GIFT: UNLOCKING FULL POTENTIAL OF LABELS IN DISTILLED DATASET AT NEAR-ZERO COST

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Paper under double-blind review

ABSTRACT

Recent advancements in dataset distillation have demonstrated the significant benefits of employing soft labels generated by pre-trained teacher models. In this paper, we introduce a novel perspective by emphasizing the full utilization of labels. We first conduct a comprehensive comparison of various loss functions for soft label utilization in dataset distillation, revealing that the model trained on the synthetic dataset exhibits high sensitivity to the choice of loss function for soft label utilization. This finding highlights the necessity of a universal loss function for training models on synthetic datasets. Building on these insights, we introduce an extremely simple yet surprisingly effective plug-and-play approach, GIFT, which encompasses soft label refinement and a cosine similarity-based loss function to efficiently leverage full label information. Extensive experiments indicate that GIFT consistently enhances state-of-the-art dataset distillation methods across various dataset scales, without incurring additional computational costs. Importantly, GIFT significantly enhances cross-optimizer generalization, an area previously overlooked. For instance, on ImageNet-1K with `IPC` = 10, GIFT enhances the state-of-the-art method RDED by 30.8% in cross-optimizer generalization [1].

1 INTRODUCTION

Dataset distillation (DD) (Wang et al., 2018) has demonstrated its potential to significantly reduce data size while maintaining comparable model performance (Cazenavette et al., 2022; 2023; Zhao et al., 2020; Zhao & Bilen, 2023; Zhao et al., 2023). Most existing DD methods focus on optimizing images (Wang et al., 2018; Zhao & Bilen, 2022; Cazenavette et al., 2022; Kim et al., 2022; Liu et al., 2022), but recent studies (Yin et al., 2023; Sun et al., 2024; Shao et al., 2024; Guo et al., 2024) have highlighted the substantial benefits of soft labels. These studies utilize labels assigned by pre-trained models (also called teacher models), yielding siginificant enhancement in stability during the synthesizing process and considerable performance. Moreover, a notable study by Qin et al. (2024) examines the role of soft labels in depth, emphasizing their importance.

To fully explore the utilization of soft labels in the state-of-the-art dataset distillation methods, we conduct a comprehensive comparison of loss functions for soft label in synthesic datasets of $\texttt{IPC} = 10$ [2] via the SOTA dataset distillation methods on Tiny-ImageNet and large-scale ImageNet-1K [3]. As shown in Figure 1, different dataset distillation methods employ distinct loss functions, and performance varies significantly across loss functions. In particular, simply replacing KL divergence loss (Hinton et al., 2015) with Soft cross-entropy loss (Bridle, 1989) for SRe^{2}L results in a significant performance drop of 13.3% on Tiny-ImageNet. This substantial gap indicates that models trained on synthetic datasets are ***highly sensitive*** to the choice of loss function.

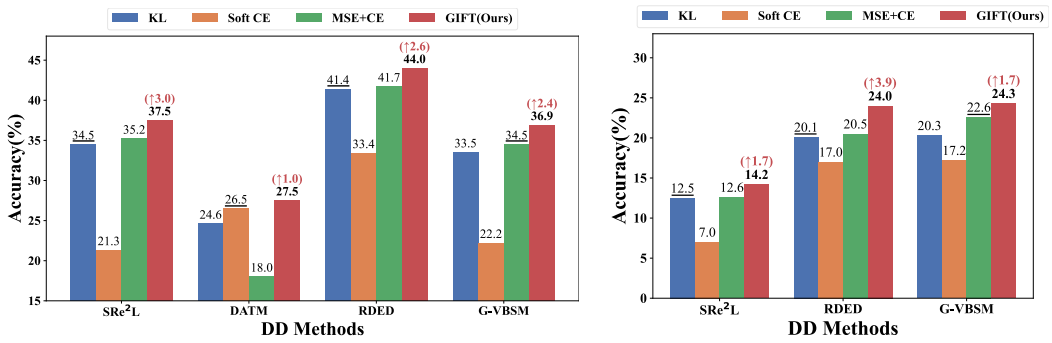
Furthermore, we observe a notable performance degradation in these loss functions when applied ***across different optimizers***. For example, when utilizing distilled data produced by RDED and training with the KL divergence loss, altering the optimizer from AdamW [4] to Adam results in a performance decrease from 47.5% to 17.8% (as shown in Table 8). *Hence, it is crucial to propose a universal and effective loss function that is robust across various scenarios.*

[1] We have provided Pytorch implementation code in Appendix F.

[2] Detailed experiments are elaborated in Section 3.

[3] The synthetic dataset of DATM for ImageNet-1k is not provided, so comparing with DATM is not possible on this dataset.

[4] RDED employs AdamW (Loshchilov, 2017) for evaluation.



(a) Tiny-ImageNet (b) ImageNet-1K

Figure 1: **Top-1 accuracy on various synthetic datasets via the SOTA dataset distillation methods across loss functions on Tiny-ImageNet and ImageNet-1K when `IPC` =10.** value means the results of the loss function used by the distillation method itself (e.g., SRe^{2}L (Yin et al., 2023) uses KL divergence (Hinton et al., 2015)). **value** means the results of our GIFT, and (↑) denotes improvements over the dataset distillation methods. It is obvious that our method GIFT significantly enhances the dataset distillation methods.

Moreover, one challenge of soft labels is that they are ***inherently suboptimal***, as the performance of the teacher model itself may be limited. For instance, a teacher model trained on ImageNet-1k on ConvNet has only 43.6% test accuracy. Despite its worse performance, such model is frequently used in Sun et al. (2024); Yin et al. (2023) to assign labels. Furthermore, in practical scenarios, it is common for the teacher model to have a smaller architecture than the student model due to cross-architecture challenge (Sun et al., 2024), which further limits the performance of the student model when only relying on an inferior teacher model. By contrast, hard labels are accurate and provide reliable supervision information. Nonetheless, directly utilizing hard labels through cross-entropy loss is not effective, as demonstrated in previous studies (Cui et al., 2023) and our experiments in Section 5.7 . *Therefore, it is crucial to effectively integrate hard label information to mitigate the limitations associated with soft labels.*

Based on the above two findings, we propose an extremely simple yet effective plug-and-play approach called Gaining Improvement from Full Labels at Near-zero CosT (GIFT) to effectively utilize both hard and soft labels. It first refines soft labels by incorporating an additional smoothing label obtained through hard label smoothing (Szegedy et al., 2016). This simple module offers two significant advantages: firstly, it can correct erroneous signals from the teacher model, particularly in cases where the teacher assigns an incorrect label of the highest value; secondly, soft labels mainly contain intra-class information, which can hinder class separation to some extent (Zhang et al., 2015). Therefore, a relatively sharp label can enhance the dispersion between classes, thereby improving generalization ability, as demonstrated in Section 5.7 . After obtaining the refined labels, we find that they are uniformly distributed and are approximately orthogonal to each other, as elaborated in Section 4 . Therefore, we verify theoretically that simply using cosine similarity as the loss function achieves optimal performance. As shown in Figure 1 (red bars), our method GIFT consistently and significantly enhances the state-of-the-art dataset distillation methods across various scale datasets.

In summary, our contributions are fourfold:

(a) To the best of our knowledge, this paper is the first to provide a comprehensive comparison of loss functions for label utilization in dataset distillation. Our study reveals the intriguing fact that models trained on synthetic datasets are ***highly sensitive*** to the choice of loss function.

(b) We propose GIFT, a simple and universal label utilization algorithm including label refinement and a cosine similarity-based loss function. GIFT is built on top of the off-the-shelf dataset distillation methods and requires no extra information, thus raising ***no additional cost***. Moreover, we provide a theoretical analysis to support the proposed use of cosine similarity.

(c) We identify a critical issue that has been overlooked in prior research: cross-optimizer generalization, as defined in Section 3.1 . We reveal that traditional loss functions suffer from significant robustness deficiencies when applied across different optimizers as detailed in Section 5.5 . In contrast, GIFT significantly enhances dataset distillation methods in cross-optimizer generalization. We conduct both empirical and theoretical analyses of this challenge in Appendix E .

(d) Experiments demonstrate that GIFT significantly improves performance over the state-of-the-art dataset distillation methods across varying scales and resolutions datasets, particularly for

large-scale dataset distillation tasks. Furthermore, GIFT significantly enhances dataset distillation methods in cross-architecture, cross-optimizer generalization and proves advantageous in applications such as continual learning.

2 Related Work

In the field of dataset distillation, the majority of existing methods fix the labels as a one-hot format (Wang et al., 2018; Zhao & Bilen, 2022; Cazenavette et al., 2022; Liu et al., 2022; Zhao & Bilen, 2023), with a primary focus on optimizing synthetic images. Recent research highlights the significant benefits of utilizing soft labels to enhance model performance (Sun et al., 2024; Guo et al., 2024; Yin et al., 2023). Methods for obtaining soft labels can be broadly classified into two categories.

Optimization-based Soft Labels. The first type involves learning labels, with several studies (Bohdal et al., 2020; Nguyen et al., 2020; Sucholutsky & Schonlau, 2021; Zhou et al., 2022; Guo et al., 2024) finding that learning labels can significantly improve performance. Recent work (Guo et al., 2024) highlights that optimizing labels can enhance training stability and improve performance.

Teacher model-based soft labels. The subsequent works directly obtain soft labels. Inspired by knowledge distillation (Hinton et al., 2015), TESLA (Cui et al., 2023)introduces a soft label assignment strategy, directly generating soft labels by leveraging pre-trained teacher models trained on real datasets. These soft labels provide rich intra-class information, thereby improving distillation performance. Following this trend, the state-of-art methods (Yin et al., 2023; Sun et al., 2024; Shao et al., 2024) also utilize soft labels predicted by teacher models, achieving significant improvements.

3 Motivation

3.1 Preliminary

Dataset Distillation. Given a large dataset $\mathcal{D} = \{(\mathbf{x}_i, y_i)\}_{i=1}^{N}$, where $\mathbf{x}_i \in \mathbb{R}^d$ represents the input sample and $y_i \in \{1, \ldots, C\}$ denotes hard label, the objective of dataset distillation is to generate a synthetic dataset $\mathcal{S} = \{(\tilde{\mathbf{x}}_j, \tilde{y}_j)\}_{j=1}^{M}$, such that a model trained on $\mathcal{S}$ performs comparably to one trained on $\mathcal{D}$. We explore how to fully utilize both soft labels and hard labels in given datasets. Therefore, we re-define the synthetic dataset $\mathcal{S}$ as $\mathcal{S} = \{(\tilde{\mathbf{x}}_j, y_j, \tilde{y}_j)\}_{j=1}^{M}$, where $\tilde{\mathbf{x}}_j$ denotes the synthetic images, and y_j and $\tilde{y}_j$ denote the corresponding hard labels and soft labels, respectively.

Cross-Optimizer Generalization. In deep learning, models use various network architectures and optimization algorithms. Optimizers like SGD and Adam have unique properties that affect model performance and generalization. Therefore, evaluating a distilled dataset's performance aross optimizers is essential to ensure its robustness across different training strategies.

Definition 1 (Cross-optimizer Generalization) . *It refers to the capability of distilled datasets to maintain robust and consistent performance across different optimization algorithms.*

3.2 Are Loss Functions Pulling the Strings in Synthetic Dataset Performance?

Why do we need to answer this question? Labels in dataset distillation are commonly and typically utilized through a variety of established loss functions, such as cross-entropy (CE) (Bridle, 1989), Kullback-Leibler (KL) divergence (Hinton et al., 2015), soft cross-entropy (Bridle, 1989) or mean squared error (MSE) (Nielsen, 2015). Specifically, the current state-of-the-art dataset distillation methods SRe^{2}L (Yin et al., 2023) and RDED (Sun et al., 2024) employ KL divergence, DATM (Guo et al., 2024) uses soft cross-entropy, and G-VBSM (Shao et al., 2024) simultaneously utilizes MSE and CE. However, different distillation methods employ varying loss functions to train models on synthetic datasets, yet there is a notable lack of comprehensive comparison among these loss functions. Hence, we investigate the performance of four state-of-the-art dataset distillation methods under three commonly used loss functions.

Experiment settings. Our experiments span both small-scale Tiny-ImageNet and large-scale ImageNet-1K. Note that the synthetic dataset for DATM on ImageNet-1K is unavailable, preventing comparative analysis on this dataset. We conduct evaluations on these synthetic datasets with $\texttt{IPC} \in \{1, 10, 50\}$. Additional visualizations for Tiny-ImageNet and ImageNet-1K at $\texttt{IPC} = 1$ and $\texttt{IPC} = 50$ are provided in Appendix D. Notably, our empirical study is conducted from the end-user perspective: we treat the distillation of the synthetic dataset as a black box and apply different loss functions during the evaluation of the synthetic datasets.

Results and Analysis. The results, visualized in Figure 1, reveal that even for the same synthetic dataset, the evaluation model performance varies significantly under different loss functions. For example, the performance of SRe^{2}L decreases by 13.2% on Tiny-ImageNet when switching from KL loss to soft CE loss but improves by 0.7% when using MSE+CE loss. These findings illustrate that the performance of models trained on synthetic datasets is ***highly sensitive*** to the choice of the loss function, *highlighting the necessity for a unified and effective loss function in dataset distillation.*

4 METHOD

Motivated by these findings, we propose an extremely simple but surprisingly effective plug-and-play approach called Gaining Improvement from Full Labels at Near-zero CosT (GIFT) to effectively utilize both hard and soft labels. GIFT includes two key modules: label refinement and a cosine similarity-based loss function. The former aims to refine soft labels by incorporating an additional smoothing label derived from hard label smoothing (Szegedy et al., 2016), while the latter is theoretically validated to achieve optimal performance simply using cosine similarity as the loss function. A PyTorch implementation of our method is provided in Appendix F.

Label Refinement. As discussed in Section 1, soft labels generated by teacher models are inherently suboptimal due to two primary reasons. Firstly, the performance of the teacher model is limited, particularly on complex datasets such as ImageNet-1K. Secondly, soft labels predominantly provide intra-class information, thereby limiting class dispersion.

An intuitive method to address these shortcomings is to integrate with hard labels. On the one hand, hard labels offer accurate and reliable supervision, which can rectify erroneous information provided by soft labels. On the other hand, they can assist in inter-class dispersion. Therefore, we refine soft labels by weighing them with smoothed hard labels, thereby solving the two limitations of soft labels.

The refined soft label is defined as $\tilde{y}_j \leftarrow \gamma \cdot \frac{y_j}{\|y_j\|} + (1-\gamma) \cdot \frac{\tilde{y}_j}{\|\tilde{y}_j\|}$, where j is the j-th synthetic images, y_j is the smoothed label obtained via label smoothing technique for hard label, and $\tilde{y}_j$ is the soft label. In our experiments, $\gamma = 0.1$ is validated to be optimal through experiments depicted in Figure 3 in Section 5.7, and Figure 8 and Figure 9 in Appendix D.

Mutual information bounded loss function. Prior study (Sun et al., 2024) points that representation learning from any samples X to targets Y is based on maximizing their mutual information. They propose to distill the dataset by maximizing $I_{\mathcal{V}}(X, Y)$, where $I_{\mathcal{V}}$ denotes the $\mathcal{V}$-information (Xu et al., 2020), which has demonstrated superior performance. However, we observe that most prior studies, including (Sun et al., 2024), have not investigated training models using $I_{\mathcal{V}}(X, Y)$. To address this gap, we explore the application of $I_{\mathcal{V}}(X, Y)$ by deriving an upper bound for the $\mathcal{V}$-information, as presented in Theorem 1 (Detailed proof is provided in Appendix A).

Theorem 1 . *The $\mathcal{V}$-information $I_{\mathcal{V}}(X, Y)$ is upper bounded by a function involving the cosine similarity between the positive pair $(\mathbf{x}_i, y_i)$, the expected cosine similarity between the anchor $\mathbf{x}_i$ and negative samples y_j, and the number of negative samples K. Specifically,*

$$\begin{aligned}\mathcal{L}_{\text{InfoNCE}} &= -\mathbb{E}\left[\log \frac{\exp(f(\boldsymbol{\phi}_{\boldsymbol{\theta}}(\mathbf{x}), y))}{\sum_{y' \in \mathcal{Y}} \exp(f(\boldsymbol{\phi}_{\boldsymbol{\theta}}(\mathbf{x}), y'))}\right] \\ &\leq -\frac{1}{\tau}\left(\mathbb{E}\left[\left(\frac{\boldsymbol{\phi}_{\boldsymbol{\theta}}(\mathbf{x}_i) \cdot y_i}{\|\boldsymbol{\phi}_{\boldsymbol{\theta}}(\mathbf{x}_i)\| \|y_i\|}\right)\right] - \frac{\mathbb{E}[\boldsymbol{\phi}_{\boldsymbol{\theta}}(\mathbf{x}_i) \cdot y_j]}{\|\boldsymbol{\phi}_{\boldsymbol{\theta}}(\mathbf{x})_i\| \mathbb{E}[\|y_j\|]}\right) + \log(K)\,,\end{aligned} \tag{1}$$

where τ denotes the temperature parameter, $\mathcal{L}_{\text{InfoNCE}}$ (Oord et al., 2018) serves as a proxy for $I_{\mathcal{V}}(X, Y)$ (Sun et al., 2024), and f represents the similarity function.

Moreover, the targets Y in the synthetic dataset are pre-generated using pre-trained models (Sun et al., 2024; Yin et al., 2023). These targets can be considered high-dimensional vectors that are approximately orthogonal to each other (Ma et al., 2022; Yu et al., 2023; Awasthi et al., 2024). Consequently, the term $\mathbb{E}[\boldsymbol{\phi}_{\boldsymbol{\theta}}(\mathbf{x}_i) \cdot y_j]$ approaches zero, allowing (1) to be simplified as:

$$\mathcal{L}_{\text{InfoNCE}} \leq -\frac{1}{\tau}\left(\mathbb{E}\left[\frac{\boldsymbol{\phi}_{\boldsymbol{\theta}}(\mathbf{x}_i) \cdot y_i}{\|\boldsymbol{\phi}_{\boldsymbol{\theta}}(\mathbf{x}_i)\| \|y_i\|}\right] - \epsilon\right) + \log(N)\,, \tag{2}$$

where ϵ is a small positive term approaching zero.

To minimize this upper bound (2), our proposed loss function for training on distilled data $\mathcal{S}$ can defined as:

$$\mathcal{L} = \mathbb{E}_{(\tilde{\mathbf{x}}_i, \tilde{y}_i)\sim\mathcal{S}} \left[1 - \frac{\boldsymbol{\phi}_{\boldsymbol{\theta}}(\tilde{\mathbf{x}}_i) \cdot \tilde{y}_i}{\|\boldsymbol{\phi}_{\boldsymbol{\theta}}(\tilde{\mathbf{x}}_i)\| \|\tilde{y}_i\|} \right], \tag{3}$$

where $\tilde{y}_j$ is the refined soft label discussed above and we replace the original training loss with (3).

5 Experiments

In this section, we evaluate the superiority of our proposed GIFT across various datasets and architectures. First, we demonstrate the superior improvements of GIFT over the state-of-the-art dataset distillation in Section 5.2 and knowledge distillation methods in Section 5.3. Next, we verify that our proposed GIFT significantly enhances cross-architecture and cross-optimizer generalization in Section 5.5, and improves continual learning in Section 5.6. Furthermore, we conduct extensive ablation experiments to investigate the effect of each component of our method in Section 5.7. More details about experiments details and results can be found in Appendix C and Appendix D.

5.1 Experiment Setup

Datasets and Networks. We conduct experiments on both large-scale and small-scale datasets, including the full 224×224 ImageNet-1k (Deng et al., 2009), Tiny-ImageNet (Le & Yang, 2015) and CIFAR-100 (Krizhevsky et al., 2009). Following previous dataset distillation studies (Yin et al., 2023; Cazenavette et al., 2022; Zhao et al., 2023; Cui et al., 2023; Guo et al., 2024), we employ ConvNet (Guo et al., 2024) and ResNet-18 (He et al., 2016) as our backbone architectures across all datasets. Specifically, Conv-3 is employed for CIFAR-10/100, while Conv-4 is used for Tiny-ImageNet and ImageNet-1K. For cross-architecture experiments, we additionally utilize large-scale networks, including ResNet-101 (He et al., 2016) and Swin-V2-Tiny (Liu et al., 2021) and small-scale networks, such as EfficientNet-B0 (Tan & Le, 2019), and MobileNet-V2 (Sandler et al., 2018) to verify the generalizability of our approach.

Baselines. We benchmark our method GIFT against state-of-the-art dataset distillation methods. We categorize current state-of-the-art methods based on two key factors: scalability to ImageNet-1K and the utilization of soft labels. These categorizations are summarized in Table 13 in Appendix C. Given that our primary focus is on enhancing the use of soft labels in dataset distillation, we restrict our comparisons to methods that leverage soft labels, including SRe^{2}L (Yin et al., 2023), RDED (Sun et al., 2024), DATM (Guo et al., 2024), G-VBSM (Shao et al., 2024), and CDA (Yin & Shen, 2023) Additionally, DATM only provides synthetic datasets on ConvNet and does not provide the ImageNet-1k synthetic dataset. CDA provides higher `IPC` synthetic datasets of Tiny-ImageNet and ImageNet-1k, distilled using ResNet architectures, so we mainly compare with CDA in Section 5.2.

Knowledge distillation (Hinton et al., 2015) is a straightforward approach that utilizes both hard and soft label information. Thus, we also compare our method GIFT with state-of-the-art knowledge distillation methods, including KD (Hinton et al., 2015), WSLD (Zhou et al., 2021), DKD (Zhao et al., 2022), and NKD (Yang et al., 2023). Further details on these methods are provided in Appendix C.

Implementation details of GIFT. Our method does not involve any distilling datasets process. We obtain all synthetic datasets directly from the source data provided by the authors [5]. Notably, distilled data is generalized using both ConvNet and ResNet-18. We replace the loss function during evaluation. Thus, our method is a plug-and-play approach that can be easily integrated into existing dataset distillation pipelines without additional dataset synthesis or modification.

For the data augmentation of synthetic datasets, only synthetic datasets generated via DATM (Guo et al., 2024) are processed using ZCA whitening, as these datasets were initially distilled through ZCA whitening. Other distilled datasets are processed using DSA (Zhao & Bilen, 2021), as detailed in Table 14. All experiments are conducted using an NVIDIA RTX 4090 GPU.

[5] ⋆ SRe^{2}L: https://github.com/VILA-Lab/SRe2L
⋆ RDED: https://github.com/LINs-lab/RDED
⋆ DATM: https://gzyaftermath.github.io/DATM/
⋆ G-VBSM: https://github.com/shaoshitong/G_VBSM_Dataset_Condensation
⋆ CDA: https://github.com/VILA-Lab/SRe2L/tree/main/CDA

Table 1: **Comparison with the state-of-the-art methods of dataset distillation on CIFAR-100 and Tiny-ImageNet.** In this table, "-" are absent due to scalability.

		CIFAR100			Tiny-ImageNet		
Network	Method	1	10	50	1	10	50
ConvNet	SRe^{2}L	13.6 ± 0.4	33.7 ± 0.5	52.3 ± 0.2	12.1 ± 0.4	34.5 ± 0.4	46.3 ± 0.1
	SRe^{2}L + Ours	15.1 ± 0.3 (↑ 1.5)	38.0 ± 0.5 (↑ 4.3)	55.4 ± 0.1 (↑ 3.1)	13.1 ± 0.2 (↑ 1.0)	37.5 ± 0.3 (↑ 3.0)	47.1 ± 0.1 (↑ 0.8)
	RDED	22.1 ± 0.3	47.5 ± 0.3	55.7 ± 0.4	17.9 ± 0.3	41.4 ± 0.3	47.2 ± 0.1
	RDED + Ours	24.7 ± 0.3 (↑ 2.5)	50.6 ± 0.3 (↑ 2.5)	57.9 ± 0.2 (↑ 2.2)	19.1 ± 0.3 (↑ 1.2)	44.0 ± 0.2 (↑ 2.6)	48.3 ± 0.1 (↑ 1.1)
	DATM	-	36.1 ± 0.2	43.0 ± 0.2	-	26.5 ± 0.2	34.2 ± 0.5
	DATM + Ours	-	37.8 ± 0.3 (↑ 1.7)	43.6 ± 0.3 (↑ 0.6)	-	27.5 ± 0.2 (↑ 1.0)	34.8 ± 0.6 (↑ 0.6)
	G-VBSM	14.7 ± 0.5	40.9 ± 0.4	54.7 ± 0.3	8.4 ± 0.4	34.5 ± 0.5	47.0 ± 0.3
	G-VBSM + Ours	16.0 ± 0.2 (↑ 1.3)	44.6 ± 0.2 (↑ 3.7)	57.2 ± 0.1 (↑ 2.5)	8.9 ± 0.3 (↑ 0.5)	36.9 ± 0.7 (↑ 2.4)	47.8 ± 0.2 (↑ 0.8)
ResNet-18	SRe^{2}L	11.5 ± 0.5	42.7 ± 0.2	57.8 ± 0.6	12.7 ± 0.3	43.5 ± 0.1	53.9 ± 0.0
	SRe^{2}L + Ours	12.7 ± 0.4 (↑ 1.2)	44.3 ± 0.3 (↑ 1.6)	58.6 ± 0.3 (↑ 0.8)	14.2 ± 0.3 (↑ 1.5)	44.2 ± 0.3 (↑ 0.7)	54.5± 0.2 (↑ 0.6)
	RDED	4.7 ± 0.1	52.8 ± 0.2	64.4 ± 0.1	15.1 ± 0.3	48.2 ± 0.4	57.6 ± 0.3
	RDED + Ours	5.0 ± 0.2 (↑ 0.3)	54.0 ± 0.3 (↑ 1.2)	65.3 ± 0.2 (↑ 0.7)	15.9 ± 0.3 (↑ 0.8)	49.2 ± 0.1 (↑ 1.0)	58.1 ± 0.1 (↑ 0.5)
	DATM	-	25.8 ± 1.0	47.5 ± 0.4	-	26.7 ± 0.2	41.9 ± 0.3
	DATM + Ours	-	26.3 ± 0.4 (↑ 0.5)	47.9 ± 0.3 (↑ 0.4)	-	29.0 ± 0.5 (↑ 2.3)	42.4 ± 0.2 (↑ 0.4)
	G-VBSM	13.4 ± 0.3	48.5 ± 0.5	62.0 ± 0.2	8.8 ± 0.3	39.9 ± 0.4	52.8 ± 0.2
	G-VBSM + Ours	13.7 ± 0.3 (↑ 0.3)	49.2 ± 0.2 (↑ 0.7)	62.5 ± 0.3 (↑ 0.5)	9.3 ± 0.3 (↑ 0.5)	40.5 ± 0.2 (↑ 0.6)	53.1 ± 0.1 (↑ 0.3)

Table 2: **Comparison with the state-of-the-art methods of dataset distillation on ImageNet-1K.** In the table, (↑) means the improvements over these methods.

	ImageNet-1K					
	ConvNet			ResNet-18		
Method	10	50	100	10	50	100
SRe^{2}L	12.5 ± 0.3	35.4 ± 1.0	40.1 ± 0.4	31.5 ± 0.3	49.5 ± 0.1	54.3 ± 0.2
SRe^{2}L + Ours	14.2 ± 0.6 (↑ 1.7)	38.1 ± 0.4 (↑ 2.7)	41.5 ± 0.2 (↑ 1.4)	31.9 ± 0.2 (↑ 0.4)	50.1 ± 0.2 (↑ 0.6)	54.8 ± 0.1 (↑ 0.5)
RDED	20.1 ± 0.4	38.5 ± 0.2	41.8 ± 0.2	41.4 ± 0.4	55.5 ± 0.2	58.8 ± 0.1
RDED + Ours	24.0 ± 0.8 (↑ 3.9)	39.5 ± 0.1 (↑ 1.0)	42.5± 0.1 (↑ 0.7)	43.2 ± 0.1 (↑ 1.8)	56.5 ± 0.1 (↑ 1.0)	59.3± 0.1 (↑ 0.5)
G-VBSM	22.6 ± 0.5	37.3 ± 0.3	40.1 ± 0.4	36.7 ± 0.2	52.3 ± 0.1	57.3 ± 0.1
G-VBSM + Ours	24.3 ± 0.2 (↑ 1.7)	39.1 ± 0.3 (↑ 1.8)	42.1 ± 0.3 (↑ 2.0)	37.9 ± 0.5 (↑ 1.2)	53.1 ± 0.2 (↑ 0.8)	57.6 ± 0.1 (↑ 0.3)

Table 3: **Comparison with CDA under higher `IPC` on small-scale Tiny-ImageNet and large-scale ImageNet-1K on ResNet-18.** In the table, (↑) means the improvements over CDA.

	Tiny-ImageNet		ImageNet-1K		
Method	50	100	50	100	200
CDA	49.5 ± 0.4	53.5 ± 0.3	53.7 ± 0.3	58.3 ± 0.3	63.4 ± 0.2
CDA + Ours	54.5 ± 0.3 (↑ 5.0)	56.6 ± 0.2 (↑ 3.1)	54.8 ± 0.2 (↑ 1.1)	59.0 ± 0.2 (↑ 0.8)	63.9 ± 0.1 (↑ 0.5)

Hyperparameter Settings. We provide detailed hyperparameter configurations for our synthetic dataset evaluation in Appendix C. Following recent works (Yin et al., 2023; Shao et al., 2024), the evaluation on all datasets uses the parameters outlined in Table 15. We set the coefficient of label smoothing $\alpha = 0.1$ and the weight hyper-parameter $\gamma = 0.1$ for all methods across various synthetic datasets, as $\gamma = 0.1$ is validated to be optimal through experiments depicted in Section 5.7 and Section 8 in Appendix D.

5.2 Can GIFT Improve Performance of Dataset Distillation?

Small-Scale Dataset Comparison. In Table 1, we present the test accuracy on CIFAR-100 and Tiny-ImageNet datasets before and after applying our GIFT algorithm. Notably, DATM does not provide synthetic datasets when `IPC` =1, nor does it provide synthetic datasets for ResNet-18. Consequently, we used ConvNet synthetic data to train ResNet-18. It is evident that *applying* GIFT *increases performance for all baseline methods*. Specifically, the SRe^{2}L method exhibits the most significant improvement, with an accuracy gain of up to 4.3% on CIFAR-100 when `IPC` =10. This is particularly noteworthy as GIFT requires no additional information or cost. The considerable accuracy gains can be achieved simply by replacing the loss function with our proposed approach.

Large-Scale Dataset Comparison. In the large-scale ImageNet-1k dataset, as reported in Table 2, our proposed method GIFT consistently improves all baseline methods across all `IPC` values in 10, 50, 100, using both ConvNet and ResNet-18 as evaluation models. Specifically, compared with the current state-of-the-art methods RDED and G-VBSM, GIFT achieves significant performance gains of 1.8%and 1.2% on ResNet-18 when `IPC` =10, respectively. The substantial performance improvements obtained by GIFT *demonstrate its capability to effectively scale to large-scale datasets.*

Comparison under Higher `IPC`. Given that only CDA (Yin & Shen, 2023) provides a higher `IPC` synthetic dataset distilled, our comparison primarily centers on CDA. The results in Table 3

Table 4: **Comparison with RDED Large-scale Netwrok.** In the table, (↑) means the improvements over RDED.

	Tiny-ImageNet		ImageNet-1K	
Method	10	50	10	50
RDED	47.1± 0.3	55.1 ± 0.3	42.3 ± 0.2	58.6 ± 0.1
RDED + Ours	48.6 ± 0.2 (↑ 1.5)	56.2 ± 0.2 (↑ 1.1)	43.5 ± 0.2 (↑ 1.2)	59.4 ± 0.2 (↑ 0.8)

Table 5: **Comparison with the knowledge distillation methods on the synthetic dataset via RDED (Sun et al., 2024) using ConvNet.** In this table, **bold** means the best result, underlined means the second best, and (↑) denotes improvements over the second best baseline.

	CIFAR100		Tiny-ImageNet		ImageNet-1K		
	10	50	10	50	10	50	100
Teacher	61.27	61.27	49.73	49.73	43.6	43.6	43.6
KD	43.2 ± 0.1	51.9 ± 0.4	33.3 ± 0.4	40.7 ± 0.2	16.7 ± 0.1	24.3 ± 0.2	27.5 ± 0.4
WSLD	38.6 ± 0.3	49.5 ± 0.5	27.1 ± 0.3	37.5 ± 0.2	13.4 ± 0.1	22.8 ± 0.1	26.2 ± 0.0
DKD	49.0 ± 0.2	56.7 ± 0.2	40.9 ± 0.2	47.2 ± 0.1	20.5 ± 0.1	33.1 ± 0.1	36.5 ± 0.1
NKD	46.3 ± 0.3	54.3 ± 0.1	37.6 ± 0.4	44.1 ± 0.2	19.84 ± 0.1	27.9 ± 0.2	30.6 ± 0.2
GIFT (ours)	**50.6 ± 0.3** (↑ 1.6)	**57.9 ± 0.2** (↑ 1.2)	**44.0 ± 0.2**(↑ 3.1)	**48.3 ± 0.1** (↑ 1.1)	**24.0 ± 0.8**(↑ 3.4)	**39.5 ± 0.1** (↑ 6.4)	**42.5± 0.1** (↑ 6.0)

demonstrate that our GIFT method substantially improves the performance of CDA. Furthermore, it also achieves significant enhancements at higher IPC.

Comparison on Large-scale Network. In addition to conventional networks like ResNet-18, we employ the state-of-the-art dataset distillation method, RDED, to generate distilled data for Tiny-ImageNet and ImageNet-1K using Swin Transformer (Liu et al., 2021). The results, as shown in Table 4, indicate notable enhancements, verifying the effectiveness and promise of our method.

5.3 Can Knowledge Distillation work?

A straightforward approach to combining soft labels and hard labels is knowledge distillation (Hinton et al., 2015), which transfers knowledge from a teacher model to a student model using hard labels (cross-entropy loss) and soft labels provided by a strong teacher model (KL divergence loss). In Table 5, we compare our proposed method, GIFT, with the state-of-the-art knowledge distillation techniques across synthetic datasets distilled via RDED (Sun et al., 2024) [6].

It can be observed that GIFT *outperforms all knowledge distillation methods*. We attribute the failure of knowledge distillation methods to the extremely small size of synthetic datasets, which significantly hampers the performance of knowledge distillation methods, as corroborated by (Stanton et al., 2021). Therefore, knowledge distillation is not well-suited for our problem, further highlighting the effectiveness of GIFT.

5.4 Can GIFT achieve Near-zero Cost?

We perform experiments to evaluate memory and training time costs using ResNet-18 across datasets with varying scales and resolutions, as presented in Table 6. *Our method demonstrates no additional peak memory usage and incurs negligible computational overhead.* This efficiency is due to its emphasis on label refinement and the implementation of a general and simple loss function during the evaluation phases. Importantly, despite the negligible additional cost, GIFT yields significant performance improvements across datasets of varying scales and resolutions.

5.5 Can GIFT Improve Generalization?

Cross-Architecture Generalization. To validate the enhancement of generalization capability by our GIFT, it is necessary to assess its effectiveness across various neural architectures not encountered during the dataset synthesis phase. We evaluate performance on both small and large-scale model architectures. Table 7 presents the performance before and after applying our GIFT to dataset distillation methods. The results indicate that GIFT *enhances the cross-architecture generalization of all dataset distillation methods across diverse architectures*. Notably, our method shows significant improvements when generalizing from small networks to larger networks. For instance, GIFT yields performance gains of 2.6% and 7.8% for RDED and G-VBSM, respectively, when synthesizing data using ConvNet while training model on ResNet-101.

[6] RDED is the current state-of-the-art method as shown in Table 1, so we conduct the experiment on its synthetic datasets.

Table 6: **Training Time (s) and memory (GB) costs on three synthetic datasets using ResNet-18 when IPC=10.** (+) denotes additional cost over these methods.

	CIFAR-100		Tiny-ImageNet		ImageNet-1K	
Method	Training Time	Memory	Training Time	Memory	Training Time	Memory
SRe^{2}L	180.22	0.69	1249.66	2.01	2011.24	2.32
SRe^{2}L + Ours	181.36 (+ 1.14)	0.69	1275.75 (+ 26.09)	2.01	2078.59 (+ 67.35)	2.32
RDED	171.97	0.69	1272.28	2.01	2066.35	2.32
RDED + Ours	175.17 (+ 3.20)	0.69	1298.73 (+ 26.45)	2.01	2124.61 (+ 58.26)	2.32
DATM	132.51	1.36	1018.31	12.55	-	-
DATM + Ours	139.06 (+ 6.55)	1.36	1039.65 (+ 21.34)	12.55	-	-
G-VBSM	183.90	0.69	1256.35	2.01	2074.72	2.32
G-VBSM + Ours	187.83 (+ 3.93)	0.69	1282.63 (+ 26.28)	2.01	2129.98 (+ 55.26)	2.32

Table 7: **Top-1 accuracy on cross-architecture generalization on Tiny-ImageNet.** We use the synthetic datasets distilled (D) on ConvNet and ResNet-18 on Tiny-ImageNet when IPC=10. Then, evaluations (E) are performed across both small-scale and large-scale architectures. (↑) denotes improvements over these methods.

		Small-Scale Architecture				Large-Scale Architecture	
	D/E	ConvNet	ResNet-18	EfficientNet-B0	MobileNet-V2	ResNet-101	Swin-V2-Tiny
ConvNet	SRe^{2}L	34.5 ± 0.4	43.04 ± 0.1	11.2 ± 1.1	14.0 ± 0.6	9.9 ± 0.5	10.3 ± 0.4
	SRe^{2}L + Ours	37.5±0.3 (↑ 3.0)	44.2 ± 0.3 (↑ 1.16)	15.3 ± 1.0 (↑ 4.1)	14.4 ± 0.3 (↑ 0.4)	10.6 ± 0.3 (↑ 0.7)	11.2 ± 0.2 (↑ 0.9)
	RDED	41.4 ± 0.3	46.5 ± 0.2	30.3 ± 1.4	30.2 ± 0.2	28.2 ± 1.9	26.8 ± 0.6
	RDED + Ours	44.0±0.2 (↑ 2.6)	47.2 ± 0.1 (↑ 0.7)	31.4 ± 0.9 (↑ 1.1)	31.3 ± 0.2 (↑ 1.1)	30.8 ± 1.8 (↑ 2.6)	28.7 ± 0.4 (↑ 1.9)
	DATM	36.1 ± 0.2	27.3 ± 0.2	18.0 ± 0.3	14.7 ± 0.2	15.3 ± 0.8	4.1 ± 3.1
	DATM + Ours	37.8 ± 0.3 (↑ 1.7)	29.0 ± 0.2 (↑ 1.7)	18.4± 0.5 (↑ 0.4)	17.5 ± 0.1 (↑ 2.8)	16.8± 0.5 (↑ 1.5)	16.3 ± 0.3 (↑ 12.2)
	G-VBSM	34.5 ± 0.5	42.2 ± 0.3	13.7 ± 1.4	15.0 ± 0.4	7.7 ± 0.6	10.4 ± 0.4
	G-VBSM + Ours	36.9±0.7 (↑ 2.4)	42.8 ± 0.2 (↑ 0.6)	16.3 ± 1.0 (↑ 2.6)	15.8± 0.4 (↑ 0.8)	15.5 ± 0.3 (↑ 7.8)	13.2± 0.1 (↑ 2.8)
ResNet-18	SRe^{2}L	19.2 ± 0.1	43.5 ± 0.1	11.6 ± 0.4	11.9 ± 0.3	8.7 ± 1.0	8.0 ± 0.2
	SRe^{2}L + Ours	19.4 ± 0.2 (↑ 0.2)	44.2±0.3(↑ 0.7)	12.2 ± 0.2 (↑ 0.6)	12.3 ± 0.1 (↑ 0.4)	9.0 ± 0.5 (↑ 0.3)	8.8± 0.3 (↑ 0.8)
	RDED	29.2 ± 0.3	48.2 ± 0.4	24.1 ± 0.7	23.5 ± 0.3	21.8 ± 0.3	19.6 ± 0.4
	RDED + Ours	29.9 ± 0.1 (↑ 0.7)	49.2±0.1 (↑ 1.0)	25.2 ± 0.2 (↑ 1.1)	24.1 ± 0.3 (↑ 0.6)	23.5± 0.3 (↑ 1.7)	20.4± 0.3 (↑ 0.8)
	G-VBSM	16.0 ± 0.3	39.9 ± 0.4	8.8 ± 0.1	11.5 ± 0.4	6.3 ± 1.1	6.5 ± 0.3
	G-VBSM + Ours	16.5 ± 0.4 (↑ 0.5)	40.5±0.2 (↑ 0.6)	10.1± 0.2 (↑ 1.3)	11.8 ± 0.3 (↑ 0.3)	9.2 ± 0.6 (↑ 2.9)	8.2± 0.3 (↑ 1.7)

Table 8: **Top-1 accuracy (%) on cross-optimization generalization on Tiny-ImageNet and CIFAR100 when `IPC` =10.**We evaluate the performance of synthetic datasets across various optimizers.

Dataset	CIFAR100			Tiny-ImageNet		
Optimizer	SGD	Adam	AdamW	SGD	Adam	AdamW
SRe^{2}L	1.5 ± 0.1	8.7 ± 0.1	34.5 ± 0.4	0.6 ± 0.0	3.1 ± 0.1	33.7 ± 0.5
SRe^{2}L + Ours	43.0 ± 0.8 (↑ 42.6)	44.7 ± 0.6 (↑ 37.5)	38.0 ± 0.5 (↑ 3.5)	43.8 ± 0.5 (↑ 43.2)	45.2 ± 0.2 (↑ 42.1)	37.5± 0.3 (↑ 3.0)
RDED	1.9 ± 0.0	17.8 ± 0.1	47.5 ± 0.3	0.6 ± 0.0	4.5 ± 0.2	41.4 ± 0.3
RDED + Ours	53.4 ± 0.2 (↑ 51.5)	53.7 ± 0.4 (↑ 35.9)	50.6 ± 0.3 (↑ 2.6)	46.6 ± 0.3 (↑ 46.0)	46.5 ± 0.2 (↑ 42.0)	44.0 ± 0.2 (↑ 2.6)
DATM	37.3 ± 0.3	36.7 ± 0.1	36.1 ± 0.2	28.2 ± 0.1	27.8 ± 0.1	26.5 ± 0.2
DATM + Ours	38.5± 0.2 (↑ 1.2)	40.0± 0.2 (↑ 3.3)	37.8 ± 0.3 (↑ 1.7)	30.1 ± 0.3 (↑ 1.9)	29.1 ± 0.1 (↑ 1.3)	27.5 ± 0.2 (↑ 1.0)
G-VBSM	44.2 ± 1.8	41.2 ± 0.4	40.9 ± 0.4	41.4 ± 0.4	36.5 ± 0.4	34.5 ± 0.5
G-VBSM + Ours	49.8 ± 0.4 (↑ 5.6)	51.3 ± 0.6 (↑ 10.1)	44.6 ± 0.2 (↑ 3.7)	44.5 ± 0.1 (↑ 3.1)	45.3 ± 0.1 (↑ 8.8)	36.9 ± 0.7 (↑ 2.4)

The success of our method is attributed to its stability. In cross-architecture scenarios, soft labels may not be sufficient due to architectural differences (Vyas et al., 2020). However, our cosine similarity approach inherently includes a normalization operation, mitigating the negative impact of label fluctuation. These results are promising, indicating that our method, which does not incur additional computational costs, is well-suited for applications involving large-scale models.

Cross-optimizer Generalization. Similar to cross-architecture generation, it is crucial to estimate the cross-optimizer generalization of dataset distillation methods. Different optimizers, such as SGD and Adam, exhibit distinct characteristics that influence model performance and generalization. Therefore, in practical applications, it is necessary to choose the most appropriate optimizer according to the training conditions. In this experiment, we report the accuracy before and after applying our GIFT to baseline methods across multiple optimizers not seen during dataset distillation, as shown in Table 8. The results clearly indicate that GIFT *enhances the generalization ability of all baseline methods.* More results on ImageNet-1K can be found in Table 16 in Appendix D.

It is notable that SRe^{2}L and RDED perform poorly in this cross-optimizer challenge. However, with our method, performance increased by 42.6% and 51.5% using SGD on CIFAR-100. We present an emperical and theoretical analysis of cross-optimizer generalization in Appendix E.

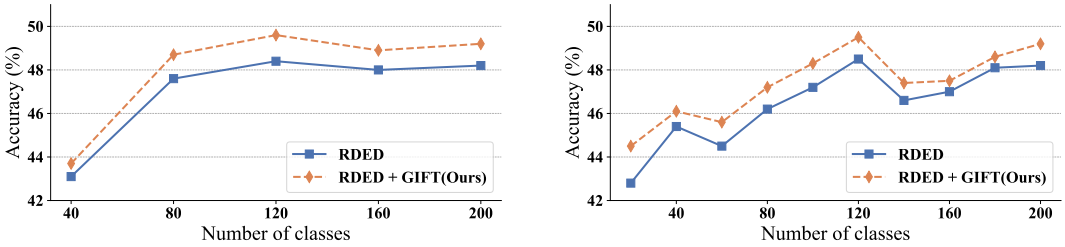
Table 9: **Comparsion with loss functions employed in dataset distillation**. The experiment is conducted on synthetic datasets distilled via RDED (Sun et al., 2024). In this table, **bold** means the best result, underlined means the second best, and (↑) denotes improvements over the second best baseline.

		CIFAR100		Tiny-ImageNet		ImageNet-1K		
		10	50	10	50	10	50	100
Hard Label	CE	26.6 ± 0.4	40.8 ± 0.1	14.2 ± 0.3	26.9 ± 0.6	9.1 ± 0.1	17.5 ± 0.1	21.5 ± 0.1
Soft Label	KL	47.5 ± 0.3	55.7 ± 0.4	41.4 ± 0.3	47.2 ± 0.1	20.1 ± 0.4	38.5 ± 0.2	41.8 ± 0.2
	JS	47.9 ± 0.1	55.9 ± 0.3	41.8 ± 0.2	47.3 ± 0.2	20.5 ± 0.3	38.6 ± 0.3	41.9 ± 0.3
	MSE	47.6 ± 0.4	55.9 ± 0.1	41.6 ± 0.2	47.3 ± 0.0	20.7 ± 0.4	38.8 ± 0.4	41.9 ± 0.1
	Soft CE	40.8 ± 0.3	52.1 ± 0.3	33.4 ± 0.2	44.1 ± 0.4	17.0 ± 0.3	30.5 ± 0.8	37.2 ± 0.6
Hard& Soft Label	KL + CE	48.2 ± 0.4	56.3 ± 0.5	41.6± 0.3	46.8± 0.5	20.3± 0.2	35.2± 0.2	39.0 ± 0.2
	MSE + CE	47.4 ± 0.2	56.2 ± 0.0	41.7 ± 0.5	47.1 ± 0.1	20.5 ± 0.4	38.3 ± 0.3	40.5 ± 0.2
	Soft CE + CE	39.7 ± 0.3	51.1 ± 0.4	32.6 ± 0.5	43.2 ± 0.2	15.2 ± 0.4	29.1 ± 0.8	34.7 ± 0.6
GIFT (ours)		**50.6 ± 0.3** (↑ 2.4)	**57.9 ± 0.2** (↑ 1.6)	**44.0 ± 0.2**(↑ 2.3)	**48.3 ± 0.1** (↑ 1.0)	**24.0 ± 0.8**(↑ 3.3)	**39.5 ± 0.1** (↑ 0.7)	**42.5± 0.1** (↑ 0.6)

5.6 Application: Continual Learning

Following prior studies (Zhao & Bilen, 2023; Kim et al., 2022; Yin et al., 2023) that leverage synthetic datasets in continual learning to assess the quality of synthetic data, we employ the GDumb framework (Prabhu et al., 2020) for our continual learning setup. This framework sequentially stores prior training data in memory and utilizes both new and stored data for model training.

We conduct class-incremental learning on Tiny-ImageNet with an `IPC` =10 using ResNet-18. Figure 2 illustrates both 5-step and 10-step class-incremental learning strategies, partitioning the 200 classes into either 5 or 10 learning steps, corresponding to 40 and 20 classes per step, respectively. It is evident that *our results substantially improve upon the baseline method RDED* [7].



(a) 5-step (b) 10-step

Figure 2: **5-step and 10-step class-incremental learning on Tiny-ImageNet on ResNet-18**.

5.7 Ablation Study

Is Our Loss Function the Best? To validate the superiority of GIFT, we compare with existing loss functions, utilizing both hard and soft labels. The results, presented in Table 9, clearly demonstrate that GIFT *consistently outperforms other loss functions and their combinations*.

For hard label utilization, the cross-entropy (CE) loss exhibits subpar performance, mainly due to the limited information content in typically small synthetic datasets. For soft label utilization, Jensen-Shannon (JS) divergence loss marginally outperforms the KL divergence, consistent with observations in (Kim et al., 2021). In summary, existing loss functions in synthetic datasets fail to fully exploit the potential of all labels. In contrast, our method leverages both hard and soft labels simultaneously, thereby maximizing label utilization potential and improving performance.

Are Both Modules of GIFT Necessary? We conduct an ablation study to assess the necessity of the label refinement and cosine similarity loss function on the small-scale dataset in Table 10 and the large-scale dataset ImageNet-1K in Table 17 in Appendix D. We compare the complete method with variants lacking either the teacher label refinement or the cosine similarity loss function. In the absence of both modules, the method is trained using its native loss function.

It is obvious that when only one module is employed, the cosine similarity loss function significantly enhances performance due to its direct label utilization. Label refinement consistently enhances per-

[7] RDED is the current state-of-the-art method as shown in Table 1, so we conduct the experiment on its synthetic datasets.

Table 10: **Ablation study of label refinement (Refine) and cosine similarity loss function (Loss) on CIFAR 100 and Tiny-ImageNet when `IPC` =10.** This evaluation is conducted on both optimization-based (SRe^{2}L (Yin et al., 2023)) synthetic datasets and non-optimization-based (RDED (Sun et al., 2024)) synthetic datasets.

	GIFT		CIFAR100			Tiny-ImageNet		
DD Method	Refine	Loss	1	10	50	1	10	50
SRe^{2}L	✗	✗	13.6 ± 0.4	33.7 ± 0.5	52.3 ± 0.2	12.1 ± 0.4	34.5 ± 0.4	46.3 ± 0.1
	✓	✗	14.2 ± 0.4 (↑ 0.6)	34.5 ± 0.5 (↑ 0.8)	52.8 ± 0.5 (↑ 0.5)	12.5 ± 0.4 (↑ 0.4)	35.1 ± 0.4 (↑ 0.6)	46.6 ± 0.3 (↑ 0.3)
	✗	✓	14.7 ± 0.4 (↑ 1.1)	37.3 ± 0.4 (↑ 3.6)	54.6 ± 0.1 (↑ 2.3)	12.7 ± 0.4 (↑ 0.6)	36.9 ± 0.3 (↑ 2.4)	46.9 ± 0.1 (↑ 0.6)
	✓	✓	15.1 ± 0.3 (↑ 1.5)	38.0 ± 0.5 (↑ 4.3)	55.4 ± 0.1 (↑ 3.1)	13.1 ± 0.2 (↑ 1.0)	37.5 ± 0.3 (↑ 3.0)	47.1 ± 0.1 (↑ 0.8)
RDED	✗	✗	22.1 ± 0.3	47.5 ± 0.3	55.7 ± 0.4	17.9 ± 0.3	41.4 ± 0.3	47.2 ± 0.1
	✓	✗	22.9 ± 0.3 (↑ 0.8)	48.0 ± 0.3 (↑ 0.5)	56.3 ± 0.1 (↑ 0.6)	18.2 ± 0.3 (↑ 0.3)	41.9 ±0.4 (↑ 0.5)	48.1 ± 0.2 (↑ 0.9)
	✗	✓	23.8 ± 0.2 (↑ 1.7)	49.5 ± 0.2 (↑ 2.0)	57.0 ± 0.1 (↑ 1.3)	18.5 ± 0.3 (↑ 0.6)	42.9 ± 0.2 (↑ 1.5)	47.5 ± 0.1 (↑ 0.3)
	✓	✓	24.7 ± 0.3 (↑ 2.6)	50.6 ± 0.3 (↑ 3.1)	57.9 ± 0.2 (↑ 2.2)	19.1 ± 0.3 (↑ 1.2)	44.0 ± 0.2 (↑ 2.6)	48.3 ± 0.1 (↑ 1.1)

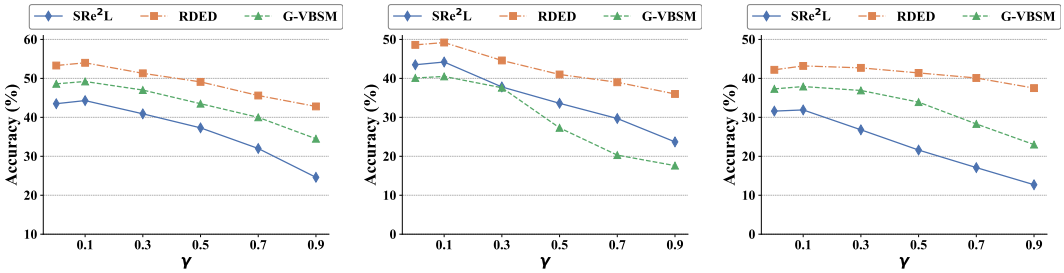
formance, regardless of the presence of cosine similarity loss function, demonstrating its effectiveness. *Thus, both modules are essential for enhancement, consistent with our analysis in Section 4*.

Moreover, to verfiy the efficacy of label refinement, we compare the label accuracy before and after refinement. The results, shown in Figure 10 in Appendix D, demonstrate that it leads to significant performance improvements, highlighting the critical role of the proposed label refinement.

Influence of Hyper-parameter γ. We examine the impact of the weight hyperparameter γ, defined in Section 4. As shown in Figure 3, GIFT *achieves optimal performance when* $\gamma = 0.1$ *across various datasets*. This consistency is attributed to the fact that the soft labels are generated by pre-trained models. Specifically, both RDED and SRe^{2}L utilize the same pre-trained model.

Notably, for values of γ greater than 0.1, a significant performance decline is observed across all methods as γ increases. A plausible explanation is that larger values of γ diminish the intra-class information content in soft labels. This observation aligns with our findings in Table 9, where training with exclusively hard labels via CE results in poor performance. To verify that $\gamma = 0.1$ is also optimal for different settings, we conduct experiments on different network architectures and augmentation, as shown in Figure 8 and Figure 9 in Appendix D.

Can GIFT Enhance utilization of Hard and Smoothed Labels? *To evaluate the efficacy of GIFT across various data types*, we conduct experiments on both distilled and randomly selected datasets, employing hard and smoothed labels. The results are presented in Table 18 and Table 19 in Appendix D. Obviously, GIFT *consistently enhances label utilization across various label types.*



(a) CIFAR-100 (b) Tiny-ImageNet (c) ImageNet-1K

Figure 3: Top-1 accuracy (%) for the state-of-the-art dataset distillation methods on various synthetic datasets when `IPC` =10 on ResNet-18 with different γ.

6 Conclusion and Limitation

This work introduces a novel perspective on dataset distillation by emphasizing the full utilization of synthetic labels. We first conduct a comprehensive comparison of existing loss functions used for soft labels in dataset distillation. Our findings reveal that models trained on synthetic datasets exhibit significant sensitivity to the choice of loss function. Based on these insights, we propose a simple yet effective plug-and-play method, GIFT, designed to fully exploit synthetic labels. Experimental results across various scales and resolutions of image datasets demonstrate that GIFT consistently outperforms state-of-the-art dataset distillation algorithms. In this work, we mainly focus on the image classification task. However, we believe the extensions of this work to other tasks such as text data (Devlin et al., 2018) and architectures like LSTM (Graves & Graves, 2012).

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A PROOF OF THEOREM 1

Proof. The InfoNCE loss is defined as:

$$\mathcal{L}_{\text{InfoNCE}} = -\mathbb{E}\left[\log \frac{\exp(\text{sim}(z_i, y_i)/\tau)}{\sum_{j=1}^{N} \exp(\text{sim}(z_i, y_j)/\tau)}\right] \tag{4}$$

where $\text{sim}(z_i, y_i)$ represents the cosine similarity between x_i and y_i:

$$\text{sim}(z_i, y_i) = \frac{z_i \cdot y_i}{\|z_i\|\|y_i\|} \tag{5}$$

Substituting the expression for cosine similarity into the InfoNCE loss:

$$\begin{aligned}
\mathcal{L}_{\text{InfoNCE}} &= -\mathbb{E}\left[\log \frac{\exp\left(\frac{z_i \cdot y_i}{\|z_i\|\|y_i\|\tau}\right)}{\sum_{j=1}^{N} \exp\left(\frac{z_i \cdot y_j}{\|z_i\|\|y_j\|\tau}\right)}\right] \\
&= -\mathbb{E}\left[\log \exp\left(\frac{z_i \cdot y_i}{\|z_i\|\|y_i\|\tau}\right) - \log \sum_{j=1}^{N} \exp\left(\frac{z_i \cdot y_j}{\|z_i\|\|y_j\|\tau}\right)\right] \\
&= -\mathbb{E}\left[\left(\frac{z_i \cdot y_i}{\|z_i\|\|y_i\|\tau}\right) - \log \sum_{j=1}^{N} \exp\left(\frac{z_i \cdot y_j}{\|z_i\|\|y_j\|\tau}\right)\right] \\
&= -\mathbb{E}\left[\left(\frac{z_i \cdot y_i}{\|z_i\|\|y_i\|\tau}\right)\right] + \mathbb{E}\left[\log \sum_{j=1}^{N} \exp\left(\frac{z_i \cdot y_j}{\|z_i\|\|y_j\|\tau}\right)\right]
\end{aligned} \tag{6}$$

Applying Jensen's inequality to the logarithm:

$$\mathcal{L}_{\text{InfoNCE}} \leq -\mathbb{E}\left[\left(\frac{z_i \cdot y_i}{\|z_i\|\|y_i\|\tau}\right)\right] + \log\left(\mathbb{E}\left[\sum_{j=1}^{N} \exp\left(\frac{z_i \cdot y_j}{\|z_i\|\|y_j\|\tau}\right)\right]\right) \tag{7}$$

Assuming the negative samples y_j are drawn from a similar distribution, we approximate the denominator:

$$\sum_{j=1}^{N} \exp\left(\frac{z_i \cdot y_j}{\|z_i\|\|y_j\|\tau}\right) \approx N \exp\left(\frac{\mathbb{E}[z_i \cdot y_j]}{\|z_i\|\mathbb{E}[\|y_j\|]\tau}\right) \tag{8}$$

Substituting this approximation into the upper bound:

$$\boxed{\mathcal{L}_{\text{InfoNCE}} \leq -\frac{1}{\tau}\left(\mathbb{E}\left[\left(\frac{z_i \cdot y_i}{\|z_i\|\|y_i\|}\right)\right] - \frac{\mathbb{E}[z_i \cdot y_j]}{\|z_i\|\mathbb{E}[\|y_j\|]}\right) + \log(N)} \tag{9}$$

□

B RELATED WORK

B.1 DATASET DISTILLATION

In the field of dataset distillation, the majority of existing methods fix the labels as a one-hot format (Wang et al., 2018; Zhao et al., 2020; Zhao & Bilen, 2022; Cazenavette et al., 2022; Kim et al., 2022; Liu et al., 2022; Zhao & Bilen, 2023), with a primary focus on optimizing synthetic images. Recent research highlights the significant benefits of utilizing soft labels to enhance model performance (Sun et al., 2024; Guo et al., 2024; Yin et al., 2023). These benefits are particularly pronounced when training models on extremely small synthetic datasets, due to the enriched intra-class information soft labels provide. Methods for obtaining soft labels can be broadly classified into two categories.

Optimization-based Soft Labels. The first type involves learning labels, with several studies (Bohdal et al., 2020; Nguyen et al., 2020; Sucholutsky & Schonlau, 2021; Zhou et al., 2022; Deng & Russakovsky, 2022; Guo et al., 2024) finding that making labels learnable can significantly improve performance and efficiency. LD (Bohdal et al., 2020) first introduces label distillation and reveals that even only learning labels without learning images can achieve satisfactory performance with high efficiency. Recent work (Guo et al., 2024) further highlights that optimizing labels can enhance training stability and improve performance.

Teacher model-based soft labels. The subsequent works directly obtain soft labels. Inspired by knowledge distillation (Hinton et al., 2015), TESLA (Cui et al., 2023)introduces a soft label assignment strategy, directly generating soft labels by leveraging pre-trained teacher models trained on real datasets. These soft labels provide rich intra-class information, thereby improving distillation performance. Following this trend, the state-of-art methods (Yin et al., 2023; Sun et al., 2024; Shao et al., 2024) also utilize soft labels predicted by teacher models, achieving significant improvements.

B.2 Knowledge Distillation

A straightforward method to simultaneously utilize soft and hard labels is knowledge distillation (Hinton et al., 2015), which transfers knowledge from a large teacher model to a small student model. In this training process, the student model is supervised by hard labels and soft labels from the teacher's output. Many following works aim to enhance the use of soft labels for more effective knowledge transfer. (Yuan et al., 2020) investigated the regularization property of soft labels and introduced a teacher-free distillation approach. WSLD (Zhou et al., 2021) analyzes soft labels and distributes different weights for them from a perspective of bias-variance trade-off. DKD (Zhao et al., 2022) decouples the logit and assigns different weights for the target and non-target classes.

Despite the promising potential of knowledge distillation in transferring knowledge from teacher to student models using soft labels, its application to our problem yields limited improvement. A detailed analysis and comparison of these limitations are provided in Section 5.3.

C Experiment Details

Datasets. As described in Section 5.1, we evaluate the state-of-the-art dataset distillation methods and our proposed GIFT on both small-scale and large-scale datasets. More Information about datasets utilized are listed in Table 11.

Table 11: Details about the datasets

Dataset	Num of Classes	IPC of Trainset	IPC of Testset
CIFAR-10	10	5000	1000
CIFAR-100	100	500	100
Tiny-ImageNet	200	500	50
ImageNet-1k	1000	732 - 1300	50

Models. The experiment utilized a plethora of pre-trained models, and we provided the accuracy of these pre-trained models in the Table 12. The results are provided for reference only.

Baselines. To elucidate the rationale behind our method selection for comparison, we categorize current state-of-the-art methods based on two key factors: scalability to ImageNet-1K and the utilization of soft labels. These categorizations are summarized in Table 13.

Given that our primary focus is on enhancing the use of soft labels in dataset distillation, we restrict our comparisons to methods that involve soft labels:

- TESLA (Cui et al., 2023) marks the first distillation approach that *extends to the full ImageNet-1K*, circumventing the extensive memory demands associated with MTT-derived

Table 12: Accuracy of pretrained models.

Dataset	Model	Size	Accuracy
CIFAR-10	resnet18_modified	32×32	93.86
	ConvNet-3	32×32	82.24
CIFAR-100	resnet18_modified	32×32	72.27
	ConvNet-3	32×32	61.27
Tiny-ImageNet	resnet18_modified	64×64	61.98
	ConvNet-4	64×64	49.73
ImageNet-1k	resnet18	224×224	69.31
	ConvNet-4	64×64	43.6

Table 13: **Categorize methods based on their utilization of soft labels and their scalability to ImageNet-1K.**

	RDED	CDA	G-VBSM	SRe2L	DATM	SeqMatch	DREAM	IDC	FTD	DataDAM	MTT	DM	DSA
Use Soft Label	✓	✓	✓	✓	✓	×	×	×	×	×	×	×	×
Scale to ImageNet-1K	✓	✓	✓	✓	×	×	✓	×	×	×	×	×	×

methods through a constant memory footprint. However, TESLA does not provide public synthesic datasets, so we are not able to conduct on it.

- SRe^{2}L (Yin et al., 2023) and RDED (Sun et al., 2024): both of them use soft labels assigned by a teacher model and use them via KL divergence.
- DATM (Guo et al., 2024): initial soft labels assigned by multiple teacher models and then optimized based on trajectory matching. Finally, this method employs soft cross-entropy loss for soft labels.
- G-VBSM (Shao et al., 2024): soft labels are assigned by multiple teacher models and then used via MSE-CE loss function.
- CDA (Yin & Shen, 2023): soft labels are assigned by a teacher model and are used via soft cross-entropy loss.

Knowledge distillation (Hinton et al., 2015) is a straightforward method to utilize labels, especially for soft labels. Therefore, we also compare our method GIFT with the state-of-the-art knowledge distillation methods that focus on soft labels utilization:

- KD (Hinton et al., 2015): it is the first method to transfer knowledge using both hard and soft labels from the teacher's output.
- WSLD (Zhou et al., 2021): it analyzes soft labels and then distributes different weights for them from a perspective of bias-variance trade-off.
- DKD (Zhao et al., 2022): it decouples the logits and assigns different weights for the target and non-target classes.
- NKD (Yang et al., 2023): it finds the sum of the two non-target logits is different, preventing logits' distributions from being identical. Therefore, it normalizes the non-target logits to equalize their sum.

Evaluating main results. For both dataset distillation and performance evaluation, we employ identical neural network architectures. Consistent with previous studies (Cazenavette et al., 2022; Cui et al., 2023; Zhao et al., 2023), we use Conv-3 for CIFAR-10 and CIFAR-100 distillation tasks, Conv-4 for Tiny-ImageNet (with the exception of DREAM, which utilizes Conv-3) and ImageNet-1K, Conv-5 for ImageNet-10, and Conv-6 for ImageNet-100 distillation. In line with (Cazenavette et al., 2022; Cui et al., 2023), MTT and TESLA apply a reduced resolution for distilling 224×224 images. According to (Yin et al., 2023), for retrieving and evaluating distilled datasets, SRe^{2}L and GIFT adopt ResNet-18.

Evaluating the distilled dataset. Consistent with recent works (Yin et al., 2023; Shao et al., 2024), the evaluation on the distilled dataset follows the parameters outlined in Table 15. Furthermore, we implement Differentiable Siamese Augmentation (DSA) as described by (Zhao & Bilen, 2021) to enhance images during both the distillation and evaluation phases of our experiments.

Differentiable Siamese Augmentation (DSA). We use DSA (Differentiable Siamese Augmentation) as a tool for image augmentation. For the sake of clarity, we delineate the DSA operations utilized in Table 14, alongside their respective transforms and probabilities.

Table 14: Differentiable Siamese Augmentation(DSA) and ratios

DSA	Transform	Ratio
Color	Color Jitter	Brightness=1.0 Saturation=2.0 Contrast=0.5
Crop	Random Crop	Crop Pad=0.125
Cutout	Random Cutout	Cutout=0.5
Flip	Random Horizontal Flip	Flip=0.5
Scale	Random Scale	Scale=1.2
Rotate	Random Rotation	Rotate=15.0

Table 15: Evaluation Hyperparameter setting

Config	Value	Explanation
Epochs	300/1000	300 for ImageNet-1k, 1000 for default
Optimizer	AdamW	NA
Learning Rate	0.001	NA
Batch Size	10/50/100/200	10 for $0 <$ Num of Images ≤ 10, 50 for $10 <$ Num of Images ≤ 500, 100 for $500 <$ Num of Images ≤ 20000, 200 for $20000 <$ Num of Images
Scheduler	MultiStepLR	milestones=[$2 \times$ epochs // 3, $5 \times$ epochs // 6] gamma=0.2
Augmentation	DSA strategy	color, crop, cutout, flip, scale, rotate

D EXPERIMENT RESULTS

Comprehensive Comparison Between Different Loss Functions Our experiments span two datasets, including Tiny-ImageNet, and ImageNet-1K on $\texttt{IPC} \in \{1, 10, 50\}$ using ConvNet (**?**). Note that the synthetic dataset for DATM on ImageNet-1K is unavailable, precluding comparisons on this dataset. We evaluate at $\texttt{IPC} \in \{1, 10, 50\}$. The results, visualized in Figure 4, Figure 6, Figure 5 and Figure 7, reveal that ***the performance of models trained on synthetic datasets is highly sensitive to the choice of the loss function***, highlighting the necessity for a unified and effective loss function in dataset distillation.

Influence of Hyper-parameter γ on ConvNet. We also examined the impact of the hyper-parameter γ using ConvNet, and the results are shown in Figure 8. Similar to the findings with ResNet, GIFT *achieves optimal performance when* $\gamma = 0.1$.

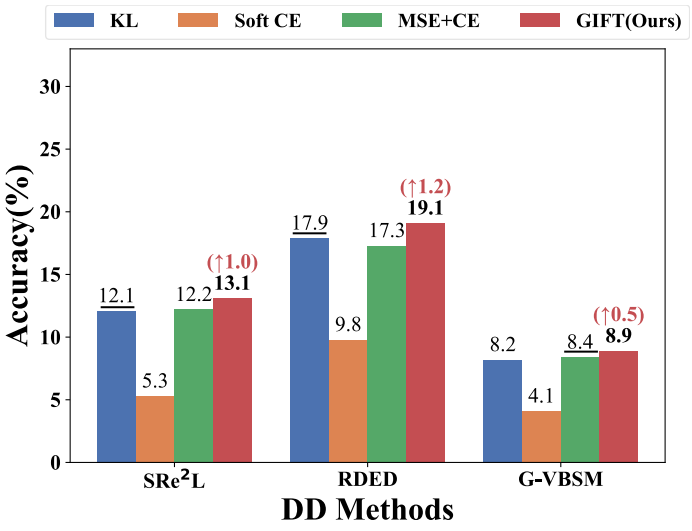


Figure 4: Top-1 accuracy on various synthetic datasets via the SOTA dataset distillation methods across loss functions on Tiny-ImageNet when IPC=1.

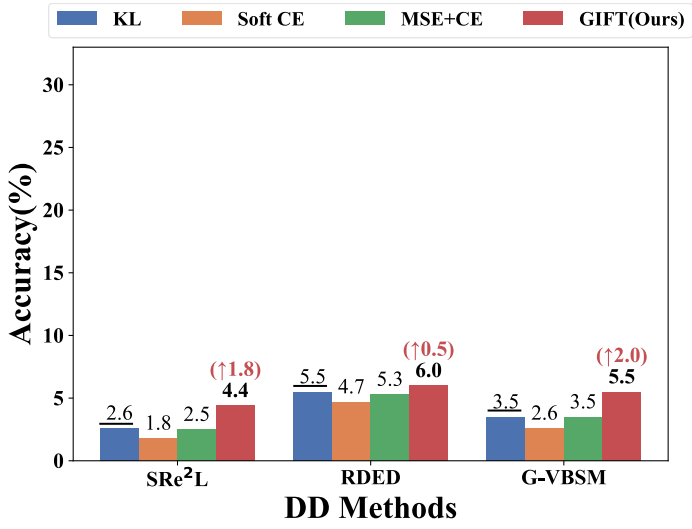


Figure 5: Top-1 accuracy on various synthetic datasets via the SOTA dataset distillation methods across loss functions on ImageNet-1K when IPC=1.

Table 16: **Top-1 accuracy on cross-optimization generalization on ImageNet-1K when IPC=10.**We evaluate the performance of synthetic datasets across various optimizers.

ImageNet-1K						
Dataset	ConvNet			ResNet		
Method	SGD	Adam	AdamW	SGD	Adam	AdamW
SRe^{2}L	0.1 ± 0.0	0.1 ± 0.0	12.5 ± 0.1	0.1 ± 0.	0.1 ± 0.0	31.5 ± 0.3
SRe^{2}L + Ours	18.2 ± 0.2 (↑ 18.1)	26.6 ± 0.2 (↑ 26.5)	14.2 ± 0.6 (↑ 1.7)	36.1 ± 0.1 (↑ 36.0)	24.5 ± 0.2 (↑ 24.4)	31.9 ± 0.2 (↑ 0.4)
RDED	0.1 ± 0.0	0.1 ± 0.0	20.1 ± 0.4	0.1 ± 0.0	0.1 ± 0.0	41.4 ± 0.4
RDED + Ours	26.7 ± 0.6 (↑ 26.5)	30.9 ± 0.7 (↑ 26.5)	24.0 ± 0.8 (↑ 3.2)	45.8 ± 0.4 (↑ 30.8)	29.1 ± 0.3 (↑ 29.0)	43.2 ± 0.1 (↑ 1.8)
G-VBSM	20.4 ± 0.8	25.0 ± 0.4	22.6 ± 0.5	38.7 ± 0.2	27.0 ± 0.2	36.7 ± 0.2
G-VBSM + Ours	27.4 ± 0.8 (↑ 7.0)	29.8 ± 0.5 (↑ 4.8)	24.3 ± 0.2 (↑ 1.7)	41.8 ± 0.1 (↑ 3.1)	27.8 ± 0.8 (↑ 0.8)	37.9 ± 0.5 (↑ 1.2)

Ablation study on ImageNet-1K. We also conducted an ablation study to assess the necessity of the teacher label refinement and cosine similarity loss function on the large-scale dataset in Table 17. This evaluation was performed on both optimization-based (SRe^{2}L) and non-optimization-based

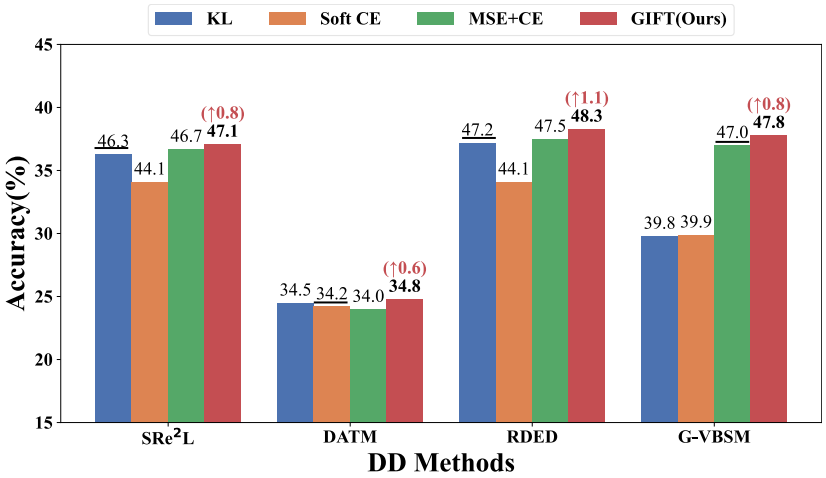


Figure 6: Top-1 accuracy on various synthetic datasets via the SOTA dataset distillation methods across loss functions on Tiny-ImageNet when IPC=50.

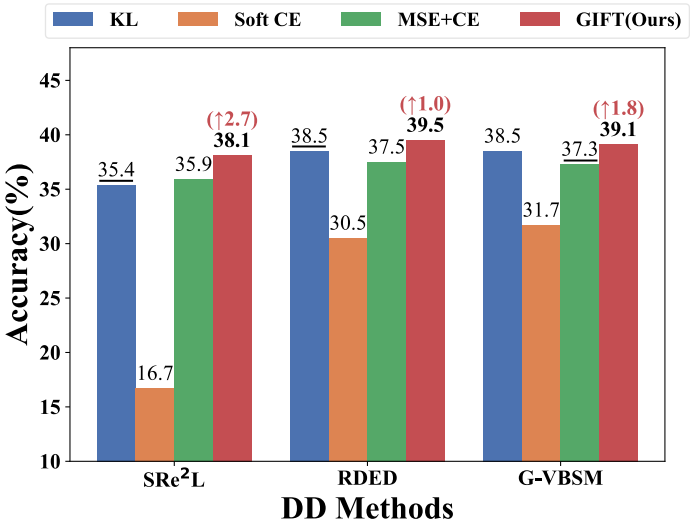
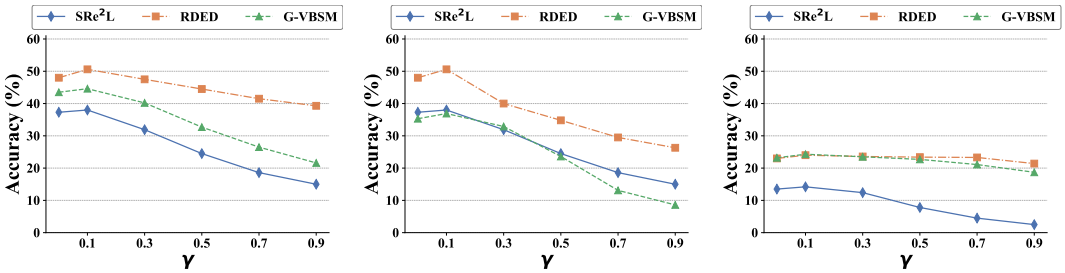


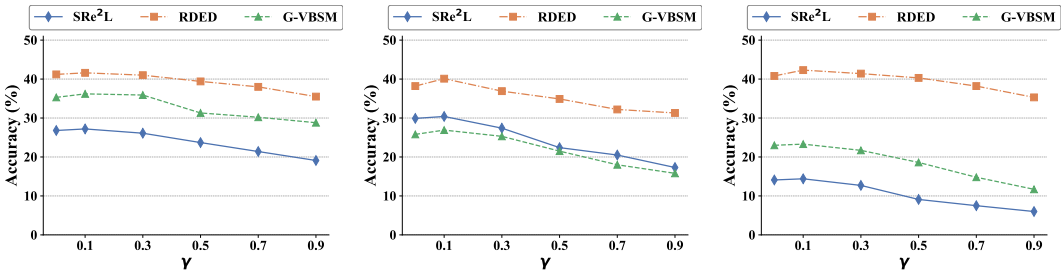
Figure 7: Top-1 accuracy on various synthetic datasets via the SOTA dataset distillation methods across loss functions on ImageNet-1K when IPC=50.



(a) CIFAR-100 (b) Tiny-ImageNet (c) ImageNet-1K

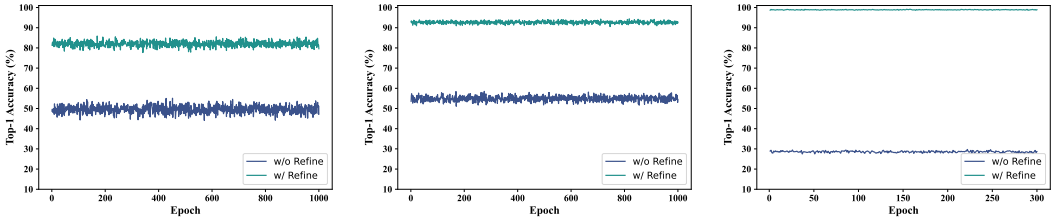
Figure 8: Top-1 accuracy for the SOTA dataset distillation methods on various synthetic datasets when `IPC` =10 on ConvNet with different γ.

(RDED) synthetic datasets. It is obvious *both modules are essential for performance enhancement, consistent with our analysis in* *Section 4*.



(a) CIFAR-100 (b) Tiny-ImageNet (c) ImageNet-1K

Figure 9: Top-1 accuracy for the SOTA dataset distillation methods on various synthetic datasets with different data augmentation techniques when IPC =10 on ResNet-18 with different γ.



(a) CIFAR-100 (b) Tiny-ImageNet (c) ImageNet-1K

Figure 10: Top-1 accuracy for the SOTA dataset distillation methods on various synthetic datasets when IPC =10 on ResNet-18.

Efficacy of Label Refinement. The necessity of incorporating hard labels into the soft labels generated by teacher models arises from the inherent limitations in the performance of these teacher models. Specifically, the test accuracies of teacher models are only 61.27%, 49.73%, and 43.6% for CIFAR-100, Tiny-ImageNet, and ImageNet-1K, respectively, when trained on commonly used ConvNet architectures in dataset distillation. Consequently, the accuracy of soft labels is constrained by the suboptimal nature of the teacher models. To mitigate potential inaccuracies in these soft labels, we integrate hard labels to enhance reliability.

To verify the efficacy of the label refinement, we record the label accuracy before and after refinement across each training epoch for three datasets. The parameter γ, controlling the integration ratio, is set to 0.1. As depicted in Figure 10, refining soft labels results in significant performance improvements of 37.1%, 40.95%, and 71.39% for CIFAR-100, Tiny-ImageNet, and ImageNet-1K, respectively, highlighting the critical role of the proposed label refinement.

Cross-Optimizaer on ImageNet-1K In this experiment, we report the accuracy before and after applying our GIFT to baseline methods across multiple optimizers not seen during dataset distillation onImageNet-1K , as shown in Table 16. The results clearly indicate that GIFT *enhances the generalization ability of all baseline methods.* This leads to more stable gradients, especially in scenarios with small dataset sizes.

GIFT Enhance Utilization of Hard and Smoothed Labels To evaluate the efficacy of GIFT across various data types, we conduct experiments on both distilled and randomly selected datasets, employing hard and smoothed labels, with IPC =10. (1) For the distilled dataset, we use the state-of-the-art dataset distillation method, RDED, which uses soft labels generated by teacher models. In the experiments, we maintain the distilled images and replace soft labels with hard and smoothed labels for model training. (2) For random dataset, we randomly select 10 images for each class from the original dataset. The results for two types of data are presented in Table 18 and Table 19. It is evident that *applying our method to label utilization consistently improves performance for both the distilled and the randomly selected data.*

Table 17: **Ablation study of label refinement (Refine) and cosine similarity loss function (Loss) on ImageNet-1K.** In the table, (↑) means the improvements over these methods.

	ImageNet-1K					
	ConvNet			ResNet-18		
Method	10	50	100	10	50	100
SRe^{2}L	12.5 ± 0.3	35.4 ± 1.0	40.1 ± 0.4	31.5 ± 0.3	49.5 ± 0.1	54.3 ± 0.2
SRe^{2}L + Refine	13.3 ± 0.4 (↑ 0.8)	36.3 ± 0.4 (↑ 0.9)	40.5 ± 0.4 (↑ 0.4)	31.8 ± 0.3 (↑ 0.3)	49.7 ± 0.3 (↑ 0.2)	54.5 ± 0.1 (↑ 0.2)
SRe^{2}L + Loss	13.1 ± 0.6 (↑ 0.6)	36.8 ± 0.3 (↑ 1.2)	40.7 ± 0.3 (↑ 0.6)	31.7 ± 0.2 (↑ 0.2)	49.8 ± 0.2 (↑ 0.3)	54.5 ± 0.2 (↑ 0.2)
SRe^{2}L + Refine + Loss	14.2 ± 0.6 (↑ 1.7)	38.1 ± 0.4 (↑ 2.7)	41.5 ± 0.2 (↑ 1.4)	31.9 ± 0.1 (↑ 0.4)	50.1 ± 0.2 (↑ 0.6)	54.8 ± 0.1 (↑ 0.5)
RDED	20.1 ± 0.4	38.5 ± 0.2	41.8 ± 0.2	41.4 ± 0.4	55.5 ± 0.2	58.8 ± 0.1
RDED + Refine	21.2 ± 0.5 (↑ 1.2)	38.7 ± 0.2 (↑ 0.2)	42.3 ± 0.4 (↑ 0.5)	42.3 ± 0.2 (↑ 0.9)	55.8 ± 0.3 (↑ 0.3)	59.2 ± 0.3 (↑ 0.4)
RDED + Loss	21.7 ± 0.6 (↑ 1.6)	39.3 ± 0.1 (↑ 0.8)	42.1 ± 0.1 (↑ 0.3)	42.0 ± 0.2 (↑ 0.6)	55.9 ± 0.1 (↑ 0.4)	59.1 ± 0.1 (↑ 0.3)
RDED + Refine + Loss	24.0 ± 0.8 (↑ 3.9)	39.5 ± 0.1 (↑ 1.0)	42.5± 0.1 (↑ 0.7)	43.2 ± 0.1 (↑ 1.8)	56.5 ± 0.2 (↑ 1.0)	59.3± 0.1 (↑ 0.5)
G-VBSM	22.6 ± 0.5	37.3 ± 0.3	40.1 ± 0.4	36.7 ± 0.2	52.3 ± 0.1	57.3 ± 0.1
G-VBSM + Refine	23.3 ± 0.4 (↑ 0.7)	37.8 ± 0.3 (↑ 0.5)	40.9 ± 0.3 (↑ 0.7)	37.2 ± 0.3 (↑ 0.5)	52.7 ± 0.2 (↑ 0.4)	57.5 ± 0.2 (↑ 0.2)
G-VBSM + Loss	23.8 ± 0.2 (↑ 1.2)	38.3 ± 0.4 (↑ 1.0)	41.8 ± 0.3 (↑ 1.7)	37.5 ± 0.5 (↑ 0.8)	52.8 ± 0.2 (↑ 0.5)	57.4 ± 0.1 (↑ 0.1)
G-VBSM + Refine + Loss	24.3 ± 0.2 (↑ 1.7)	39.1 ± 0.3 (↑ 1.8)	42.1 ± 0.3 (↑ 2.0)	37.9 ± 0.5 (↑ 1.2)	53.1 ± 0.2 (↑ 0.8)	57.6 ± 0.1 (↑ 0.3)

Table 18: Evaluation of Loss Functions Across Hard and Smoothed Labels on the Distilled Data Generated via RDED with `IPC` =10.

Label Type	Loss Function	CIFAR100	Tiny-ImageNet	ImageNet-1K
Hard	CE	21.6 ± 0.2	13.5 ± 0.3	8.3 ± 0.4
	Ours	22.8 ± 0.2 (↑ 1.2)	14.8 ± 0.3 (↑ 1.3)	9.8 ± 0.2 (↑ 1.5)
Smoothed	SoftCE	21.9 ± 0.2	13.8 ± 0.2	8.5 ± 0.2
	KL	21.7 ± 0.3	13.3 ± 0.3	8.0 ± 0.3
	MSE	22.1 ± 0.1	14.1 ± 0.1	8.8 ± 0.3
	Ours	23.1 ± 0.2 (↑ 1.0)	15.2 ± 0.3 (↑ 1.1)	10.2 ± 0.2 (↑ 1.4)

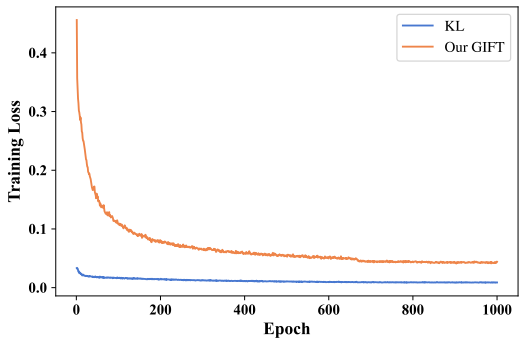
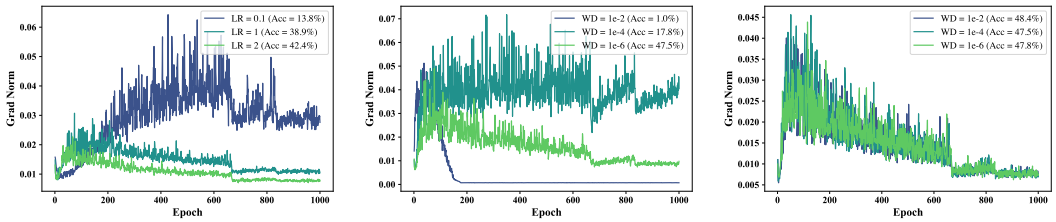


Figure 11: Comparison of Training Loss Between KL and Our GIFT Across Training Epochs



(a) SGD (b) Adam (c) AdamW

Figure 12: Gradient Norms Across Various Optimizers and Hyperparameters.

E Emperical And Theoretical Analysis of Cross-Optimizer Generalization

We begin by analyzing the three optimizers, namely:

Table 19: Evaluation of Loss Functions Across Hard and Smoothed Labels on the Randomly Selected Data with IPC=10.

Label Type	Loss Function	CIFAR100	Tiny-ImageNet	ImageNet-1K
Hard	CE	18.9 ± 0.3	9.4 ± 0.1	4.0 ± 0.3
	Ours	20.3 ± 0.1 (↑ 1.4)	11.6 ± 0.1 (↑ 2.2)	5.1 ± 0.2 (↑ 1.1)
Smoothed	SoftCE	19.0 ± 0.3	9.8 ± 0.3	4.5 ± 0.2
	KL	17.9 ± 0.2	8.5 ± 0.3	3.9 ± 0.1
	MSE	19.2 ± 0.1	9.7 ± 0.2	4.6 ± 0.3
	Ours	20.4 ± 0.2 (↑ 1.2)	11.8 ± 0.2 (↑ 2.0)	5.6 ± 0.2 (↑ 1.0)

- SGD (Robbins & Monro, 1951) directly computes gradients from loss values, significantly impacting the update of model parameters.
- Adam (Kingma & Ba, 2014) includes weight decay in the gradient computation, meaning that *when the primary gradient signal (from the loss) is small, weight decay can overshadow it, leading to ineffective updates toward minimizing the loss.
- AdamW (Loshchilov, 2017) separates the concerns of optimization and regularization. By applying weight decay independently, it ensures that the optimization process remains focused on minimizing the loss function, while regularization acts as a controlled adjustment to the parameter magnitudes.

Optimizers inherently exhibit diverse characteristics, resulting in distinct training dynamics when applied to distilled datasets generated by various methods. Specifically, *these distilled datasets, trained with varying loss functions, exhibit distinct loss values.* We reveal that the performance of the optimizers is ***highly influenced*** by these loss values, as demonstrated by the subsequent empirical evidence and theoretical analysis.

E.1 Emperical Analysis

When employing the KL divergence loss function, the RDED generally exhibits low loss values, as depicted in Figure 11. Notably, our GIFT framework does not achieve small loss values.

To examine the impact of loss values on optimizer performance, we conduct experiments utilizing RDED-generated distilled data. We train models using three distinct optimizers, each with distinct hyperparameter configurations, and compute the gradient norm for each. Specifically, we varied the learning rate for the SGD optimizer and modified the weight_decay parameter for both the Adam and AdamW optimizers.

The gradient norms of these models, presented in Figure 12, demonstrate that when loss values are small, the training dynamics exhibit heightened sensitivity to the optimizer choice. Therefore, the performances of different optimizers are highly influenced by the loss values. Notably, our GIFT framework can not obtain small loss values, achieving robust performance across various optimizers.

E.2 Theoretical Analysis

E.2.1 Stochastic Gradient Descent (SGD)

Stochastic Gradient Descent (SGD) is a foundational optimization algorithm widely used for training machine learning models, particularly neural networks. SGD iteratively updates model parameters to minimize the loss function by moving in the direction of the negative gradient of the loss with respect to the parameters.

SGD Update Rules. Define the following:

- θ_t: Parameters at time step t.
- $g_t = \nabla_\theta L(\theta_{t-1})$: Gradient of the loss function L with respect to parameters θ at time step $t-1$.

- η: Learning rate.

The basic SGD update rule is:

$$\theta_t = \theta_{t-1} - \eta g_t$$

Sensitivity to Loss Values in SGD. The gradient $g_t = \nabla_\theta L(\theta_{t-1})$ indicates the direction and magnitude of change needed to minimize the loss function. Larger loss function values typically result in larger gradients. Therefore, in SGD, both the loss values and the learning rate η directly affect the model updates.

E.2.2 ADAM OPTIMIZER

Adam (Adaptive Moment Estimation) is an optimization algorithm that combines the advantages of two extensions of stochastic gradient descent: Adaptive Gradient Algorithm (AdaGrad) and Root Mean Square Propagation (RMSProp). Adam maintains per-parameter learning rates adapted based on the first and second moments of the gradients.

Adam Update Rules. Define the following:

- θ_t: Parameters at time step t.
- $g_t = \nabla_\theta L(\theta_{t-1})$: Gradient of the loss function L with respect to parameters θ at time step $t-1$.
- m_t: First moment estimate (exponentially decaying average of past gradients).
- v_t: Second moment estimate (exponentially decaying average of past squared gradients).
- β_1, β_2: Decay rates for the first and second moments, respectively.
- ϵ: Small constant to prevent division by zero.
- η: Learning rate.

The update rules are as follows:

$$\begin{aligned}
m_t &= \beta_1 m_{t-1} + (1-\beta_1) g_t \\
v_t &= \beta_2 v_{t-1} + (1-\beta_2) g_t^2 \\
\hat{m}_t &= \frac{m_t}{1-\beta_1^t} && \text{(Bias-corrected first moment)} \\
\hat{v}_t &= \frac{v_t}{1-\beta_2^t} && \text{(Bias-corrected second moment)} \\
\theta_t &= \theta_{t-1} - \eta \frac{\hat{m}_t}{\sqrt{\hat{v}_t} + \epsilon}
\end{aligned}$$

Weight Decay in Adam. In the original Adam implementation, weight decay is typically incorporated by adding an L_2 regularization term directly to the loss function:

$$L'(\theta) = L(\theta) + \frac{\lambda}{2} \|\theta\|_2^2$$

The gradient of the modified loss function with respect to θ is:

$$\nabla_\theta L'(\theta) = \nabla_\theta L(\theta) + \lambda \theta$$

Consequently, the gradient used in the Adam update rule is augmented with the weight decay term:

$$g_t = \nabla_\theta L(\theta_{t-1}) + \lambda \theta_{t-1}$$

Substituting this into the Adam update equations, the parameter update rule becomes:

$$\theta_t = \theta_{t-1} - \eta \frac{\hat{m}_t}{\sqrt{\hat{v}_t} + \epsilon}$$

Here, $\hat{m}_t$ and $\hat{v}_t$ incorporate the additional gradient component $\lambda \theta_{t-1}$.

E.2.3 ADAMW OPTIMIZER

AdamW is a modification of the Adam optimizer that decouples weight decay from the gradient-based update. AdamW addresses the intertwined nature of weight decay and gradient updates in the original Adam, leading to improved generalization performance and more stable training dynamics.

AdamW Update Rules. The primary distinction in AdamW lies in how weight decay is applied. Instead of incorporating weight decay into the gradient computation, AdamW applies it directly to the parameters after the standard Adam update. The update rule is expressed as:

$$\theta_t = \theta_{t-1} - \eta \frac{\hat{m}_t}{\sqrt{\hat{v}_t} + \epsilon} - \eta\lambda\theta_{t-1}$$

Alternatively, this can be broken down into two sequential steps:

$$\theta'_t = \theta_{t-1} - \eta \frac{\hat{m}_t}{\sqrt{\hat{v}_t} + \epsilon}$$
$$\theta_t = \theta'_t - \eta\lambda\theta_{t-1}$$

In this formulation:

- The first step performs the standard Adam gradient-based update. - The second step applies
- weight decay independently of the gradient computation.

Sensitivity to Loss Values in AdamW. By decoupling weight decay from the gradient-based update, AdamW mitigates the issue of weight decay dominating parameter updates when the loss $L(\theta)$ is small. In AdamW, the gradient-based update remains primarily responsible for minimizing the loss, while weight decay independently enforces regularization. This separation ensures that even when $\nabla_\theta L(\theta)$ is minimal, the optimizer can continue to adjust parameters based on the loss gradient without being overly constrained by the weight decay term.

When $L(\theta_{t-1})$ is small, $\nabla_\theta L(\theta_{t-1}) \approx 0$. In AdamW, the update rule is:

$$\theta_t = \theta_{t-1} - \eta \frac{\hat{m}_t}{\sqrt{\hat{v}_t} + \epsilon} - \eta\lambda\theta_{t-1}$$

The gradient-based update $-\eta \frac{\hat{m}_t}{\sqrt{\hat{v}_t}+\epsilon}$ remains tied to the loss gradient, allowing continued optimization of $L(\theta)$. Simultaneously, the weight decay term $-\eta\lambda\theta_{t-1}$ independently controls the magnitude of θ without influencing the direction dictated by the loss gradient. This ensures that weight decay does not overshadow the gradient-based updates, enabling effective model training even when the loss is minimal.

E.2.4 WHY EXCESSIVE WEIGHT DECAY IN ADAM IMPEDES UPDATES WHEN LOSS IS SMALL?

Adam's Update Mechanism Under Small Loss. Consider the Adam update rule with weight decay integrated into the gradient:

$$\theta_{t+1} = \theta_t - \eta \frac{\hat{m}_t}{\sqrt{\hat{v}_t} + \epsilon},$$

where $g_t = \nabla_\theta L(\theta_t) + \lambda\theta_t$ Assume that the loss $L(\theta_t)$ is sufficiently small, implying $\nabla_\theta L(\theta_t) \approx 0$. Thus $g_t \approx \lambda\theta_t$. Therefore, the update rule is expressed as:

$$\theta_{t+1} \approx \theta_t - \eta \frac{\lambda\theta_t}{\sqrt{v_t} + \epsilon} \approx \theta_t \left(1 - \frac{\eta\lambda}{\sqrt{v_t} + \epsilon}\right),$$

Here, the parameter θ_t is scaled by a factor less than 1 (assuming $\eta\lambda/(\sqrt{v_t} + \epsilon) > 0$), leading to a reduction in θ_t. If λ is large, the scaling factor can be significantly less than 1, causing θ_t to diminish rapidly. This aggressive shrinking overshadows the limited gradient from the loss function, effectively halting meaningful updates aimed at minimizing $L(\theta)$.

AdamW's Update Mechanism Under Small Loss. In AdamW, the update rule is:

$$\theta_{t+1} = \theta_t - \eta \frac{\hat{m}_t}{\sqrt{\hat{v}_t} + \epsilon} - \eta\lambda\theta_t$$

Even when $L(\theta_t)$ is small, the gradient-based update term $-\eta \frac{\hat{m}_t}{\sqrt{\hat{v}_t}+\epsilon}$ remains focused on minimizing the loss, while the weight decay term $-\eta\lambda\theta_t$ independently enforces regularization.

This separation ensures that:

- The optimization process remains primarily influenced by the loss gradient.
- Weight decay controls the magnitude of the parameters without dictating the direction of updates.

Thus, AdamW allows the model to continue optimizing $L(\theta_t)$ effectively, even when the loss is already minimal, while maintaining controlled regularization through weight decay.

F PYTORCH IMPLEMENTATION CODE

```python
# num_class : number of classes
# output : tensor of model outputs
# soft_label : Tensor, shape=[bsz, C]
# hard_label : Tensor, shape=[bsz, 1]
# alpha : smoothing parameter for label smoothing

def GIFT(num_class, output , soft_label, hard_label, alpha):
    # apply label smoothing to hard label
    smooth_label = label_smoothing(hard_label, num_class, alpha)

    # refine soft label
    soft_label = F.normalize(soft_label, dim=1)
    smooth_label = F.normalize(smooth_label, dim=1)
    refined_soft_labels = weight * smooth_label + (1 - weight) * soft_label

    # calculate the coisen similariy
    loss = F.cosine_similarity(output, refined_soft_labels, dim=1)
    return loss
```

Figure 13: Pytorch Implementation Code