Knowledge Distillation with the Reused Teacher Classifier

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Abstract

Knowledge distillation aims to compress a powerful yet cumbersome teacher model into a lightweight student model without much sacrifice of performance. For this purpose, various approaches have been proposed over the past few years, generally with elaborately designed knowledge representations, which in turn increase the difficulty of model development and interpretation. In contrast, we empirically show that a simple knowledge distillation technique is enough to significantly narrow down the teacher-student performance gap. We directly reuse the discriminative classifier from the pre-trained teacher model for student inference and train a student encoder through feature alignment with a single $\ell_2$ loss. In this way, the student model is able to achieve exactly the same performance as the teacher model provided that their extracted features are perfectly aligned. An additional projector is developed to help the student encoder match with the teacher classifier, which renders our technique applicable to various teacher and student architectures. Extensive experiments demonstrate that our technique achieves state-of-the-art results at the modest cost of compression ratio due to the added projector.

1. Introduction

Given a powerful teacher model with large numbers of parameters, the goal of knowledge distillation (KD) is to help another less-parameterized student model gain a similar generalization ability as the larger teacher model [4,24]. A straightforward way to achieve this goal is by aligning their logits or class predictions given the same inputs [2,24]. Due to its conceptual simplicity and practical effectiveness, KD technique has achieved great success in a variety of applications, such as object detection [8], semantic segmentation [32] and the training of transformers [45].

One limitation of the vanilla KD is that the performance gap between the original teacher model and the distilled student model is still significant. To overcome this drawback, a bunch of approaches have been proposed in the last few years [19,48]. Most of them benefit from exploiting additional supervision from the pre-trained teacher model, especially the intermediate layers [1,6,39,44,46,50,53]. Besides aligning the plain intermediate features [6,39,50], the existing efforts are typically based on elaborately designed knowledge representations, such as mimicking spatial attention maps [53], pairwise similarity patterns [36,37,46] or maximizing the mutual information between teacher and student features [1,44,55]. Although we indeed see constant improvements of these works in student performance, neither effective representations nor well-optimized hyper-parameters ensuring their success are easily achievable in practice. Furthermore, the diversity of transferred knowledge hinders the emergence of a unified and clear interpretation of the final improvement in student performance.

In this paper, we present a simple knowledge distillation technique and demonstrate that it can significantly bridge the performance gap between teacher and student models with no need for elaborate knowledge representations. Our proposed “SimKD” technique is illustrated in Figure 1. We...
argue that the powerful class prediction ability of a teacher model is credited to not only those expressive features but just as importantly, a discriminative classifier. Based on this argument, which is empirically supported later on, we train a student model through feature alignment in the preceding layer of the classifier and directly copy the teacher classifier for student inference. In this way, if we could perfectly align the student features with those of the teacher model, their performance gap will just disappear. That is to say, the feature alignment error alone accounts for the accuracy of student inference, which makes our knowledge transfer more comprehensible. According to our experimental results, a single $\ell_2$ loss for feature alignment already works surprisingly well. Such a simple loss saves us from carefully tuning hyper-parameters as previous works do in order to balance the effect of multiple losses [1,6,24,44,46,50,53].

As the dimensions of extracted features from teacher and student models usually differ from each other, a projector is thus added after the student feature encoder to remedy this dimension mismatch. This projector generally incurs a less than $3\%$ cost to the pruning ratio in teacher-to-student compression, but it makes our technique applicable to arbitrary model architectures. The pruning ratio could be even enlarged in a few cases where the parameter number of the added projector plus the reused teacher classifier is less than that of the original student classifier (see Figure 7). We conduct extensive experiments on standard benchmark datasets and observe that our SimKD consistently outperforms all compared state-of-the-art approaches with a variety of teacher-student architecture combinations. We also show that our simple technique generalizes well in different scenarios such as multi-teacher knowledge distillation and data-free knowledge distillation.

2. Related Work

Knowledge distillation (KD) is a technique to compress the knowledge from a powerful teacher model, such as an ensemble of multiple deep neural networks, into a smaller student model [4,19,24,48]. The transferred knowledge is initially regarded as the conditional distribution of outputs given input samples [24]. From this viewpoint, the predictions, or soft targets, from the pre-trained teacher model play a major role in the improvement of student performance. A common belief behind the success of this technique is that those teacher-learned soft targets can capture the relationships among different categories and serve as an effective regularization during student training [2,7,24,51].

In order to make KD more practical for model compression, we need to further resist the performance degradation in teacher-to-student compression [19,48]. Leveraging more information from the pre-trained teacher model, especially the intermediate layers is a general solution towards this problem. A bunch of such works have sprung up seeking for better student performance in the last few years, collectively known as feature distillation. They mostly propose diverse representations to capture appropriate transferred knowledge, such as the crude intermediate feature maps [39] or their transformations [1,23,53], sample relations encoded by the pairwise similarity matrices [36,37,46] or modeled by contrastive learning [44,49,55]. More recently, a few works turn to designing cross-layer associations to make full use of those intermediate features of the teacher model [6,10]. With the help of aforementioned knowledge representations or reformed transfer strategies, the student model will be trained with gradient information coming from not only the final layer, i.e., the classifier, but also from those early layers. However, additional hyper-parameters need careful tuning in these methods to balance the effect of different losses and it is still unclear how the newly introduced supervisory signal would exert positive influence on the final performance of student models.

To some extent, our key idea of reusing the teacher classifier is related to the previous studies on hypothesis transfer learning (HTL) [38]. HTL aims to utilize the learned source domain classifier to help the training of the target domain classifier, on the condition that only a small amount of labeled target dataset and no source dataset are accessible [15,28,29]. A recent work further gets rid of the requirement of labeling target dataset and extends the vanilla HTL to the unsupervised domain adaptation setting by resorting to a pseudo-labeling strategy [31]. Different from this one, our goal is to reduce the teacher-student performance gap on the same dataset, rather than adapting the pre-trained model to achieve good performance on another dataset with a different distribution. In addition, our SimKD is much simpler than this work and still achieves surprisingly good results in the standard KD setting.

3. Method

3.1. Vanilla Knowledge Distillation

Generally, the popular deep neural networks designed for image classification tasks in the current era can be regarded as the stack of a feature encoder with multiple non-linear layers, together with a classifier that usually contains a single fully-connected layer with softmax activation function [22,25,33,41,54]. Both two components will be trained end-to-end with the back-propagation algorithm. The symbolic description is presented as follows.

Given a training sample $x$ with one-hot label $y$ from a $K$-category classification dataset, we denote the encoded feature in the penultimate layer of the student model as $f^s = \mathcal{F}^s(x; \theta^s) \in \mathbb{R}^{C_s}$. This feature is subsequently passed into the classifier with weight $W^s \in \mathbb{R}^{K \times C_s}$ to obtain the logits $g^s = W^sf^s \in \mathbb{R}^K$ as well as the class prediction $p^s = \sigma(g^s / T) \in \mathbb{R}^K$ with a softmax activation function $\sigma(u) = \frac{e^u}{ \sum_{i=1}^K e^{u_i}}$. The predictions from the trained teacher model $y^t$ are used as ground-truth to train the student model $\hat{f}^s = \mathcal{F}^s(x; \hat{\theta}^s) \in \mathbb{R}^{C_s}$ by minimizing the cross-entropy loss function $L^s = - \log(p^s[y^t])$. $T$ is a hyper-parameter that controls the temperature of the softmax function. In our experiments, $T$ is set to $0.1$.
In contrast, we propose a simple knowledge distillation technique named SimKD, which breaks away from these stringent demands while still achieving state-of-the-art results on extensive experiments. As shown in Figure 2c, a key ingredient of SimKD is the "classifier-reusing" operation, i.e., we directly borrow the pre-trained teacher classifier for student inference rather than training a new one. This eliminates the need of label information to calculate the cross entropy loss and makes the feature alignment loss become the only source for generating gradient.

Overall, we argue discriminative information contained in the teacher classifier matters, but has been largely overlooked in the literature of KD. We then provide a plausible explanation for its important role. Consider a situation where one model is requested to handle several tasks with different data distributions, a basic practice is to freeze or share some shallow layers as the feature extractor across different tasks while fine-tuning the last layer to learn task-specific information [5, 13, 18, 30]. In this one-model multiple-task setting, existing works hold the opinion that task-invariant information could be shared while task-specific information needs to be independently identified, generally by the final classifier. As for KD where teacher and student models with different capabilities are trained on the same dataset, analogously, we could reasonably believe that there is some capability-invariant information in the data being easily gained across different models while the powerful teacher model may contain extra essential capability-specific information that is hard for a simpler student model to acquire. Furthermore, we hypothesize that most capability-specific information is contained in deep layers and expect that reusing these layers, even only the final classifier will be helpful for the student training.

Based on this hypothesis, which is supported later by empirical evidences from various aspects, we furnish the student model with the teacher classifier for inference and force their extracted features to be matched with the follow-

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1We only present notations for the student model in this paragraph, but similar notations also hold for the teacher model.
Finally, we employ our technique to the multi-teacher and data-free knowledge distillation settings.

Datasets and baselines. Two benchmark image classification datasets including CIFAR-100 [26] and ImageNet [40] are adopted for a series of experiments. We use the standard data augmentation and normalize all images by channel means and standard deviations as [22,25,52]. Besides the vanilla KD [24], various approaches are reproduced for comparison, including FitNet [39], AT [53], SP [46], VID [1], CRD [44], SRRL [50] and SemCKD [6]. All compared approaches except KD itself are implemented incorporating the vanilla KD loss, i.e., Eq. (2).

Training details. We follow the training procedure of previous works [6, 44,50] and report the performance of all competitors on our randomly associated teacher-student combinations. Specifically, we adopt SGD optimizer with 0.9 Nesterov momentum for all datasets. For CIFAR-100, the total training epoch is set to 240 and the learning rate is divided by 10 at 150th, 180th and 210th epochs. The initial learning rate is set to 0.01 for MobileNet/ShuffleNet-series architectures and 0.05 for other architectures. The mini-batch size is set to 64 and the weight decay is set to $5 \times 10^{-4}$. For ImageNet, the initial learning rate is set to 0.1 and then divided by 10 at 30th, 60th, 90th of the total 120 training epochs. The mini-batch size is set to 256 and the weight decay is set to $1 \times 10^{-4}$. All results are reported in means (standard deviations) over 4 trials, except for the results on ImageNet are reported in a single trial. The temperature $T$ in the KD loss is set to 4 throughout this paper. More detailed descriptions for reproducibility as well as more results are included in the technical appendix.

4.1. Comparison of Test Accuracy

Table 1 to 3 present a comprehensive performance comparison of various approaches based on fifteen network combinations, where the teacher and student models are instantiated with similar or completely different architectures.

From the test accuracy comparison in Table 1 and 2, we can see that SimKD consistently outperforms all competitors on CIFAR-100 and the improvements are quite significant in some cases. For example, as for the “ResNet-8x4 & ResNet-32x4” combination, SimKD achieves 3.66% absolute accuracy improvement while the best competitor only achieves 1.81% absolute improvement on the basis of the vanilla KD. Moreover, as shown in the fourth and fifth columns of Table 1, given the same teacher model “ResNet-110x2”, SimKD could train a lightweight student model “ResNet-110” with a projector containing 0.05M additional parameters to surpass all the competitors by a considerable margin even when they are employed on a “ResNet-116” containing about more 0.10M parameters than “ResNet-110”. Test accuracy for different training epochs in Table 3 show that SimKD achieves faster convergence in training.
We also find that the student model trained with SimKD yields higher accuracy than its teacher model in the case of “ResNet-8x4 & WRN-40-2” and “ShuffleNetV2 & ResNet-110x2” combinations, which seems a bit confusing since even zero feature alignment loss only guarantees their accuracies to be exactly the same. A possible explanation from self-distillation is that the feature re-representation effect in Equation (3) may help the student model become more robust and thus achieve better results [12, 35].

4.2. Classifier-Reusing Operation Analysis

The “classifier-reusing” operation is our recipe for success in above performance comparisons. To better understand its crucial role, we conduct several experiments with two alternative strategies to deal with the student feature encoder and classifier: (1) joint training, (2) sequential training. The performance degradation resulted from these two variants confirms the value of discriminative information in the teacher classifier. Moreover, reusing more deep teacher layers will further improve the student performance.

Joint training. As the previous feature distillation ap-
The above results show the benefit of disassembling the training of student feature encoder and classifier. Additionally, the “classifier-reusing” operation carries the implication that a classifier with good discriminative ability is fairly hard to acquire. In this part, we provide evidence for this belief by training a new classifier from scratch rather than reusing the teacher classifier.

We adopt those teacher-student combinations in Table 1 as examples for evaluation. After performing feature alignment with Equation (3), we fix the student feature encoder, i.e., freeze the extracted features, and train a randomly initialized student classifier (a fully-connected layer with softmax activation) with the regular training procedure. This is exactly same as the linear evaluation protocol used in unsupervised learning evaluation [11, 20, 21].

The results of this sequential training are given in Table 4. We find that apart from “WRN-40-1 & WRN-40-2” and “ResNet-110/116 & ResNet-110x2”, the test accuracies of other student models appear a precipitous drop. Although we have tried tuning the initial learning rate a few times, it only makes a slight difference in performance. Results in Table 4 indicate that even when the extracted features have been aligned, it is still a challenge to train a satisfactory student classifier. Generally, we could achieve better student performance by tuning hyper-parameters in the classifier training step more carefully, but it is a non-trivial task. In contrast, directly reusing the pre-trained teacher classifier already works quite well. 

**Table 3. Top-1 test accuracy (%) comparison on ImageNet for different training epochs.** We adopt ResNet-18 as the student model.

| Student | 1/4 Epoch | 1/2 Epoch | Full Epoch |
|---------|-----------|-----------|------------|
| ResNet-8x4 | 49.34 | 64.98 | 70.58 |
| ResNet-110x2 | 52.75 | 66.69 | 71.29 |
| ResNet-116x2 | 52.85 | 66.66 | 71.18 |
| VGG-8 | 75.37 | 66.64 | 71.08 |
| ResNet-8x4 | 53.22 | 71.46 | 71.01 |
| ShuffleNetV2 | 55.44 | 67.36 | 71.25 |
| WRN-40-1 | 55.14 | 67.36 | 71.46 |
| VGG-16 | 54.14 | 66.89 | 71.41 |

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**Table 4. Training a new student classifier from scratch.**

| Student | Sequential | SimKD | Teacher |
|---------|-----------|-------|---------|
| WRN-40-1 | 74.48 ± 0.04 | 75.56 ± 0.27 | WRN-40-2 |
| ResNet-8x4 | 51.97 ± 0.19 | 78.08 ± 0.15 | ResNet-32x4 |
| ResNet-110x2 | 77.63 ± 0.05 | 77.82 ± 0.15 | ResNet-110x2 |
| ResNet-110x2 | 77.75 ± 0.03 | 77.90 ± 0.11 | ResNet-110x2 |
| VGG-8 | 35.72 ± 1.33 | 75.76 ± 0.12 | ResNet-32x4 |
| ResNet-8x4 | 45.03 ± 0.44 | 76.75 ± 0.23 | WRN-40-2 |
| ShuffleNetV2 | 21.56 ± 0.31 | 78.39 ± 0.27 | ResNet-32x4 |

**Figure 5. Comparison of the top-1 test accuracy (%) and negative log-likelihood (Student: ResNet-8x4, Teacher: ResNet-32x4).**

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| ResNet-110x2 | 77.75 ± 0.03 | 77.90 ± 0.11 | ResNet-110x2 |
| VGG-8 | 35.72 ± 1.33 | 75.76 ± 0.12 | ResNet-32x4 |
| ResNet-8x4 | 45.03 ± 0.44 | 76.75 ± 0.23 | WRN-40-2 |
| ShuffleNetV2 | 21.56 ± 0.31 | 78.39 ± 0.27 | ResNet-32x4 |

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**Reusing more teacher layers.** We now generalize our technique to the situation where more deep layers of the teacher model are reused for student inference and show that the student performance will be further improved.

We take ResNet architecture as an example and conduct experiments on CIAFR-100 dataset. Following the standard design, ResNet architecture consists of one convolutional layer, three building blocks and one fully-connected layer in a bottom-up fashion [22]. Every building blocks contain the same number of convolutional layers and changing these layer numbers leads to different ResNet architectures. For example, 10 layers for each building block make up a 32-layer ResNet model. Then, besides reusing the final classifier as our SimKD do, two new variants are introduced by reusing additional last one or two building blocks, and they are denoted as “SimKD+” and “SimKD++”, respectively.

From Figure 5, we can see that SimKD significantly decreases negative log-likelihood by reusing only the teacher...
classifier, and its two variants further achieve higher performance as expected, though the associated complexity is also increased. These results support our hypothesis that reusing deep teacher layers is beneficial for the student performance improvement, probably due to most capability-specific information is contained in them. Another explanation is that reusing more deep teacher layers would make the approximation of shallow teacher layers easier achievable and thus incur less performance degradation. In practice, reusing only the final teacher classifier strikes a good balance between performance and parameter complexity.

4.3. Projector Analysis

The parameter-free “classifier-reusing” operation in our SimKD has been fully evaluated above. Next, we start to dig into another component—projector from several aspects. We first present its default implementation and then show that it only requires a small number of extra parameters for achieving state-of-the-art performance. Finally, several ablation studies on the projector are provided.

Implementation. The aim of the projector \( P(\cdot) \) in Equation (3) is to perfectly match the feature vectors \( f^t \in \mathbb{R}^{C_t} \) and \( f^s \in \mathbb{R}^{C_s} \). A naïve implementation is using one convolutional layer with batch normalization and ReLU activation, which has \( C_s \times C_t + 2 \times C_t \) parameters \([50]\). However, this one-layer transformation may not suffice for accurate alignment due to the large capability gap between teacher and student models. We thus employ the last feature maps and a three-layer bottleneck transformation with dimension reduction factor \( r \) as alternatives, hoping that these will help the features aligned better. The total parameters are

\[
\frac{C_t(C_s + C_t + 4)}{r} + \frac{9C_t^2}{r^2} + 2C_t.
\]

This formula implies that the added parameters will be reduced to between a quarter and a half if \( r \) is doubled, which enables us to control the parameter complexity within an acceptable level by changing \( r \). Detailed structure of the projector and analysis are provided in the technical appendix.

Effect to pruning ratio. Figure 6 illustrates the trade-off between top-1 test accuracy and pruning ratio with different dimension reduction factor \( r \). We adopt the following equation for the calculation of pruning ratio:

\[
\text{Pruning Ratio} = 1 - \frac{\text{\#param}_{se} + \text{\#param}_{proj} + \Delta}{\text{\#param}_{t}}
\]

\[
\Delta = \text{\#param}_{se} - \text{\#param}_{sc},
\]

where \( \text{\#param}_{se}, \text{\#param}_{proj}, \text{\#param}, \text{\#param}_{tc/sc} \) refer to the parameter number of a student encoder, a projector, a whole teacher model and a teacher/student classifier, respectively. Its upper bound is approached when \( \text{\#param}_{proj} \to 0 \), which could be higher than the pruning ratio of the vanilla KD since \( \text{\#param}_{proj} + \Delta \) may be less than zero. Figure 6 shows that increasing \( r \) will raise the pruning ratio, but in turn, cause the performance drop. This reduction may be attributed to that shrinking the bottleneck dimension of the projector will restrict its representation ability and thus affect the success of feature alignment.

We then calculate the minimum pruning ratio cost of SimKD when it performs best in the competition on fourteen teacher-student combinations from Table 1 and 2. Figure 7 show that our added projector only incurs less than 1% pruning ratio cost in most cases (10/14). In some cases such as “MobileNetV2x2 & ResNet-32x4” and “ShuffleNetV1 & ResNet-32x4” with \( r = 8 \), we find the pruning ratios of SimKD are even higher than the vanilla KD, and all competitors accordingly. Throughout this paper, we set \( r \) equals 2 as default since this value strikes a good balance, i.e., gaining state-of-the-art results at the modest cost of pruning ratio. The full results are presented in the appendix.

Ablation study. We finally compare several implementations of the projector and loss function (see Appendix) for feature alignment. All results are obtained with the “ResNet-8x4 & ResNet-32x4” combination on CIFAR-100.

From Table 5, the default implementation of our projector (the last row) achieves the best performance. The accuracy drop resulted from its simplified counterparts indicates the benefit of employing a relatively powerful projector in feature alignment. Moreover, the lower accuracy (76.03 ±
4.4. Application I: Multi-Teacher Knowledge Distillation

We then demonstrate the applicability of our technique in the multi-teacher KD setting where multiple pre-trained teacher models are available for the student training. Two representative approaches are compared: “AVERAGE” denotes a simple variant of the vanilla KD, which averages the predictions of multiple teachers; “AEKD” aggregates the teacher predictions with an adaptive weighting strategy and its improved version by incorporating intermediate features is denoted as “AEKD-F” [14]. As shown in Table 6, SimKD always achieves the best performance. Additionally, we provide the results of SimKD, where a fully-connected layer projector is first used to align the feature vectors and then merged into the associated teacher classifier. The weights of multiple teacher classifiers are averaged and reused for student inference, which incurs no extra parameters.

4.5. Application II: Data-Free Knowledge Distillation

Data-free knowledge distillation aims to exploit a pre-trained teacher model without accessing its training dataset to improve the student performance. A popular paradigm is to recover the original data manifold with a generative model first and then perform knowledge distillation on the synthesized dataset [9,16,34]. Our SimKD can be easily integrated into these existing approaches by replacing their KD training step as our “reusing-classifier” operation and the associated feature alignment. Table 7 shows that with the help of our SimKD, the student performance is also improved in the data-free knowledge distillation application.

5. Conclusion

In this paper, we have explored a simple knowledge distillation technique where the pre-trained teacher classifier is reused for student inference and the student model is trained with a single $\ell_2$ loss for feature alignment. We design several experiments to analyze the workings of our technique and conduct extensive experiments to demonstrate its superiority over state-of-the-art approaches. We hope this study will be an important baseline for future research.

6. Limitation and Future Work

A simple parameter reusing is served as our first attempt to explore the potential value of the teacher classifier. This requires a projector when feature dimensions are mismatched and thus increases the model complexity. How to develop a projector-free alternative needs further investigation. Another limitation is that our technique is only applicable for supervised knowledge distillation, such as image classification [24], dense prediction [42] and machine translation [43]. It is also worthwhile to develop a successful variant of our technique for unsupervised learning scenario.

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Table 5. Comparison of projectors. “1x1/3x3Conv” denotes a convolutional layer with 1x1/3x3 kernel size. “DW” denotes depthwise separable convolutions. Standard batch normalization and ReLU activation are used after each layer.

| Projector | Test loss ($\ell_2$) | Accuracy (%) |
|-----------|----------------------|--------------|
| 1x1Conv   | 0.345 ± 0.001        | 75.15 ± 0.27 |
| 1x1Conv-1x1Conv | 0.343 ± 0.001 | 75.71 ± 0.33 |
| 1x1Conv-3x3Conv (DW)-1x1Conv | 0.306 ± 0.001 | 77.76 ± 0.12 |
| 1x1Conv-3x3Conv-1x1Conv | 0.301 ± 0.001 | 78.08 ± 0.15 |

Table 6. Results of the multi-teacher KD. We adopt ShuffleNetV2 as the student model and train it under two groups of pre-trained teacher models: ① includes three ResNet-32x4. ② includes two ResNet-32x4 and one ResNet-110x2.

| Method         | ①    | ②    |
|----------------|-------|-------|
| Student        | 72.60 ± 0.12 | 72.60 ± 0.12 |
| AVERAGE [14]   | 75.94 ± 0.20 | 76.33 ± 0.14 |
| AEKD [14]      | 75.99 ± 0.18 | 76.17 ± 0.43 |
| AEKD-F [14]    | 77.24 ± 0.32 | 77.08 ± 0.28 |

SimKD$_v$ 77.43 ± 0.21 77.60 ± 0.23
SimKD 78.59 ± 0.05 78.59 ± 0.05

Table 7. Results of the data-free KD. We adopt WRN-40-2 as the teacher model with two different student models.

| Method Require data? | WRN-40-1 | WRN-16-2 |
|----------------------|----------|----------|
| Student Yes          | 71.92 ± 0.17 | 73.51 ± 0.32 |
| ZSKT [34] No         | 33.60 ± 3.88 | 45.03 ± 1.73 |
| DAFL [9] No          | 45.32 ± 1.46 | 45.94 ± 1.66 |
| CMI [16] No          | 64.80 ± 0.35 | 65.11 ± 0.43 |
| CM+SimKD No          | 66.78 ± 0.29 | 67.31 ± 0.89 |
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