training on low-memory devices (e.g., laptops or smartphones) with only 5.4 GB VRAM usage.

denote the inclusion of annealing with binary variable α_p. This modification ensures continuous supervision of the teacher's pseudo-label into student's model during the SSL training, mitigating the catastropic forgetting issue. Our algorithm is illustrated in Figure 1.

Our algorithm can robustly improve from both labels and pseudo-labels. When the pseudo-labels are accurate, the model benefits from the knowledge distillation task throughout both stage of training. Conversely, when the pseudo-labels are noisy, the model can still benefit from SSL's objective, with less impact from the inaccurate pseudo-label due to KD task being learned at the separate classification head h_p. We integrate our method with AdaMatch (Berthelot et al., 2021), which is a highly performant SSL baseline across various datasets and domains, as demonstrated by benchmark results in Wang et al. (2022b). We denote this method by **ZeroMatch**.

5 Aren't existing LLM adaptation solutions good enough?

The problem of transferring the knowledge of large language models (LLMs) to domain-specific tasks have been widely studied, and many of them are applicable to semi-supervised learning as well. Two prominent strategies among them are: fine-tuning (including its parameter-efficient variants) and prompt engineering. While these approaches have proven effective in many fully supervised settings, they present limitations when applied to semi-supervised learning tasks under low-compute environments. In this section, we highlight these limitations and discuss how ZeroMatch provides a more practical alternative.

(Parameter-efficient) fine-tuning cannot avoid large memory footprint. In terms of statistical performance, fine-tuning open-weight LLMs—including parameter-efficient fine-tuning methods (Hu et al., 2022; Lester et al., 2021) and test-time adaptation techniques (Sun et al., 2020; Hong et al., 2023; Song et al., 2023)—often achieves the strongest results, as these methods allow models to fully exploit their rich parameterization. However, such approaches are resource-intensive: both model loading and gradient backpropagation scale with the full model size. We illustrate this limitation in Fig. 2, which compares

Table 1: Summary of data used in the experiments. For each dataset, we run experiments with at most 3 pseudo-label sets from different foundation models. The foundation model $\hat{f}$ used to generate each pseudo-label set are shown below.

Domain	Dataset	# Train	# Val	#Test	# Class	Foundation model $\hat{f}$
NLP	Amazon Review	250,000	25,000	650,000	5	GPT-4o, Llama3.3-70B, FLAN-T5
	AG News	100,000	10,000	7,600	4	
	Yahoo! Answer	500,000	50,000	60,000	10	
CV	CIFAR100	50,000	-	10,000	100	GPT-4.1, CLIP
	Flowers102	1,020	-	6,149	102	
	Resisc45	3,150	-	25,200	45	

LoRA fine-tuning and ZeroMatch using the LLaMA-70B model as an example. LoRA requires roughly 140 GB of GPU memory just to load model parameters, and more than 160 GB when including intermediate activations during backpropagation, making it infeasible for users without access to high-end GPU clusters. In contrast, ZeroMatch enables the use of LLM in SSL fine-tuning task with smaller training backbone on modest hardware, such as a single GPU or even edge devices. This decouples the use of high quality information of LLMs from the computational demands of training, allowing effective model training locally without incurring high computational costs.

Prompt engineering cannot utilize semi-supervised datasets effectively. Prompt engineering approaches, such as in-context learning, are often used to leverage a few labeled examples by placing them directly within the model's input context. While this strategy enables models to adapt to new tasks without computation-heavy parameter updates, it commonly yields underwhelming performance compared to fine-tuning-based methods (Lehman et al., 2023), particularly when the target task involves complex feature–label relationships that require extensive supervised training. Moreover, prompt-based methods are inherently limited in utilizing large unlabeled datasets due to the restricted context window of foundation models. Even if it becomes technically possible with increased context window size, most foundation models are not trained to interpret or exploit unlabeled data, making effective semi-supervised learning infeasible in this solution.

While in-context learning could, in principle, be employed to generate pseudo-labels for unlabeled data—potentially complementing ZeroMatch's zero-shot responses—we exclude this option in our experiment analysis to isolate and evaluate the effects of labeled supervision within our framework.

In addition to the computational and methodological advantages discussed above, ZeroMatch offers further practical benefits that extend its usability across a wider range of real-world constraints, as described below.

ZeroMatch is compatible with closed-source LLMs Many high-performing LLMs (e.g., GPT-4o) are closed-weight and accessible only through limited APIs. These APIs often restrict training capabilities—for instance, OpenAI's fine-tuning API supports only supervised learning with fixed input-output pairs, making training with SSL algorithm infeasible. ZeroMatch remains compatible in such scenarios. Extracting pseudo-labels from the LLM's text output is straightforward and does not require access to internal representations or gradients. This makes our approach practical even when constrained to inference-only interactions with proprietary LLMs.

ZeroMatch reduces data-leakage risks. Using LLMs often requires uploading data to remote servers where the model is hosted, raising concerns of data leak—especially when working with privacy-sensitive domains such as healthcare or finance. Assuming that the model training happens in private device, our setup significantly reduces this risk by limiting data exposure to remote machines to one-time inference call. Once the data is processed, it can be immediately discarded, eliminating the need for persistent storage or repeated transmission. This is notably safer than fine-tuning LLMs, which requires storing the data in remote machine for continuous access throughout its training process.

6 Experiments

6.1 Experiment Setup

Datasets We use 6 publicly-available datasets across vision and natural language processing (Table 1). Dataset sizes range from 100s to 100,000s of data points. To evaluate the effect of label size, for each dataset, we create up to three tasks with different sizes of labeled data while the total number of unlabeled data stays the same. When sampling the labeled datapoints, same number of labeled samples are drawn for each class. For example, in the CIFAR100 dataset, we create sets with 100, 200, and 400 labeled data points, each having 1, 2, 4 labels per class, respectively. Detailed explanations of each dataset are provided in Appendix A.1.

Teacher pseudo-labels from foundation models For pseudo-labels of each dataset, we consider multiple sets of zero-shot responses with varying quality. For NLP datasets, we generate pseudo-labels with GPT-4o (OpenAI, 2024), Llama3.3-70B (AI, 2024), and FLAN-T5 (Chung et al., 2024). Among FLAN-T5 models with different weight sizes, we choose two models: one with the best quality, and one having the lowest quality, based on its test accuracy. We name each FLAN-T5 pseudo-label set as 'A' and 'B' in the order of decreasing quality. See Appendix A.2.2 for exact models used. For image datasets, we use GPT-4.1 (OpenAI, 2025) and CLIP (Radford et al., 2021). We provide benchmark results of zero-shot pseudo-labels on test set in Table 12 in Appendix A.2.2. Further information on pseudo-label generation procedures are discussed in Appendix A.2.

Training setup Data-specific training configurations are explained in detail in Appendix A.3. For image classification, we train ViT-Small (Dosovitskiy, 2020) with AdamW optimizer for T =204,800 steps for CIFAR100, and T =102,400 steps for Flowers102 and Resisc45. For NLP classification tasks, we use pre-trained BERT-Base (Devlin, 2018) using the AdamW optimizer for T =102,400 steps. To ensure a fair comparison with AdaMatch (an SSL baseline), we use exact same hyperparameters used for AdaMatch. For hyperparmeters specific to our method, we use $\alpha_p = 1$ (indicating that the annealing is applied) and $\lambda_p = 1$ for all experiments. Discussion on default choice of α_p and λ_p, and its sensitivity analysis is provided in Appendix 6.5.3.

Implementation details We implement our method using Unified SSL Benchmark (USB) framework (Wang et al., 2022a). To minimize the complexity of integrating our method with the existing SSL baseline, we simply add an additional multi-layer perceptron (MLP) classification head with the same architecture as the baseline model's MLP head. All experiments are implemented in PyTorch and run with a single NVIDIA A5000 24GB GPU, but we note that our experiments can run on a GPU with much smaller VRAM due to training backbone being small (see Section 6.5.4 for computational requirements of our method.).

6.2 Baselines

6.2.1 Pseudo-supervision

When given a semi-supervised dataset that includes pseudo-labels, a straightforward approach is to fill in the prediction targets for the unlabeled samples using the pseudo-labels, resulting in fully pseudo-labeled unlabeled set $\hat{\mathcal{D}_U} = \{(u_1, \hat{y}_1^U), (u_2, \hat{y}_2^U), \ldots, (u_{N_U}, \hat{y}_{N_U}^U)\}$. The model can then be trained using a supervised learning algorithm on this fully-labeled dataset $\hat{\mathcal{D}} = \mathcal{D}_L \cup \hat{\mathcal{D}_U}$. We refer to this method as *pseudo-supervision*. Pseudo-supervision has been shown to improve performance in semi-supervised learning scenarios, particularly when a zero-shot method provides accurate pseudo-labels for the task at hand (Hegselmann et al., 2023; Nam et al., 2023). However, when the zero-shot predictions are inaccurate, it remains unclear whether pseudo-supervision will still be beneficial. We refer to Appendix A.4 for implementation details.

6.2.2 Pseudo-label as feature input

Another straightforward approach to use pseudo-label to improve learning is to include them as one-hot features, which is often employed in tabular learning setting to include categorical features (Borisov et al., 2022). For this baseline, we run SSL algorithm (AdaMatch) with one-hot converted pseudo-labels as an

Table 2: Accuracy (%) in Yahoo Answers, AG News, Amazon Review with pseudo-labels from GPT-4o and Llama3.3-70B. Median and standard deviation of 3 different random seeds are reported. Best score among experiments with same pseudo-label set are in bold. 'FM' refers to the foundation model used to generate the pseudo-label set.

	Dataset	Yahoo Answers			AG News			Amazon Review		
FM	Label size	250	500	2000	20	40	200	125	250	1000
None	Adamatch	64.81±1.29	67.3±0.53	69.42±0.42	88.13±2.55	85.21±1.44	88.33±1.94	45.03±4.05	52.39±1.65	56.18±0.45
GPT-4o	Zero-shot	68.81±0.00	68.81±0.00	68.81±0.00	86.25±0.00	86.25±0.00	86.25±0.00	59.14±0.00	59.14±0.00	59.14±0.00
	Pseudo-supervise	67.68±0.06	67.30±0.20	67.56±0.06	86.13±0.15	86.33±0.08	86.33±0.14	56.94±0.27	56.65±0.21	56.83±0.25
	PL feature Input	70.56±0.27	71.00±0.57	71.47±0.67	86.25±0.46	88.00±0.90	88.39±1.00	50.38±0.67	53.30±1.23	57.08±0.39
	ZeroMatch (ours)	**70.90±1.07**	**71.11±0.09**	**72.09±0.32**	**88.50±0.22**	**88.70±0.22**	**88.76±1.20**	**60.12±0.33**	**59.82±0.39**	**60.19±0.48**
LLama3.3 -70B	Zero-shot	69.15±0.00	69.15±0.00	69.15±0.00	88.41±0.00	88.41±0.00	88.41±0.00	55.79±0.00	55.79±0.00	55.79±0.00
	Pseudo-supervise	67.85±0.21	67.67±0.39	67.17±0.14	88.47±0.08	88.53±0.18	88.45±0.08	53.74±0.33	54.34±0.11	54.14±0.53
	PL feature input	70.70±0.23	71.37±0.21	**72.18±0.25**	86.79±7.98	88.41±0.02	88.24±0.92	51.55±0.93	54.39±0.79	57.01±0.37
	ZeroMatch (ours)	**71.28±0.29**	**71.46±0.95**	71.68±0.19	**88.79±0.05**	**88.96±0.07**	**88.86±0.17**	**57.36±0.81**	**59.46±0.13**	**60.06±0.28**

Table 3: Accuracy (%) in CIFAR-100, Flowers102, Resisc45 with pseudo-labels from GPT-4.1. Median and standard deviation of 3 different random seeds are reported. Best score among experiments with same pseudo-label set are in bold. 'FM' refers to the foundation model used to generate the pseudo-label set.

	Dataset	CIFAR100			Flowers102	Resisc45
FM	Label size	100	200	400	204	90
None	Adamatch	71.43±2.48	78.32±0.46	84.02±0.74	86.71±0.69	78.87±0.80
GPT-4.1	Zero-shot	83.25±0.00	83.25±0.00	83.25±0.00	88.37±0.00	79.28±0.00
	Pseudo-supervise	84.84±0.03	84.93±0.27	85.12±0.13	85.40±0.25	79.59±0.18
	PL feature input	72.81±1.33	82.48±1.87	85.78±0.44	89.53±1.44	82.01±1.09
	ZeroMatch (ours)	**88.01±0.05**	**87.97±0.20**	**88.12±0.14**	**95.17±0.88**	**87.83±0.72**

additional feature input to the model. We name this approach to be *PL feature input*. This approach can learn to accomodate or ignore pseudo-label feature in SSL depending on how helpful they are in learning the task. See Appendix A.4 for implementation details.

6.2.3 Additional comparisons with previous works

We discuss additional comparisons of ZeroMatch with other previous works in Appendix B. While our work mainly focus on involving FM to SSL setting in pseudo-label format, there are other previous works outside this category that also tries to enhance SSL with FMs, such as fine-tuning FMs for SSL (e.g. GRIP (Menghini et al., 2023), CPL (Zhang et al., 2024) and FineSSL (Gan & Wei, 2024)). We provide overview of how these method compares with ZeroMatch in practice in Appendix B.1. We also discuss comparison with doubly-robust self-training method (Zhu et al., 2024) which addresses problem similar to ours in Appendix B.2.

6.3 ZeroMatch Enhances SSL with High Quality Pseudo-labels from Large Foundation Models

Benchmark results for the NLP datasets with GPT-4o and Llama3.3-70B are presented in Table 2, and image datasets with GPT-4.1 are presented in Table 3. When combined with pseudo-labels from high-quality large foundation models, ZeroMatch achieves the highest scores in most of the settings (22 of 23 total settings, except 2000-label case of Yahoo Answers with LLama3.3-70B). Our results shows that ZeroMatch consistently improves upon SSL baseline and zero-shot, implying effective usage of both labels and zero-shot pseudo-labels as supervision sources. For example, in Amazon Review dataset with 40 labels and pseudo-label from Llama3.3-70B, ZeroMatch achieves an 71.28% compared to Zero-shot of 69.15% and Adamatch 64.81%, yielding an improvement of 2.13% and 6.47% respectively. Our method also outperforms pseudo-supervision and PL feature input baselines, with highest improvement coming from 100-label setting of CIFAR100 with GPT-4.1 where ZeroMatch produces 15.2% improvement compared to PL feature input, and 8.23% improvement in 90-label setting of Resisc45 with GPT-4.1 for pseudo-supervision. This indicates that ZeroMatch is the most efficient in utilizing all supervision sources among baselines that uses same data.

Table 4: Accuracy (%) in Yahoo Answers, AG News, Amazon Review with pseudo-label from FLAN-T5 models. 'A' and 'B' in FM column indicates using highest and lowest quality pseudo-label sets (decreasing in order) from FLAN-T5 models. Median and standard deviation of 3 different random seeds are reported. Best score among experiments with same pseudo-label set are in bold.

	Dataset	Yahoo Answers			AG News			Amazon Review		
FM	Label size	250	500	2000	20	40	200	125	250	1000
None	Adamatch	64.81±1.29	67.3±0.53	69.42±0.42	88.13±2.55	85.21±1.44	88.33±1.94	45.03±4.05	52.39±1.65	56.18±0.45
A	Zero-shot	66.63±0.00	66.63±0.00	66.63±0.00	91.43±0.00	91.43±0.00	91.43±0.00	52.37±0.00	52.37±0.00	52.37±0.00
	Pseudo-supervise	65.79±0.18	66.31±0.46	65.92±0.33	91.37±0.07	91.22±0.08	91.42±0.08	51.11±0.27	50.86±0.27	50.41±0.41
	PL feature input	67.93±0.80	69.6±0.39	70.82±0.25	91.43±5.51	**91.43±0.01**	90.70±0.85	50.00±1.01	54.56±0.67	56.53±0.61
	ZeroMatch (ours)	**69.78±0.94**	**70.51±0.19**	**71.81±0.07**	**91.51±0.12**	91.42±0.21	**91.62±0.15**	**58.83±0.51**	**59.69±0.60**	**60.95±0.13**
B	Zero-shot	35.29±0.00	35.29±0.00	35.29±0.00	87.06±0.00	87.06±0.00	87.06±0.00	35.7±0.00	35.7±0.00	35.7±0.00
	Pseudo-supervise	36.38±0.51	36.29±0.38	36.37±0.51	88.7±0.16	88.51±0.20	88.41±0.18	36.02±0.04	35.97±0.05	36.04±0.03
	PL feature input	65.52±0.48	65.88±0.89	69.29±0.53	84.61±2.08	86.45±1.55	86.66±1.01	48.93±1.89	53.76±1.62	56.06±0.30
	ZeroMatch (ours)	**67.05±0.76**	**67.13±0.73**	**69.61±0.22**	**90.42±0.19**	**90.24±0.08**	**90.25±0.16**	**50.23±1.35**	**53.78±1.74**	**56.12±0.64**

6.4 ZeroMatch Improves Performance on SSL Baselines Despite Low-Quality Teacher Pseudo-labels

We also present benchmark results with pseudo-labels from FLAN-T5 and CLIP. While FLAN-T5 and CLIP models are generally less powerful models compared with GPT-4 and Llama models, this configuration demonstrates following practical settings:

- **Unseen task data**: user may train with personal data that is not seen from the foundation models. Based on training data sources listed in technical reports of FLAN-T5 (Chung et al., 2024) and CLIP (Radford et al., 2021) models, we ensure that these models are not trained with our benchmark dataset. On the other hand, recent models like GPT and Llama does not reveal the data source, therfore we cannot ensure that our benchmark datasets (which is public) are not in training the source of these models.

- **Restrictions in model access**: user may not be able to access state-of-the-art large foundation models and be limited to using certain types of less powerful foundation models, due to company restrictions, contract, or high implementation cost involved in accomodating the new model.

NLP benchmark results with FLAN-T5 are presented in Table 4. Image classification results with CLIP models are presented in Table 5. Our results shows that ZeroMatch consitently outperforms or maintains the performance of baseline within one standard deviation all other baselines in most cases (26 of 28 total settings, except CIFAR100 with 400-labels and Flowers102), demonstrating its robustness against low-quality teacher pseudo-labels. For example, for Amazon Review with FLAN-T5 pseudo-label set A, ZeroMatch achieves an accuracy of 58.83%, outperforming PL feature input's accuracy of 50.00%. Notably, when pseudo-label's quality is low, ZeroMatch consistently improves (or at least maintain the performance within one standard deviation) when number of labels increase. For example, the scores of Yahoo Answers with FLAN-T5 set B increases from 67.05% to 69.61% as number of labels increase. This implies that our method utilizes labeled samples to correct and improve when pseudo-label may not be helpful. On the other hand, PL feature input baseline fails to improve in AG News when increasing labels from 40 to 200 with FLAN-T5 A set, where the score decreased from 91.43% to 90.70%. Our method remains largely effective against pseudo-supervision under low-quality pseudo-label setting. For example, in 250 label setting of Yahoo Answers, pseudo-supervision reaches 36.38% accuracy with pseudo-label set B, which is worse than 67.05% of ZeroMatch by large margin.

6.5 A Deeper Look into ZeroMatch

6.5.1 Accomodating embeddings can further improve ZeroMatch

While our problem setup focuses on leveraging pseudo-labels from foundation models, embeddings (from foundation models trained with embedding tasks) may also provide information often helpful for learning the task. We also provide a way to accomodate these embeddings in our framework to further improve performance on target tasks. Please see Appendix A.4 for implementation details. We provide benchmarks

Table 5: Accuracy (%) in CIFAR-100, Flowers102, Resisc45 with pseudo-labels from CLIP models. Median and standard deviation of 3 different random seeds are reported. Best score among experiments with same pseudo-label set are in bold. 'FM' refers to the foundation model used to generate the pseudo-label set.

	Dataset	CIFAR100			Flowers102	Resisc45
FM	Label size	100	200	400	204	90
None	Adamatch	71.43±2.48	78.32±0.46	84.02±0.74	86.71±0.69	78.87±0.80
CLIP-Large	Zero-shot	60.65±0.00	60.65±0.00	60.65±0.00	72.13±0.00	60.32±0.00
	Pseudo-supervise	70.97±0.41	71.86±0.63	74.05±0.42	74.19±0.57	63.93±0.21
	PL feature input	71.21±2.56	80.11±0.49	84.42±0.22	**89.51±0.42**	80.85±1.43
	ZeroMatch (ours)	**84.30±0.71**	**85.77±0.05**	**86.13±0.01**	88.94±1.66	**83.91±1.54**
CLIP-Base	Zero-shot	48.07±0.00	48.07±0.00	48.07±0.00	60.17±0.00	49.63±0.00
	Pseudo-supervise	62.19±0.26	65.96±0.37	71.03±0.23	64.09±0.30	55.82±0.84
	PL feature input	71.3±3.26	78.85±1.45	**83.88±0.73**	87.56±0.29	80.85±2.26
	ZeroMatch (ours)	**79.78±0.99**	**80.87±0.62**	82.69±0.23	**89.61±2.39**	**82.58±0.85**

Table 6: Accuracy (%) in Flowers102, Resisc45 with pseudo-labels and embeddings from CLIP models and GPT-4.1. Median and standard deviation of 3 different random seeds are reported.

Method	FM inference info used	Flowers102	Resisc45
Zero-shot	GPT-4.1 pseudo-label	88.37±0.00	79.28±0.00
Zero-shot	CLIP-large pseudo-label	72.13±0.00	60.32±0.00
ZeroMatch (ours)	GPT-4.1 pseudo-label	95.17±0.88	87.65±0.73
ZeroMatch (ours)	GPT-4.1 pseudo-label + CLIP-large embedding	**97.20±0.41**	**88.52±0.77**

of our method leveraging pseudo-labels of GPT-4.1 and embeddings from CLIP-large model on Flowers102 and Resisc45 in Table 6. Our result shows that adding embedding to our framework can outperform cases where only pseudo-labels from same foundation models are included, achieving highest score in both dataset. This indicates that our method can be easily extended to mix and match pseudo-labels with embeddings to further improve the performance.

6.5.2 Ablation study

Two main components that constructs our method (other than SSL training) is separate knowledge disillation (KD) stage, and learning KD as auxiliary loss for SSL's objective. We validate effectiveness of each component through following ablation study.

① *Is auxiliary KD loss necessary?* To validate this, we compare our method with the case without auxiliary KD loss, which essentially runs plain AdaMatch algorithm after running KD in stage 1. We name this apporach ZeroMatch without auxliary loss ('ZM w.o. aux.' in tables) and provide benchmark result in Table 7. Our results show that adding auxiliary KD loss helps, especially in the low-label setting. For example, In 125-label setting of Amazon Review with GPT-4o, our original method improves plain AdaMatch by 2.22%. Since pseudo-labels inferred from labeled data can become inaccurate in low-label setting, adding addtional supervision with teacher pseudo-labels can be particularly helpful in this case.

② *Does having separate KD stage necessary?* Since stage 2 of our algorithm also includes auxiliary KD loss, one may wonder if running stage 2 without stage 1 in our algorithm is enough to achieve the goal of merging benefits of KD and SSL. To clear this out, we compare our method with the case without running stage 1 knowledge distillation. We name this apporach ZeroMatch without stage 1 ('ZM w.o stage 1' in tables) and provide benchmark result in Table 8. Our results show that while ZeroMatch without stage 1 can sometimes achieve the similar performance to original ZeroMatch (ex. in Yahoo Answers) it may also produce large gap in performance depending on the dataset. For example, in 250-label setting Aamzon Review with 'A' pseudo-label set, ZM stage 2 only reveals 3.94% accuracy drop compared to original.

Table 7: Comparison with ZeroMatch without auxliary loss in Yahoo Answers and Amazon Review with pseudo-labels from GPT-4o and LLama3.3 models. Median and standard deviation of accuracy (%) of 3 different random seeds are reported. Best score among experiments with same pseudo-label set are in bold. 'FM' refers to the foundation model used to generate the pseudo-label set.

	Dataset	Yahoo Answers			Amazon Review		
FM	Label size	250	500	2000	125	250	1000
GPT-4o	ZM w.o. aux.	68.22±0.32	69.23±0.53	71.45±0.23	57.89±0.47	59.60±0.33	60.16±0.34
	ZeroMatch (ours)	**70.90±1.07**	**71.11±0.09**	**72.09±0.32**	**60.12±0.33**	**59.82±0.39**	**60.19±0.48**
LLama3.3-70B	ZM w.o. aux.	69.30±0.53	70.54±0.54	71.54±0.31	56.59±1.78	59.04±0.21	**60.13±0.08**
	ZeroMatch (ours)	**71.28±0.29**	**71.46±0.95**	**71.68±0.19**	**57.36±0.81**	**59.46±0.13**	60.06±0.28

Table 8: Comparison with ZeroMatch Stage 2 only in Yahoo Answers and Amazon Review with pseudo-labels from FLAN-T5 models. Median and standard deviation of accuracy (%) of 3 different random seeds are reported. Best score among experiments with same pseudo-label set are in bold. 'FM' refers to the foundation model used to generate the pseudo-label set.

	Dataset	Yahoo Answers			Amazon Review		
FM	Label size	250	500	2000	125	250	1000
A	ZM w.o stage 1	**70.01±0.63**	69.76±0.22	71.22±0.27	55.16±0.30	55.75±0.65	58.53±0.36
	ZeroMatch (ours)	69.78±0.94	**70.51±0.19**	**71.81±0.07**	**58.83±0.51**	**59.69±0.60**	**60.95±0.13**
B	ZM w.o stage 1	66.6±0.13	67.05±0.44	69.22±0.53	45.53±4.91	53.19±1.68	**56.9±0.63**
	ZeroMatch (ours)	**67.05±0.76**	**67.13±0.73**	**69.61±0.22**	**50.23±1.35**	**53.78±1.74**	56.12±0.64

Table 9: Hyperparameter sensitivity results in Yahoo Answers (250 labels) and Amazon Review (125 labels) with pseudo-labels from FLAN-T5 models.

α, λ	Yahoo Answers	Amazon Review
(0, 0.5)	69.15±0.46	59.55±1.69
(0, 1.0)	69.90±0.87	**60.20±1.02**
(1, 0.5)	68.26±0.94	59.31±1.43
(1, 1.0)	**70.71±0.36**	59.47±1.26

6.5.3 Hyperparameter sensitivity analysis

For the simplicity of setting, we mainly benchmark our method with hyperparameters $\alpha_p = 1$ and $\lambda_p = 1$ without finding the optimal setting. The reasoning behind this choice to make KD loss same as fully-supervised training when pseudo-label is accurate, and enabling annealing to allow more freedom to accomodate labeled data in the early stage of AdaMatch, which develops initial confident predictions for unlabeled data.

In this paragraph, we run a sensitivity analysis on combinations of these parameters. we conduct experiments with four different sets: $(\alpha_p, \lambda_p) = (0, 0.5), (0, 1.0), (1, 0.5), (1, 1.0)$. The results with NLP datasets with FLAN-T5 models are shown in Table 9. We find that while $(\alpha_p, \lambda_p) = (1, 1.0)$ can be a good candidate on some datasets (ex. Yahoo Answers), there may exist other optimal parameters that can further improve performance.

6.5.4 Computational cost analysis

We provide memory usage and computation cost associated with our method and SSL baseline(AdaMatch) for CIFAR100 dataset in Table 10. The usages are measured in our machine with 1 NVIDIA A10G GPU. We note that our method consumes around 50% more training time compared with AdaMatch. This is due to having separate knoweledge distillation at stage 1, with utilizing half of the batch size of AdaMatch. Also our method uses slightly more VRAM due to back-propagating through weak-augmented samples in KD auxiliary loss in stage 2, while in AdaMatch weak-augmented samples are only used with forward pass to get predictions and back-propagation happens in strong augmented samples. Some options to reduce the compute usage are applying early stopping in stage 1 knowledge distillation when pseudo-label prediction

Table 10: Computational cost on training with CIFAR100.

Method	VRAM(GB)	Training time (sec)
Adamatch	4.2	41100
ZeroMatch	5.4	61662

Table 11: ZeroMatch's performance combined with 3 different SSL baselines (FixMatch, FreeMatch, SoftMatch) in Yahoo Answers with 4 different FM pseudo-label sets.

	SSL algo.	FixMatch			FreeMatch			SoftMatch		
FM	Label size	250	500	2000	250	500	2000	250	500	2000
None	SSL only	54.04±0.53	63.56±2.03	66.59±0.48	60.84±2.91	66.27±0.45	67.29±0.77	62.30±0.91	64.84±0.94	67.43±0.87
GPT-4o	Zero-shot	68.81±0.00	68.81±0.00	68.81±0.00	68.81±0.00	68.81±0.00	68.81±0.00	68.81±0.00	68.81±0.00	68.81±0.00
	ZeroMatch (ours)	**70.43±0.13**	**70.96±0.33**	**72.11±0.22**	**70.91±0.37**	**70.72±0.11**	**72.52±0.28**	**71.46±0.90**	**71.20±0.20**	**72.22±0.25**
LLama3.3 -70b	Zero-shot	69.15±0.00	69.15±0.00	69.15±0.00	69.15±0.00	69.15±0.00	69.15±0.00	69.15±0.00	69.15±0.00	69.15±0.00
	ZeroMatch (ours)	**70.45±0.59**	**70.75±0.34**	**71.96±0.55**	**70.98±0.43**	**71.17±0.67**	**71.68±0.12**	**71.30±0.23**	**70.93±0.45**	**71.72±0.35**
A	Zero-shot	66.63±0.00	66.63±0.00	66.63±0.00	66.63±0.00	66.63±0.00	66.63±0.00	66.63±0.00	66.63±0.00	66.63±0.00
	ZeroMatch (ours)	**69.64±0.72**	**71.19±0.20**	**71.78±0.20**	**70.36±0.40**	**70.56±0.83**	**71.47±0.27**	**69.92±0.75**	**70.88±0.64**	**72.05±0.43**
B	Zero-shot	35.29±0.00	35.29±0.00	35.29±0.00	35.29±0.00	35.29±0.00	35.29±0.00	35.29±0.00	35.29±0.00	35.29±0.00
	ZeroMatch (ours)	**66.65±1.49**	**66.82±0.40**	**69.50±0.26**	**67.79±0.82**	**68.24±0.33**	**70.15±0.10**	**67.64±0.57**	**67.47±0.52**	**69.93±0.23**

accuracy is above certain threshold, and involving strong augmentation in KD auxiliary loss instead of weak augmented sample so that backpropagation does not happen for weak augmented samples.

6.5.5 ZeroMatch with other SSL algorithms

While we mainly use AdaMatch as SSL baseline to use with ZeroMatch , we also provide benchmarks of our method with 3 additional SSL algorithms: FixMatch (Sohn et al., 2020), FreeMatch (Wang et al., 2022c), and SoftMatch (Chen et al., 2023). Results on Yahoo Answers dataset with 4 different FMs (GPT-4o, Llama3.3-70b, FLAN-T5 (A), FLAN-T5 (B)) are shown in Table 11. The results shows that ZeroMatch improves both SSL and zero-shot accuracy in all cases, implying ZeroMatch's applicability to wide range of SSL methods. While we expect that ZeroMatch can work with many types of SSL algorithms with confidence-based sampling, we note that counterexample exists. One such example is UDA (Xie et al., 2020), which uses training signal annealing (TSA) to utilize only the low-confidence labeled samples in initial training stage. This procedure conflicts with our solution since we have high-confidence samples at the start of SSL training, resulting in labeled samples not being utilized.

7 Conclusion

This work introduces ZeroMatch, a framework for robustly integrating foundation model predictions into semi-supervised learning. Through extensive experiments across multiple datasets from different domains, we demonstrate that ZeroMatch achieves state-of-the-art performance while maintaining robustness to varying pseudo-label quality. Our learning-based mechanism effectively balances between limited labels and plentiful pseudo-labels, enabling practitioners to leverage foundation models without the computational overhead of direct fine-tuning. Future work could explore extending ZeroMatch to more complex tasks and investigating theoretical guarantees for the weighting mechanism.

Broader Impact

Our work aims to make semi-supervised learning more accessible by reducing the computational resources needed to leverage foundation models. This has positive implications for democratizing AI development, particularly benefiting researchers and organizations with limited computing infrastructure.

However, improved semi-supervised learning techniques could also lower the barrier for developing AI systems with potential misuse cases. While our method focuses on improving efficiency rather than expanding capabilities, we acknowledge the need for careful consideration of deployment contexts.

The adaptive weighting mechanism we introduce could potentially mitigate some biases in foundation models by automatically reducing reliance on unreliable predictions. However, this requires further investigation, particularly regarding the method's behavior across different demographic groups and task domains.

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A Experiment Details

A.1 Datasets

We use six datasets from NLP and image classification domain. We provide description of each of them.

CIFAR-100 CIFAR-100 (Krizhevsky, 2009) dataset is a 32×32 pixels natural image recognition dataset consisting of 100 classes. There are 500 training samples and 100 test samples per each class.

Flowers102 Flowers102 (Nilsback & Zisserman, 2008) is a image dataset containing 102 flower categories commonly found in the United Kingdom. The dataset contains minumum 40 to maximum 258 images per class.

Resisc45 RESICS45 (Cheng et al., 2017) is a publicly available benchmark for Remote Sensing Image Scene Classification. Images from 45 kinds of scenes are presented.

Yahoo Answer Yahoo Answer (Chang et al., 2008) is a question text topic classification dataset with 10 categories of topics. Each class contains 140,000 training samples and 6,000 test samples. Training and validation set is drawn by sampling 50,000 samples and 5,000 samples per class from training samples, and test set is unchanged, following the data settings in USB (Wang et al., 2022a).

AG News The AG News (Zhang et al., 2015) dataset is a news text topic classification dataset with 4 classes. Original dataset contains 30,000 training samples and 1,900 test samples per class. In our experiments, 25,000 samples and 2,500 samples per class are sampled from training samples, following USB (Wang et al., 2022a). The test dataset is unchanged.

Amazon Review The Amazon Review (McAuley & Leskovec, 2013) dataset is a sentiment classification dataset with product review text input. There are 5 classes indicating the review score. Each class (score) contains 600,000 training samples and 130,000 test samples. Following USB (Wang et al., 2022a), 50,000 samples and 5,000 samples per class from training samples are used as training dataset and validation dataset respectively. The test dataset is unchanged.

We use the data splits provided by USB (Wang et al., 2022b) for NLP datasets, and splits provided by CPL (Zhang et al., 2024) for Flowers102 and Resisc45.

A.2 Obtaining pseudo-labels from foundation models

In this section, we discuss details of obtaining the zero-shot pseudo-labels to train with ZeroMatch.

A.2.1 Details of pseudo-label generation process

Image classification datasets For image classification datasets, we mainly use GPT-4.1 and CLIP models to generate pseudo-labels.

For GPT-4.1 (OpenAI, 2025), we use chat completion feature to prompt for image classification. We use following system prompt to describe the task we need:

You are an image classification system, asked to classify *{topic}*. Classify the input image into exactly one of the following types: *{candidate labels}* Respond with only the type that best fits the image.

Where the topic variable is set as 'flowers' for Flowers102, 'scene' for Resisc45, and 'tiny image' for CIFAR100. Candidate labels are set as possible labels in text format. Same procedure is applied when using other chat-completion based models (GPT-4o (OpenAI, 2024), Qwen2-VL (Wang et al., 2024), Llama3.2-Vision (AI, 2024)). After obtaining the output, we parse the output text to see if text labels in candidate label set

exists in output text. In cases where no label is detected, we use default pseudo-label: `rose` for Flowers102, `commercial area` for Resisc45, and `road` for CIFAR100.

When using CLIP model, we follow the procedures of zero-shot classification in Radford et al. (2021). We compute the feature embedding of a given image, and for each label in candidate labels, we prompt the model with following prompt: `This is a photo of {label}` and get the feature embedding. We then obtain the pseudo-label by finding the label that gives closest embedding to the image embedding, based on the cosine similarity.

NLP classification datasets - topic classification: AG News, Yahoo Answers To obtain pseudo-labels for topic classification tasks, we use following prompting template with GPT-4o, Llama3.3-70B, and FLAN-T5 models for given input text:

> Select the topic that the given article is about. The topics are: *{candidate_labels}*.
>
> Article: *{input_text}*,
> Answer:

For AG News, the candidate labels are `world, sports, business, technology`, and for Yahoo Answers, the candidate labels are `society, science, health, education, computer, sports, business, entertainment, relationship, politics`. In case the output does not contain labels from candidate labels or is not parsable, we set the pseudo-label to be `world` for AG News, and `society` for the Yahoo Answers as the default label. For GPT-4o and Llama models, we use chat completion template with following system prompt: `You are a helpful assistant.`

NLP classification datasets - sentiment classification: Amazon Review We use following prompt template with GPT-4o, Llama3.3-70B, and FLAN-T5 models models for given input text to obtain the review text's sentiment:

> *{input_text}*
> What is the sentiment of this review?
>
> OPTIONS:
> - very negative
> - negative
> - neutral
> - positive
> - very positive

In case of model output not being recognized as one of candidate labels, we select `neutral` as the default pseudo-label. For GPT-4o and LLama models, we use chat completion template with following system prompt: `You are a helpful assistant.`

A.2.2 Zero-shot benchmark results and foundation model selection

To select foundation models to be used with ZeroMatch, we consider 1) best performing large foundation models that can provide maximum statistical performance with our method and 2) lowest quality foundation models to test robustness of our method against inaccurate pseudo-labels.

We provide zero-shot benchmark results on test set in Table 12 (NLP) and Table 13 (Image).

We found that GPT-4o and LLama3.3-70B were highest performing overall, scoring top-2 on all the datasets. Among FLAN-T5 models, we find that FLAN-T5-XXL performs the best in Yahoo Answers and AG News dataset, while FLAN-T5-XL model performed better in Amazon review. To benchmark our method with highest and lowest accuracy, FLAN-T5-XXL and FLAN-T5-small were selected as A and B set of pseudo-labels

Table 12: Zero-shot pseudo-label accuracies(%) for NLP datasets (test set).

FM	Yahoo Answers	AG News	Amazon Review
GPT-4o	68.81	86.25	**59.14**
Llama3.3-70B	**69.15**	**88.41**	55.79
FLAN-T5-XXL	**66.62**	**91.43**	45.61
FLAN-T5-XL	63.97	91.39	**52.37**
FLAN-T5-large	61.33	87.66	51.96
FLAN-T5-base	55.17	88.68	42.23
FLAN-T5-small	29.44	87.07	35.7

in AG News and Yahoo Answers, and for Amazon reivew, we use FLAN-T5-XL and FLAN-T5-small as A and B set.

Table 13: Zero-shot pseudo-label accuracies(%) for image datasets (test set).

FM	CIFAR100	Flowers102	Resisc45
GPT-4.1	**83.25**	**88.37**	**79.28**
GPT-4o	81.5	86.0	73.46
Qwen2-VL	62.58	78.11	68.25
Llama3.2-90B-Vision	36.05	59.02	44.58
CLIP-large-patch14	62.27	72.13	60.32
CLIP-base-patch32	49.49	60.17	49.63

For image classification task, we benchmarked GPT-4.1, GPT-4o, Qwen2-VL, Llama3.2-90B-Vision with our target datasets, and found that GPT-4.1 was best in all the tasks (see Table 13). As a result, we accommodate GPT-4.1, CLIP-large and CLIP-base models for our benchmark.

A.3 Training setup

Setup for image classification We use ViT (Dosovitskiy, 2020) as the backbone of our model and employ pre-trained ViT-Small models, provided by the USB framework (Wang et al., 2022a). For CIFAR100, ViT-Small with patch size of 2 with image size of 32 is used, and for Flowers102 and Resisc45 datasets, ViT-Small with patch size of 16 with image size of 224 is used. The optimization is performed using the AdamW optimizer with a cosine learning rate schedule given by $\eta_t = \eta_0 \cos\left(\frac{7\pi t}{16T}\right)$ where the initial learning rate is set to $\eta_0 = 5 \times 10^{-4}$ for CIFAR100 and $\eta_0 = 1 \times 10^{-4}$ for Flowers102 and Resisc45. For CIFAR100, we train the model for a total of $T = 204,800$ steps, with a warm-up phase of 5,120 steps, and for Flowers102 and Resisc45, we run for half the size of training steps $T = 102,400$ with 2,560 warm up steps to reflect the smaller training set size. The batch sizes for both labeled and unlabeled data are set to 16. For AdaMatch-specific parameters, the threshold for the utilization cutoff mask is set to 0.95. For data augmentation, we apply random cropping and random horizontal flipping for weak augmentation, while RandAugment (Cubuk et al., 2020) is utilized for strong augmentation. For knowledge distillation stage (stage 1 of Zeromatch), we run supervised training with teacher pseudo-labels, for same number of training steps. Regarding the hyperparameters specific to our method, we report results with $\lambda_p = 1$ and with annealing ($\alpha_p = 1$). Detailed hyperparameter settings are provided in Table 14.

Setup for NLP classfication For NLP tasks, we fine-tune the pre-trained BERT-Base (Devlin, 2018) using the AdamW optimizer with a cosine learning rate schedule. The total number of training steps is set to 102,400, with a warm-up phase of 5,120 steps. Both the labeled and unlabeled batch sizes are set to 4. All input text is truncated to ensure its length remains within the context length of BERT-Base. For data augmentation, we employ back-translation (Zhu et al., 2020) using German-English and Russian-English translation as strong augmentations. No weak augmentation is applied, and the original text input is used instead. We run AdaMatch with a cutoff threshold of $\tau = 0.95$. Dataset-specific hyperparameters are detailed in Table 15. For knowledge distillation stage (stage 1 of Zeromatch), we run supervised training with teacher

pseudo-labels, for same number of training steps. We report the performance of ZeroMatch with $\lambda_p = 1$ and with annealing ($\alpha_p = 1$).

Table 14: Hyperparameters of Image classification datasets.

Dataset	CIFAR100	Flowers102	Resisc45
Image Size	32	224	224
Model	ViT-S-P4-32	ViT-S-P16-224	ViT-S-P16-224
Weight Decay		5e-4	
Labeled Batch size		16	
Unlabeled Batch size		16	
Learning Rate	5e-4	1e-4	1e-4
Layer Decay Rate	0.5	0.65	0.65
Scheduler		$\eta = \eta_0 \cos\left(\frac{7\pi k}{16K}\right)$	
Model EMA Momentum		0.0	
Prediction EMA Momentum		0.999	
Weak Augmentation	Random Crop, Random Horizontal Flip	Random Resized Crop and Interpolation, Random Horizontal Flip	
Strong Augmentation		RandAugment (Cubuk et al., 2020)	
α_p		1	
λ_p		1.0	

Table 15: Hyperparameters of NLP tasks.

Dataset	AG News	Yahoo! Answer	Amazon Review
Max Length		512	
Model		Bert-Base	
Weight Decay		1e-4	
Labeled Batch size		4	
Unlabeled Batch size		4	
Learning Rate	5e-5	1e-4	5e-5
Layer Decay Rate	0.65	0.65	0.75
Scheduler		$\eta = \eta_0 \cos\left(\frac{7\pi k}{16K}\right)$	
Model EMA Momentum		0.0	
Prediction EMA Momentum		0.999	
Weak Augmentation		None	
Strong Augmentation		Back-Translation (Xie et al., 2020)	
α_p		1	
λ_p		1.0	

A.4 Additional implementation details

Pseudo-supervision For pseudo-supervision baseline, a supervised learning algorithm is run with fully-labeled data (filled with FM pseudo-labels). To ensure a fair comparison with SSL baselines, we use the same number of labeled and unlabeled batches participating during the optimization process. In each optimization step, when a labeled batch of size B_L and an unlabeled batch of size B_U are given, Pseudo-supervision optimizes the following loss:

$$\mathcal{L}_{PS} = \frac{1}{B}\left(\sum_{i=1}^{B_L} \mathcal{H}(y_i, \mathbf{p}(y|x_i)) + \sum_{i=1}^{B_U} \mathcal{H}(\hat{y}_i^U, \mathbf{p}(y|u_i))\right).$$

where $B = B_L + B_U$.

Pseudo-label as feature input To implement pseudo-label as feature input baseline, we change the model architecture to accomodate one-hot pseudo-labels. When training sample x_i with its corresponding one-hot coverted pseudo-label $\tilde{y}_i$ passes through the training model with encoder g and classifier head h, the model concatenates input feature output $g(x)$ and one-hot pseudo-label $\tilde{y}_i$ as additional feature output, producing $h(g(x_i), \tilde{y}_i)$ as output. Note that the input dimension of head h is adjusted to accomodate additional feature dimension (number of classes). With each sample having pair pseudo-label, this modification allows running SSL baseline (Adamatch) without further modification, and model can learn to accomodate or ignore pseudo-label feature depending on how helpful they are in learning the task.

Accomodating embeddings to ZeroMatch To accomodate feature embeddings from foundation models in ZeroMatch, we concatenate embeddings with our feature encoder output before passing to classifier head layer. When the training model has architecture of encoder g and classifier head h, we modify the model's MLP head layer's input dimension so that encoded feature and embeddings are concatenated and put into the head h. As a result, when training sample x_i with its embedding e_i are given, the model outputs $h(g(x_i), e_i)$. Same procedure is applied to the auxiliary KD classifier head for stage 2 in our algorithm, producing $h_p(g(x_i), e_i)$ to be supervised with teacher pseudo-label.

B Additional comparsion with previous works

B.1 Compare with fine-tuning foundations models for semi-supervised learning

As discussed in Sec. **??**, direct fine-tuning large foundation models (or using its parameter-efficient variants) may offer higher statistical performance than ZeroMatch by leveraging its vast number of parameters. However, such approaches incur significantly higher memory and computational costs. In contrast, our setup trains a compact backbone model that requires only modest resources (less than 8GB of GPU memory), making it suitable for resource-constrained environments. For fair comparison, we compare our method against recent approaches that fine-tune FMs for SSL, that has computational requirements comparable to ours.

We compare our apporach with GRIP (Menghini et al., 2023), CPL (Zhang et al., 2024) and FineSSL (Gan & Wei, 2024) which adopts prompt tuning strategies to vision-language models such as CLIP (Radford et al., 2021) and iteratively refines pseudo-label predictions based on confidence and features.

While direct comparisons of these works with ours is not possible due to settings largely different in model and training algorithms, we present settings where our method can outperform these methods, and provide comparison on the details on training and information used. We benchmark our method on exact same data settings that these works have conducted their experiments on.

Visual prompt tuning methods visual prompt tuning method (VPT) (Jia et al., 2022) is prompt-tuning method for Vision-language models that tunes the prefix part of input layer while keeping textual encoder fixed. FineSSL, CPL and GRIP provide VPT benchmarks with CLIP models. We provide comparison of ZeroMatch on FineSSL's CIFAR-100 results in Table 16, and results of GRIP and CPL with Flowers102 and Resisc45 dataset in Table 17.

Table 16: Comparison with FineSSL's VPT (visual prompt tuning) results on CIFAR100 with 400 labels (4 labels per class). * indicates numbers published in FineSSL.

Method	FM Inference info used	Training backbone	Fine-tuning method	Accuracy
FineSSL*	-	CLIP ViT-B-16	VPT-deep	80.44±0.24
Zero-shot	CLIP ViT-L-14 - pseudo-label	-	-	60.65±0.00
ZeroMatch (ours)	CLIP ViT-L-14 - pseudo-label	ViT-S-2	Full fine-tuning	**86.73±1.42**

Our results show ZeroMatch's outperforming scores for all the baseline methods. This is largely due to leveraging high-quality outputs of larger foundation model - For CIFAR-100, we use pseudo-labels from CLIP ViT-L-14, and for Flowers102, we leverage GPT-4.1. We also note that the training backbone we use is

Table 17: Comparison with GRIP and CPL's VPT results on Flowers102 and Resisc45 datasets with 2 labels per class. * indicates numbers published in the paper.

Method	FM Inference info used	Training backbone	Finetuning method	Flowers102	RESISC
Zero-shot*	CLIP ViT-B-32 - pseudo-label	-	-	63.67	54.48
GRIP*	CLIP text encoder - embedding	CLIP ViT-B-32	VPT	67.95±1.2	71.22±0.77
CPL*	CLIP text encoder - embedding	CLIP ViT-B-32	VPT	73.52±0.37	78.46±0.74
Zero-shot	GPT-4.1 pseudo-label	-	-	88.37	79.28
ZeroMatch (ours)	GPT-4.1 pseudo-label	ViT-S-16	Full fine-tuning	**95.17±0.88**	**87.65±0.73**

smaller than the baselines. We use ViT-Small which uses less number of attention heads compared with CLIP-ViT-B models.

This result implies that our method can outperform many baselines that fine-tunes the foundation models by simply involving the highest quality foundation model, while training a smaller model for the task on low-compute device.

Textual prompt tuning methods Textual prompt tuning (Zhou et al., 2022) is another common prompt-tuning based methods which tunes the input prefix of textual encoder of vision-language models, while keeping visual encoder fixed. Textual encoder is trained with embeddings obtained from large visual encoder, and it can be implemented with using the visual encoder through inference mode only. This setting resembles our problem setup in that the inference outputs of larger models are used to train smaller model. We provide benchmarks comparing our method to GRIP and CPL's textual prompt tuning results in Table 18.

Table 18: Comparison with GRIP and CPL's TPT (Textual Prompt Tuning) results on Flowers102 and Resisc45 datasets with 2 labels per class. * indicates numbers published in the paper.

Method	FM Inference info used	Training backbone	Finetuning method	Flowers102	RESISC
Zero-shot*	CLIP ViT-B-32 - pseudo-label	-	-	63.67	54.48
GRIP*	CLIP ViT-B-32 - embedding	CLIP text encoder	Textual prompt tuning	83.6±0.68	74.11±0.68
CPL*	CLIP ViT-B-32 - embedding	CLIP text encoder	Textual prompt tuning	89.66±0.36	80.98±0.11
Zero-shot*	CLIP ViT-L-14 - pseudo-label	-	-	73.98	62.67
CPL*	CLIP ViT-L-14 - embedding	CLIP text encoder	Textual prompt tuning	96.80±0.63	87.75±0.29
Zero-shot	GPT-4.1 pseudo-label	-	-	88.37	79.28
ZeroMatch (ours)	GPT-4.1 pseudo-label	ViT-S-16	Full fine-tuning	95.17±0.88	87.65±0.73
ZeroMatch (ours)	GPT-4.1 pseudo-label + CLIP ViT-L-14 - embedding	ViT-S-16	Full fine-tuning	**97.20±0.41**	**88.52±0.77**

While our method paired with pseudo-labels from GPT-4.1 can outperform CPL and GRIP with CLIP-ViT-B model, CPL's results with CLIP ViT-L outperforms our score. We additionally benchmark our method with embeddings from CLIP-ViT-L model, which CPL uses as the supervision source. The results show that our method improves with added embedding information, outperforming other baselines, implying that embedding is a helpful information source for learning the benchmark task.

B.2 Comparison with doubly-robust self-training

Doubly-robust self-training (Zhu et al., 2024) addresses a problem setting similar to ours, proposing a method that robustly improves performance despite varying quality of pseudo-labels. The method employs the following loss function:

$$\mathcal{L}_{DR} = \frac{1}{N_L}\sum_{i=1}^{N_L}\mathcal{H}(y_i, \mathbf{p}(y|x_i)) - \frac{1}{N_L}\sum_{i=1}^{N_L}\mathcal{H}(\hat{y}_i^L, \mathbf{p}(y|x_i)) + \frac{1}{N}\left(\sum_{i=1}^{N_L}\mathcal{H}(\hat{y}_i^L, \mathbf{p}(y|x_i)) + \sum_{i=1}^{N_U}\mathcal{H}(\hat{y}_i^U, \mathbf{p}(y|u_i))\right).$$

When the pseudo-labels are accurate, the loss function approximates training with the full dataset $\mathcal{D}_L$ and $\mathcal{D}_U$, both with ground truth labels. Conversely, when the pseudo-labels are inaccurate, the loss function

asymptotically approaches training with only the labeled samples $\mathcal{D}_L$. The work provides convergence improvement guarantees over training with labeled data alone, with varying pseudo-label quality, under certain regularity conditions. While the study presents experimental results using a single pseudo-label set inferred from a pre-trained model, its practical effectiveness with inaccurate pseudo-labels in low-label settings is unexplored. To implement this method and ensure a fair comparison with ours, we use the same number of labeled and unlabeled batches participating during the optimization process. In each optimization step, when a labeled batch of size B_L and an unlabeled batch of size B_U are given, the method optimizes the following:

$$\mathcal{L}_{DR} = \frac{\alpha_t}{B_L}\sum_{i=1}^{B_L}\mathcal{H}(y_i, \mathbf{p}(y|x_i)) - \frac{\alpha_t}{B_L}\sum_{i=1}^{B_L}\mathcal{H}(\hat{y}_i^L, \mathbf{p}(y|x_i)) + \frac{1}{B}\left(\sum_{i=1}^{B_L}\mathcal{H}(\hat{y}_i^L, \mathbf{p}(y|x_i)) + \sum_{i=1}^{B_U}\mathcal{H}(\hat{y}_i^U, \mathbf{p}(y|u_i))\right).$$

where $B = B_L + B_U$ and α_t represents the annealing parameter, following the original implementation in Zhu et al. (2024).

We provide comparison of doubly-robust method with ZeroMatch on Yahoo Answers and Amazon Reviews in Table 19. Our results show that our method outperforms doubly-robust method all settings. We hypothesize this is due to asymptotic guarantees of Doubly-robust Self-training method failing to hold in the low-label regime.

Table 19: Comaparison with doubly-robust self-training method in Yahoo Answers and Amazon Review with pseudo-labels from FLAN-T5 models. Median and standard deviation of accuracy (%) of 3 different random seeds are reported. Best score among experiments with same pseudo-label set are in bold. 'FM' refers to the foundation model used to generate the pseudo-label set.

	Dataset	Yahoo Answers			Amazon Review		
FM	Label size	250	500	2000	125	250	1000
A	Doubly-robust	51.39±12.13	44.32±10.91	47.9±5.68	46.94±0.72	47.25±0.63	47.76±0.87
	Zero-shot	66.63±0.00	66.63±0.00	66.63±0.00	52.37±0.00	52.37±0.00	52.37±0.00
	ZeroMatch (ours)	**69.78±0.94**	**70.51±0.19**	**71.81±0.07**	**58.83±0.51**	**59.69±0.60**	**60.95±0.13**
B	Doubly-robust	24.53±4.84	22.52±5.54	33.88±2.07	35.8±0.13	35.9±0.07	35.96±0.03
	Zero-shot	35.29±0.00	35.29±0.00	35.29±0.00	35.7±0.00	35.7±0.00	35.7±0.00
	ZeroMatch (ours)	**67.05±0.76**	**67.13±0.73**	**69.61±0.22**	**50.23±1.35**	**53.78±1.74**	**56.12±0.64**

C Limitations

In this section, we discuss few limitations of our work.

- We only benchmark our method on the case where fixed number of labeled data are sampled per each class. This may not demonstrate practical scenario where labels and classes have imbalanced distributions. Future directions can include benchmarking our method on such setting.
- While we assume that all the input data are coming from single distribution, practical scenarios may include distribution shifts in the data, especially if the data are collected from sensors of the moving edge devices (e.g. camera in different environments). Future work can explore solutions to adapt to these setup shifts.
- While most of our experimental results show that our method outperforms zero-shot method, there is no methodological guarantee this always hold. Future directions can explore ensuring robust improvement over zero-shot.
- We also note that our method's performance inherently depends on the quality of the pseudo-labels generated from foundation models. Robustness against labels that are not from foundation models (e.g. weak supervision signal, patterned noise) are not tested and may not work with our method. Future direction can further explore application to different type of label noise.