Toward Data Efficient Model Merging between Different Datasets without Performance Degradation

Masanori Yamada MASANORI.YAMADA@NTT.COM
NTT Social Informatics Laboratories

Tomoya Yamashita
NTT Social Informatics Laboratories

Shin'ya Yamaguchi
NTT Computer and Data Science Laboratories

Daiki Chijiwa
NTT Computer and Data Science Laboratories

Editors: Vu Nguyen and Hsuan-Tien Lin

Abstract

Model merging is attracting attention as a novel method for creating a new model by combining the weights of different trained models. While previous studies reported that model merging works well for models trained on a single dataset with different random seeds, model merging between different datasets remains unsolved. In this paper, we attempt to reveal the difficulty in merging such models trained on different datasets and alleviate it. Our empirical analyses show that, in contrast to the single-dataset scenarios, dataset information needs to be accessed to achieve high accuracy when merging models trained on different datasets. However, the requirement to use full datasets not only incurs significant computational costs but also becomes a major limitation when integrating models developed and shared by others. To address this, we demonstrate that dataset reduction techniques, such as coreset selection and dataset condensation, effectively reduce the data requirement for model merging. In our experiments with SPLIT-CIFAR10 model merging, the accuracy is significantly improved by 31% when using the full dataset and 24% when using the sampled subset compared with not using the dataset. Our code is available at this URL.

Keywords: Model Merging, Mode Connectivity

1. Introduction

Model merging (Leontev et al., 2020; Singh and Jaggi, 2020; Ainsworth et al., 2023) is an approach to creating a new model that combines the weights contained in different deep neural networks (DNNs). One scenario involves merging fine-tuned models from the same pre-trained model (Goddard et al., 2024; Daheim et al., 2024; Leontev et al., 2020; Matena and Raffel, 2022). However, this paper focuses on the more general scenario of merging models trained with different random seeds, specifically in the context of image classification. This scenario is more challenging due to the differences in initialization. The recent discovery of a DNN property called Linear Mode Connectivity (LMC) (Frankle et al., 2020) brings us closer to successful model merging. The LMC indicates that if the optimal weights of two DNNs are given, they are trapped in the same basin of the loss landscape. This means that the model created from the average of these weights has a high accuracy since there is no loss barrier between the weights with LMC. Rahim (Entezari et al., 2021) and

© 2024 M. Yamada, T. Yamashita, S. Yamaguchi & D. Chijiwa.

Ainsworth (Ainsworth et al., 2023) reported that two networks trained with different random seeds have an LMC if the neurons are properly aligned.

Previous studies (Ainsworth et al., 2023; Leontev et al., 2020; Singh and Jaggi, 2020) reported that model merging works well for models trained on a single dataset with different random seeds, called model merging on a single dataset. On the other hand, model merging is difficult for models trained on different datasets, called model merging between different datasets. Merging knowledge from different datasets has practical significance. Thus, this study addresses the following research question.

- RQ1: What makes model merging between different datasets more difficult than model merging on a single dataset?

To address RQ1, we focus on the difference between loss landscapes of the datasets that are incrementally increasing the gap from the original one. Specifically, we design a series of synthetic datasets based on MNIST, on which we analyze how the optimal basin in loss landscape differs due to the increasing gap. Previous work (Ainsworth et al., 2023) observed that for a single dataset, sufficiently close optimal weights reside within the same basin, effectively eliminating the loss barrier. In contrast, we find that in the case of different datasets, even if the optimal weights are close between these datasets, the loss barriers still remain, as shown in Fig. 1c. Moreover, we observed that overly close optimal weights yield a rather high loss barrier between them as shown in Fig. 1d.

In this paper, we attempt to effectively merge models trained with different datasets by overcoming the challenges identified in our RQ1 analysis. Existing methods (Entezari et al., 2021; Ainsworth et al., 2023) remove the loss barrier by aligning neurons and averaging weights to merge models. The methods for aligning neurons can be categorized into (i) merging with weights (MW) that aligns neurons based on their weights, and (ii) merging with weights and datasets (MWD) that aligns neurons based on their weights and dataset information. Since there was no difference in accuracy between the two methods and methods using only weights are less costly, existing studies (Ainsworth et al., 2023; Jordan et al., 2022) mainly focus on MW. However, in the model merging between the different datasets, it is not obvious whether the merging methods using only weights are sufficient, since the closest optimal weights have a large loss value on the datasets of each other as discussed in the previous paragraph. Thus, the following research question naturally arises.

- RQ2: For model merging between different datasets, does the method of using weight and dataset information improve accuracy compared to using only weights?

In all cases in our experiments, MWD greatly improved accuracy compared to MW in contrast to the single dataset cases. Furthermore, to investigate dataset information requirements while minimizing reliance on optimization methods, such as the linear matching and Sinkhorn algorithm, we generate various alignments without a dataset. As a result, we found that no criteria used in the MW methods are positively correlated with the loss on the mixed dataset composed of the different datasets. On the other hand, the alignment criteria created from the dataset correlate well with the loss on the mixed dataset. Therefore, we conclude that dataset information is currently required for effective model merging between different datasets.

While model merging between different datasets can achieve high accuracy through neuron alignment with datasets, the necessity of utilizing full datasets presents a significant limitation. This limitation is particularly pronounced in scenarios when only the models are published without their datasets. Furthermore, the requirement of full datasets for model merging leads to significantly increased storage costs. In collaborative projects across multiple organizations, these limitations pose notable challenges. Sharing individually trained models is generally feasible, but exchanging large datasets often faces practical barriers, such as privacy, security, or logistical issues. Thus, we further investigate a third research question addressing these challenges.

- RQ3: Can we reduce the data points required for effective model merging?

To address RQ3, we propose a method for model merging using a small surrogate dataset instead of a full-scale real dataset. We explore two approaches for generating a surrogate dataset: (i) Coreset selection (Mirzasoleiman et al., 2020; Guo et al., 2022), which aims to select a subset of the most informative training samples, and (ii) Dataset condensation (Zhao et al., 2021; Nguyen et al., 2021), which distills the knowledge of a dataset into small numbers of data points to achieve high accuracy with less data. Our experiments demonstrate that model merging using both our proposed methods achieves higher accuracy than the baselines, which include the MW method and existing techniques for model merging between different datasets. In particular, it is surprising that high accuracy is achieved even when using a simple coreset selection with random sampling from each class. This is because the proposed method has the advantage of using the optimal weight information of each dataset. The neuron alignment operation keeps a low loss value on the mixed dataset, since its alignment strictly keeps the optimized loss value on the individual datasets. Our main contributions are summarized as follows:

- We show that model merging becomes more difficult as datasets become more different and reveal that the difficulty of model merging is caused by the closest optimal weights having a large loss value on the datasets of each other as datasets become more different.
- We find that dataset information is currently required for effectively merging models between different datasets and that the alignment criteria created from the weights are not positively correlated with the performance.
- We propose a method of merging models by using a surrogate dataset including random sampling instead of the real dataset. This approach greatly reduces the number of data points required.

2. Preliminary

We present a short preliminary for model merging. First, we formulate the problem of model merging extended between different datasets. Then, we introduce permutation symmetry of neurons in DNN, which plays an important role in model merging. Finally, we introduce existing methods for model merging.

2.1. Goal of Model Merging

Let us consider merging the model parameters $\mathbf{w_A}$ and $\mathbf{w_B}$ trained on datasets generated from dataset probability distribution P_A and P_B respectively. The mixed dataset probability distribution[1] is defined as $P_{AB}(\mathbf{x}, y, \alpha) = (1-\alpha) P_A(\mathbf{x}, y) + \alpha P_B(\mathbf{x}, y)$, where $\alpha \in [0, 1]$ is a constant for the mixing ratio of datasets, for simplicity $\alpha = \frac{1}{2}$ is used. Note that the general α can be discussed in a similar way. The goal of model merging is to obtain operator $\star$ as follows

$$\mathcal{L}_{AB}(\mathbf{w_{AB}}) \simeq \mathcal{L}_{AB}(\mathbf{w_A} \star \mathbf{w_B}), \tag{1}$$

where $\mathbf{w_A} = \arg\min_{\mathbf{w}} \mathcal{L}_A(\mathbf{w})$, $\mathbf{w_B} = \arg\min_{\mathbf{w}} \mathcal{L}_B(\mathbf{w})$, and $\mathbf{w_{AB}} = \arg\min_{\mathbf{w}} \mathcal{L}_{AB}(\mathbf{w})$. $\mathcal{L}_A(\mathbf{w})$ denotes loss on P_A as $\mathcal{L}_A = E_{P_A(\mathbf{x},y)}[-\log p(y|\mathbf{x}, \mathbf{w})]$. In this paper we assume for simplicity that Models A and B have the same architecture.

2.2. Permutation Symmetry

DNNs have neuron permutation symmetry, which is realized by rearranging the weights. Neuron permutation symmetry refers to the property that the output remains invariant with respect to the rearrangement of neurons. Let us consider a specific example of a simple feedforward network. Even if we apply a permutation matrix π_ℓ to the weights of the ℓ-th layer $\mathbf{w}_\ell$, the output remains invariant if we apply the inverse of π_ℓ in the weights of the $(\ell+1)$-th layer. In other words, $\mathbf{w_{\ell+1}} \pi_\ell^{-1} \sigma(\pi_\ell \mathbf{w}_\ell \mathbf{x}_\ell) = \mathbf{w_{\ell+1}} \sigma(\mathbf{w}_\ell \mathbf{x}_\ell)$. Here, σ represents the activation function, and $\mathbf{x}_\ell$ denotes the input of the ℓ-th layer. To maintain invariant input-output relations in the neural network, we fix the input and output layers and only permute the neurons in the hidden layers. By utilizing this freedom of rearrangement, we can permute the weights without changing the loss value.

2.3. Model Merging

Existing research (Entezari et al., 2021; Ainsworth et al., 2023) demonstrates that suitably aligning and averaging the weights to merge models can effectively minimize the loss on a single dataset. The suitable alignment and averaging of the weights are formulated as

$$\mathbf{w_A} \star \mathbf{w_B} = (1-\lambda) \mathbf{w_A} + \lambda \pi(\mathbf{w_B}), \tag{2}$$

where π is permutation weights for all layers and $\lambda \in [0, 1]$ is constant. We present two methods introduced in Ainsworth (Ainsworth et al., 2023).

WM: Weight Matching (WM) permutes the weights to reduce the L2 distance between weights of trained models as

$$\arg\min_{\pi} \left\| \mathrm{vec}(\mathbf{w_A}) - \mathrm{vec}(\pi(\mathbf{w_B})) \right\|^2. \tag{3}$$

This search for permutations can be reduced to a classic linear assignment problem and be performed quickly. Equation (3) can be optimized using only weight without datasets.

1. The mixed distribution refers to a combination of two separate datasets rather than the averaging of the individual data points as in mixup.

Table 1: **Effects of different datasets on WM.** L2 distance between $\mathbf{w_A}$ and $\mathbf{w_B}$ permuted using WM, along with the loss and accuracy of the merged model on the mixed dataset.

Degree	L2	Sharpness	Loss	Acc
0°	3.84×10^{-5}	2.85×10^{-4}	0.008	98.49
15°	3.96×10^{-5}	3.34×10^{-4}	0.062	97.53
30°	4.00×10^{-5}	3.42×10^{-4}	0.217	94.69
45°	4.05×10^{-5}	3.58×10^{-4}	0.390	89.68
60°	4.07×10^{-5}	3.77×10^{-4}	0.804	80.33
75°	4.06×10^{-5}	3.72×10^{-4}	1.098	74.19
90°	4.03×10^{-5}	3.65×10^{-4}	1.280	70.86

STE: Straight Through Estimator (STE)[2] learns permutations to reduce the loss of parameters after merging as

$$\begin{aligned} &\min_{\tilde{\mathbf{w}}_\mathbf{B}} \mathcal{L}_{AB}\left(\left(1-\lambda\right)\mathbf{w_A} + \lambda \mathrm{proj}\left(\tilde{\mathbf{w}}_\mathbf{B}\right)\right), \\ &\mathrm{proj}\left(\mathbf{w}\right) = \underset{\pi(\mathbf{w_B})}{\arg\min} \left\|\mathrm{vec}\left(\mathbf{w}\right) - \mathrm{vec}\left(\pi\left(\mathbf{w_B}\right)\right)\right\|^2. \end{aligned} \tag{4}$$

STE requires a dataset to estimate the loss. For merging models trained on a single dataset, Ainsworth (Ainsworth et al., 2023) reports that WM achieves similar accuracy to STE, despite not using the dataset. Therefore, WM was the main subject of investigation in their study (Ainsworth et al., 2023).

3. Model Merging between Different Datasets

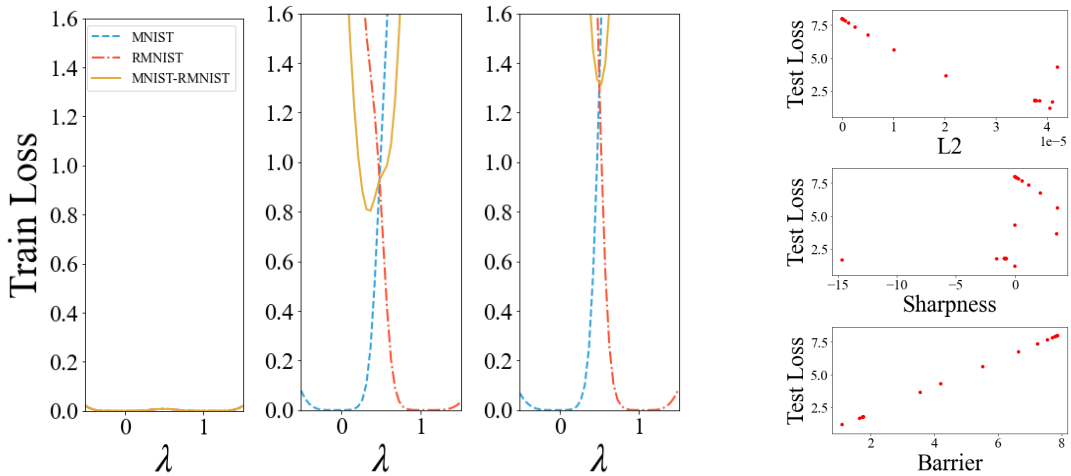
To investigate model merging between different datasets, we first provide an intuitive understanding of model merging between different datasets and identify the causes of merging difficulties. Then, we show that datasets are required to effectively merge models between different datasets. Finally, we propose a model merging method using a surrogate dataset that decreases the requirement for the full dataset.

3.1. Causes of Difficulties with Model Merging

To reveal why model merging between different datasets is difficult, we first present a theoretical intuition and then verify the intuition in an experiment.

Theoretical intuition. The goal of model merging is to find $\mathbf{w_{AB}}$ that reduces loss $\mathcal{L}_{AB}$ from $\mathbf{w_A}$ and $\mathbf{w_B}$. To discuss the relationship between these weights, we first clarify the relationship between loss on different datasets. The loss on a mixed dataset, called loss

2. Note that while STE is typically an optimization method for non-differentiable problems, in this paper, it is used as the name of a model merging technique.



(a) 0° (single dataset) (b) 45° (c) 90° (d) Correlation

Figure 1: **Impact of dataset differences on the loss landscape.** Figures (1a, 1b, and 1c) visualize the loss on the mixed dataset in three different scenarios, each created by varying the degree of rotation, to explain the difficulty of model merging between different datasets. In each figure, we plotted training loss evaluated on three datasets (MNIST. RMNIST, MNIST-RMNIST) along the linear interpolation parameter $\lambda \in [0, 1]$, with $\lambda = 0$ representing the optimal weights for MNIST and $\lambda = 1$ representing the optimal weights for RMNIST. Figure (1d) shows the relationship between L2 distance, sharpness, loss barrier, and test loss on a mixed dataset when various weight permutations are generated between MNIST and RMNIST-90. Reducing the L2 distance and sharpness does not necessarily decrease the test loss.

barrier[3], is as follows

$$\mathcal{L}_{AB}(\mathbf{w}) = \frac{1}{2}\left(\mathcal{L}_A(\mathbf{w}) + \mathcal{L}_B(\mathbf{w})\right) \tag{5}$$

since the loss is the expected value $\mathcal{L}_{AB} = E_{P_{AB}(y,\mathbf{x})}\left[-\log p\left(y|\mathbf{x}, \mathbf{w}\right)\right]$ and can be separated for each dataset by using the linearity of the expectation. This equation shows that the loss landscape of $\mathcal{L}_{AB}$ is the sum of the loss landscapes of $\mathcal{L}_A$ and $\mathcal{L}_B$, as shown in Fig. 1. We explain why WM has more difficulty merging models between different datasets than a single dataset. The permutation of WM brings $\mathbf{w_B}$ closer to $\mathbf{w_A}$. In scenarios of model merging between single datasets, $\mathcal{L}_A$ and $\mathcal{L}_B$ share optimal weights. Consequently, through WM, $\mathbf{w_A}$ converges towards $\mathbf{w_B}$, and setting these as $\mathbf{w_{AB}}$ results in a smaller loss. On the other hand, as the datasets become more divergent, the closest optimal weights have a large loss value on the datasets of each other, leading to an increased loss barrier.

Experimental Design. To validate the above theoretical intuition, we show the loss landscape and the L2 distance between the closest optimal weights by continuously increasing the difference between Datasets A and B. We design Rotated-MNIST (RMNIST), which

3. This is a natural extension to the different datasets of the loss barrier on the single dataset (Ainsworth et al., 2023). For more information, refer to the supplementary materials.

consists of MNIST images rotated by various angles, and conduct model merging experiments between MNIST and RMNIST. RMNIST uses rotations of 0°, 15°, 30°, 45°, 60°, 75°, and 90°. We train Model A on MNIST (Dataset A) and Model B on RMNIST (Dataset B), then use WM to permute$\mathcal{L}_B$, measuring L2 distance between closest optimal weights as shown in Table 1 and Fig. 1.

Experimental Verification. Table 1 shows that the L2 distance between the closest optimal weights of Models A and B diverges as the datasets become increasingly different, which leads to a decrease in the accuracy of the merged model. To directly verify this theoretical intuition, we visualize the loss landscape between the optimal weight of the MNIST and RMNIST in Fig. 1. The blue, red, and yellow lines represent the loss landscapes on MNIST, RMNIST, and MNIST-RMNIST[4], respectively. Figure 1 shows that the loss barrier (yellow line) increases as the angle of MNIST-RMNIST becomes more different.

3.2. Conditions for Successful Merging

Figures 1b and 1c show WM does not make these optimal weights close enough to ignore the increase in loss. This suggests that a simple WM approach, focusing only on minimizing the L2 distance, is insufficient for effectively merging models between different datasets. To address this challenge, we investigate three types of information related to model merging to identify the information required for successfully merging models: (i) L2 distance between weights (Eq. 3), (ii) sharpness, and (iii) loss barrier (Eq. 5), where the sharpness between $\mathbf{w_A}$ and $\mathbf{w_B}$ is defined as

$$\frac{1}{2}\left[\left(\mathbf{w_B}-\mathbf{w_A}\right)^\top \frac{\partial \mathcal{L}_A\left(\mathbf{w_A}\right)}{\partial \mathbf{w}}+\left(\mathbf{w_A}-\mathbf{w_B}\right)^\top \frac{\partial \mathcal{L}_B\left(\mathbf{w_B}\right)}{\partial \mathbf{w}}\right]. \tag{6}$$

As shown in Fig. 1c, the loss barrier is determined by both the L2 distance and the degree of increase in loss. Therefore, to represent the information about the increase in loss, we introduce the concept of sharpness. Fig. 1d shows the relationship between L2 distance, sharpness, loss barrier, and test loss on a mixed dataset when various weight permutations are generated between MNIST and RMNIST-90 (for the detailed experimental setup in Sec. A.2). The use of various permutations helps to avoid dependency on the search methodology. Figure 1d indicates that the test loss does not become smaller as the L2 distance becomes smaller. Figure 1d also shows that the sharpness is poorly correlated with test loss of the merged model. This is because loss barriers that deviate from the optimal weights become difficult to estimate when using local gradients on the optimal weights[5]. On the other hand, the loss barrier, which is training loss on mixed datasets, correlates well with test loss[6]. These experimental results indicate that directly reducing the loss barrier is most likely to lead to successful model merging when different datasets are used. Since directly reducing the loss barrier requires the use of STE with datasets to be applied, datasets are currently required for efficient model merging. We will show that STE works effectively between different datasets in Sec. 4.

4. We represent the pairs of datasets for model merging as [the dataset used to train Model A]-[the dataset used to train Model B].
5. In fact, we tried a method using regularization to reduce sharpness for WM, but it did little to improve accuracy (see supplementary materials).
6. It is checked for a generalization gap.

3.3. Model Merging with Surrogate Datasets

Model merging between different datasets requires a smaller loss barrier by using the datasets. However, this is a major constraint on sharing all data in terms of heterogeneous data utilization, data privacy, and data storage cost. To relax this constraint, we propose a method that uses a surrogate dataset instead of a real dataset. We employ two methods to create the surrogate dataset: coreset selection and dataset condensation.

Coreset selection aims at reducing the size of a dataset by selecting a smaller, representative group of data points, with the goal of approximating training on the full dataset. Various coreset selection methods have been proposed, but when an extremely small coreset is selected, the performance is almost identical to that of random sampling (Guo et al., 2022). We experimented with five methods, including random sampling, for generating surrogate datasets and merging models with these surrogate datasets and found that the accuracy was the same as that of random sampling (see supplementary materials). Therefore, we will primarily discuss random sampling in the rest of this paper.

Dataset condensation is a method for condensing a large dataset into a small set of informative synthetic samples for training DNNs from scratch. Various methods have been proposed for dataset condensation, and we use a major method called Gradient Matching (Zhao et al., 2021) in this paper. Gradient Matching creates a condensed dataset so that the gradients of the weights trained on the original dataset match the gradients of the condensed dataset. Dataset condensation is more complex than coreset selection using random sampling. However, with more sophisticated methods (Guo et al., 2023; Nguyen et al., 2021) being proposed recently, there is potential for significant improvements in accuracy in the future.

To summarize the overall procedure for model merging without the full dataset, we first prepare trained models for P_A and P_B and then perform coreset selection and dataset condensation on P_A and P_B to create a surrogate dataset. Next, we mix surrogate Datasets A and B to create surrogate Dataset AB. Finally, we merge models with STE using surrogate Dataset AB instead of the full dataset P_{AB}.

4. Experiments

Outline. This section experimentally confirms that STE is effective for model merging between different datasets and that a reasonable permutation can be achieved even using STE with surrogate datasets. The basic experimental procedure is to first train independently on P_A and P_B to obtain $\mathbf{w_A}$ and $\mathbf{w_B}$. Then the weights $\mathbf{w_B}$ are permuted. Finally, model parameters are merged as $\mathbf{w_{AB}} = (1-\lambda)\,\mathbf{w_A} + \lambda\pi\,(\mathbf{w_B})$ and sliding λ to evaluate the accuracy on P_{AB}.

Datasets. First, we conduct model merging between different datasets with shared labels, such as MNIST-RMNIST and USPS-MNIST. Both MNIST (LeCun et al., 1998) and USPS (Hull, 1994) are grey-scaled character datasets. Originally, Rotated-MNIST (RMNIST) is a dataset with MNIST rotated by an arbitrary angle, but in this section, we set the rotation angle of RMNIST to 90°. Next, we experiment with the case of no label sharing as SPLIT-CIFAR10 and MNIST-FMNIST. SPLIT-CIFAR10 divides CIFAR10 (Krizhevsky et al., 2009) into two datasets, one with labels 0-4 and the other with labels 5-9. MNIST-FMNIST merges models between two completely different datasets: MNIST, which includes

digit images, and Fashion-MNIST (FMNIST) (Xiao et al., 2017), which includes fashion images[7].

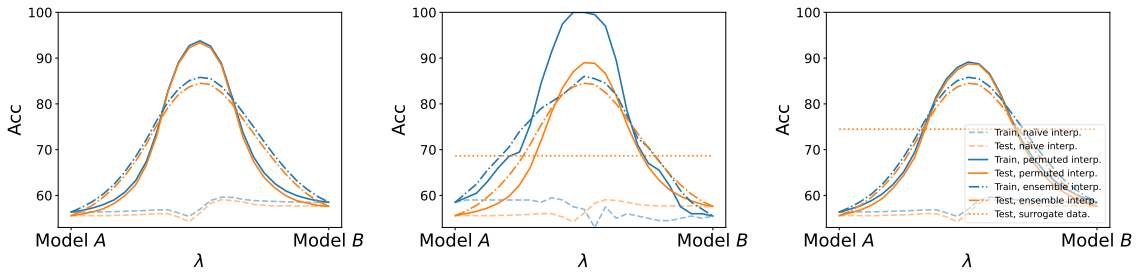
Setup. We use the same setup for the preprocessing and network architecture as the existing method (Ainsworth et al., 2023). MNIST, USPS, RMNIST, and FMNIST use a fully connected network, and CIFAR10 uses ResNet20×16, which is 16 times wider than ResNet20. This is because existing research has shown that model merging on a single dataset in CIFAR10 cannot be effective unless the width is sufficiently large. Since Batch Normalization is also known to destroy the LMC, we use REPAIR (REnormalizing Permuted Activations for Interpolation Repair) (Jordan et al., 2022) to avoid this. We provide the results of model merging on a single dataset as a preliminary experiment in supplementary materials. To make surrogate datasets, we applied both coreset selection (Coreset) and dataset condensation (Data Cond) techniques. For Coreset, we show that random sampling is the best choice for the coreset selection in supplementary materials. As for Data Cond, we use Gradient Matching (Zhao et al., 2021) for USPS, MNIST, RMNIST, and FMNIST, and public datasets[8] using sophisticated methods (Nguyen et al., 2021) for SPLIT-CIFAR10. We use 10 images per class for USPS, MNIST, RMNIST, and FMNIST, and 50 images per class for SPLIT-CIFAR10. For full experimental details in Sec. A.

Baselines. We compare the five methods as a baseline for model merging. **Naïve**: Simple average method as $\mathbf{w_{AB}} = (1-\lambda)\,\mathbf{w_A} + \lambda \mathbf{w_B}$. **WM**: The weights are permuted to close the L2 distance between the weights of the two models and then averaged. **ZipIt!**: ZipIt! (Stoica et al., 2023) merges models using correlated neurons, which allows for the combination of neurons both between different networks and within the same network. We use the full dataset to estimate correlated neurons. **OT**: Model Fusion via OT (Singh and Jaggi, 2020) is sophisticated model merging, with a higher degree of freedom than weights permutation. **OT (Tuned)**: It uses λ with the highest test accuracy from $\lambda \in [0, 1]$. Since there is a large divergence in performance between $\lambda = 0.5$ and Tuned for OT, we include both, while the other methods include results for $\lambda = 0.5$. We also compare with another non-merging baseline due to its similar problem setting to model merging. **Ensemble**: It averages the predictions of the model. Note that ensemble is compared as a reference due to the doubled inference cost.

4.1. Model Merging between Different Datasets.

First, for an intuitive understanding of our experiments, we present the model merging between MNIST and RMNIST. MNIST is Dataset A and RMNIST is Dataset B, and the models trained on MNIST and RMNIST are denoted as Models A and B, respectively. Figure 2 shows the accuracy of the merged model on P_{AB}, which is merged by STE and STE with dataset condensation. Model A ($\lambda = 0$) has an accuracy of around 55% on the MNIST and RMNIST mixed dataset, since it is almost 100% accurate on MNIST and 10% on RMNIST. Model B ($\lambda = 1$) is similar. As shown in Fig. 2a, the permuted (STE) achieves 93% of test accuracy compared to 56% for Naïve. This is surprising as there is an effective weight for model merging in the permutation of neurons.

7. Both MNIST and FMNIST have 10 classes, and to merge with all weights, including up to the last layer, class 0 in MNIST and class T-shirt/top in FMNIST mean Label 0.
8. github.com/google-research/google-research/tree/master/kip



(a) STE (Full Data) (b) STE (Coreset) (c) STE (Data Cond)

Figure 2: **Model merging between different datasets is possible after permuting even with significantly small surrogate datasets.** Accuracy interpolating between models trained on MNIST and RMNIST. The vertical axis represents accuracy on the mixed dataset MNIST-RMNIST. The solid orange line represents the test accuracy of the merged model using STE. Figure 2a shows model merging with full data. Figures 2b and 2c show merging with only 10 samples per class, using coreset selection and dataset condensation. The horizontal dashed lines represent Coreset AB and Data Cond AB methods.

Table 2: **Test accuracies (%) on D_{AB} for various model merging between different dataset.** In model merging between different datasets, the results demonstrate that both STE and STE with surrogate datasets achieve higher accuracy than other methods of merging models. We omitted the error bars from five seeds as they are sufficiently small, being less than 1%.

	MNIST-RMNIST	USPS-MNIST	SPLIT-CIFAR10	MNIST-FMNIST
Model A	55.58	76.04	48.40	53.21
Model B	57.61	62.99	48.90	51.81
Model AB	98.19	96.92	95.63	94.03
Ensemble	84.51	93.46	79.79	75.93
Data Cond AB	74.47	82.55	39.54	73.28
Coreset AB	67.77	76.69	38.50	66.03
Naïve	56.14	68.85	10.00	45.75
WM	70.92	84.21	58.91	55.61
OT	37.06	79.20	24.01	24.76
OT (Tuned)	58.57	82.39	46.62	48.10
ZipIt!	71.35	79.96	72.05	58.95
STE (Full)	93.52	95.50	89.80	83.76
STE (Coreset)	88.78	93.30	82.60	77.77
STE (Data Cond)	88.78	92.50	71.95	80.94

Next, similar experiments are conducted across the various datasets. The results are shown in Tab. 2. In the table, **Model AB** is the oracle model trained with the mixed dataset, while Models A and B are the pre-merging models trained on Datasets A and B, respectively. STE (Full) outperforms all other baseline methods and ensemble. STE (Full) achieves high accuracy, especially for merging, which is difficult even with OT and ZipIt!

such as MNIST-FMNIST. For model merging on a single dataset, WM and STE (Full) are reported to perform similarly (Ainsworth et al., 2023). However, in model merging between different datasets, we find that STE (Full) significantly outperforms WM. This implies that not only the weights but also the information about the datasets is important when merging between different datasets.

4.2. Model Merging with Surrogate Datasets

Table 3: **Impact of surrogate datasets sample size.** It compares test accuracy for STE (Coreset) and Corset AB on SPLIT-CIFAR10 with varying numbers of samples. Columns represent the number of samples per class.

	1	10	50	100	500
STE (Coreset)	61.15	75.13	82.77	84.85	88.62
Coreset AB	19.32	25.53	41.61	49.31	76.47

Through our experiments with surrogate datasets, we demonstrate that model merging is effective even with a reduced number of data points. We compare our method to STE (Coreset) and STE (Data Cond). **STE (Coreset)** uses a surrogate datasets made with coreset selection, and **STE (Data Cond)** uses one made with dataset condensation. We find that the proposed method significantly outperforms the naïve method, even with as few as 10 data points per class (approximating 0.2% of the training dataset). This suggests a notable efficiency in model merging when dealing with limited data. In comparison to other baselines, STE (Coreset) and STE (Data Cond) achieve higher accuracy than the other baseline methods except for Ensemble, which has a high inference cost. It is particularly surprising that coreset selection, even with a small number of data points chosen through simple random sampling, is sufficient.

To assess the effectiveness of model merging in scenarios with limited data points, we compare our method with the **Coreset AB** and **Data Cond AB** methods, which are each trained from scratch on surrogate Dataset AB, created through coreset selection and dataset condensation, respectively. This comparison is crucial because if effective performance is achieved with training from scratch on the smaller surrogate dataset of P_{AB}, it could suggest that the additional benefits of model merging are limited. Despite this possibility, our method demonstrates superior accuracy over both the Coreset AB and Data Cond AB methods. This advantage comes from its ability to align the weights and maintain optimized loss values for each dataset, resulting in lower loss values on the mixed dataset. Table 3 shows the impact of the number of surrogate datasets samples on model merging. In all cases, STE (Coreset) outperforms Coreset AB. These findings are further supported by the results in Figs.2b and 2c and are comprehensively summarized in Table2.

4.3. Computational Cost of Mode Merging

In this section, we evaluate the computational cost of the model merging. Our comparison includes three models: Model AB, STE (Data Cond), and STE (Coreset), chosen for their demonstrated high accuracy in Table 2. Figure 3 shows test accuracy and the number of steps for training and merging on the SPLIT-CIFAR10. Model merging using surrogate

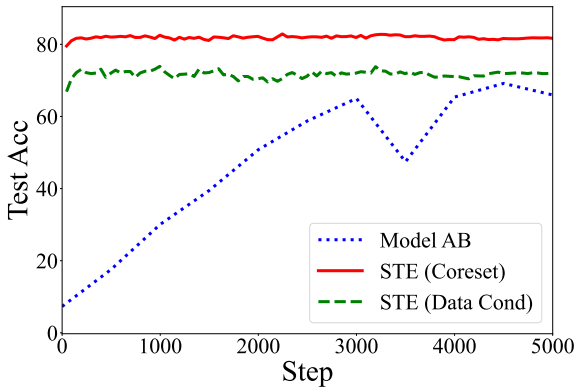


Figure 3: **STE with surrogate datasets is much faster than full training.** This Table shows a comparison of computational costs: full training vs. model merging. The vertical axis represents the test accuracy on Dataset AB. The horizontal axis shows the number of steps required both for training from scratch on Dataset AB and for merging models trained on Datasets A and B. To ensure a fair comparison, training and merging are performed with the same batch size.

datasets achieves higher accuracy with fewer steps than Model AB, which is trained on the mixed dataset.

5. Related Work

First, we introduce existing methods that have a similar purpose to model merging and organize the differences with model merging. Then, we introduce LMC, which is closely related to model merging. Finally, the differences with existing model merging research are summarized.

Continuous learning. Continuous learning is a method for learning new knowledge while retaining previously acquired knowledge (Silver et al., 2013). A major strategy in continuous learning is to separate the weights used for learning between Datasets A and B (Kirkpatrick et al., 2017; Mallya and Lazebnik, 2018).

Federated learning. Federated learning is a learning method without directly sharing the datasets in cases where each training dataset is distributed (McMahan et al., 2017). Federated learning is promising in terms of data privacy, security, and the use of heterogeneous data, since datasets are not shared. Instead of sharing data points, gradients of weights for losses are shared. Like model merging with condensed datasets, federated learning aims to create a model that adapts to the entire dataset without the need to share the raw data.

Continuous learning and federated learning often involve a dependency where the training of Model B relies on Model A, limiting adaptability to pre-trained models. Conversely, model merging allows flexible combinations with other models like Model C without retraining. This is because model merging is conducted independently after the training of Models A and B.

Ensemble. Ensemble methods (Breiman, 1996; Wolpert, 1992; Schapire, 1999) improve the accuracy by taking the average of the predictions of several different models. As was shown in Sec. 4, the ensemble method works surprisingly well for merging between different

datasets. However, ensemble methods have disadvantages in terms of computational cost and memory efficiency since they use the predictions of all models in inference.

LMC. The concept of mode connection, where the optimal weights of the scholastic gradient descent (SGD) have connected paths between each other, was introduced by Timur (Garipov et al., 2018). Furthermore, Jonathan (Frankle et al., 2020) proposed the LMC and found a relationship between the LMC and the Lottery Hypothesis (Frankle and Carbin, 2019). It has been reported that LMC is valid if the neurons of two networks trained with different random seeds are appropriately permuted (Entezari et al., 2021; Ainsworth et al., 2023). Furthermore, LMC has been reported to be valid between fine-tuning models trained with different random seeds from a single pre-training model (Neyshabur et al., 2020). Thus, LMC has attracted attention as a tool for understanding SGD, the Lottery Hypothesis, and fine-tuning.

Merging Methods. Model merging can be categorized into two scenarios: FT-Merge and Pretrain-Merge. **FT-Merge** is a specific scenario where models fine-tuned from a same pre-trained model are merged. In the case of FT-Merge, merging can be done through weight averaging or similar methods, including Gradient Matching (Daheim et al., 2024), Elastic Weight Consolidation (Leontev et al., 2020) and Fisher-Weighted Averaging (Matena and Raffel, 2022), as implemented in mergekit (Goddard et al., 2024)[9]. This is possible for FT-Merge because, being fine-tuned from the same initial weights with a small learning rate, the two fine-tuned models exist in the same loss basin. Therefore, there is no loss barrier between the two models, allowing the weight averaging strategy to work well. **Pretrain-Merge** (our problem setting) is a method that merges models trained from arbitrary initial values, not constrained by fine-tuning. Pretrain-Merge aims to merge models from different initial values, and it does not have the constraints present in FT-Merge, i.e., sharing the same pre-trained model. Pretrain-Merge methods using optimal transport (OT) (Singh and Jaggi, 2020) and using correlation of neurons (Stoica et al., 2023) have been proposed. We compare these methods as baselines in our experiment.

6. Limitations

Our results have several limitations. (1) The analysis in Sec. 3 assumes the existence of optimal weights $\mathbf{w_A}$ and $\mathbf{w_B}$, which are close enough to be considered convex functions, as shown in Fig. 1. (2) We showed that STE can reach effective permutations experimentally, but there is a large number of permutation patterns, thus there is no theoretical guarantee, and theoretical analysis is a remaining task. (3) Our experiments are limited to image classification between the same model architectures. Adaptation of model merging to natural language datasets and generative models is an intriguing application (e.g. Checkpoint Merger of Stable Diffusion web UI (AUTOMATIC1111, 2022)).

7. Conclusion and Future Work

This paper investigated model merging between different datasets. We found that there is an effective weight for model merging in the permutation of neurons. This finding is a motivation for future research to improve the efficiency of permutation search for model

9. Excluding Elastic Weight Consolidation.

merging between different datasets. Furthermore, we proposed model merging by using a surrogate dataset, without sharing all data points. Future work needs to examine whether a surrogate dataset protects privacy. In other research directions, the model merging between many models is of interest. In DNN training, huge computational costs are being spent to develop huge models to improve accuracy, but this may be a limitation from the viewpoint of system energy consumption. Efficient merging of multiple models could pave the way for new learning methods as (Li et al., 2022) to replace current learning methods where a single data point affects all parameter updates.

References

Samuel Ainsworth, Jonathan Hayase, and Siddhartha Srinivasa. Git re-basin: Merging models modulo permutation symmetries. In *The Eleventh International Conference on Learning Representations*, 2023.

AUTOMATIC1111. Stable diffusion web ui. https://github.com/AUTOMATIC1111/stable-diffusion-webui, 2022. Accessed: May 8, 2023.

Leo Breiman. Bagging predictors. *Machine learning*, 24:123–140, 1996.

Nico Daheim, Thomas Möllenhoff, Edoardo Ponti, Iryna Gurevych, and Mohammad Emtiyaz Khan. Model merging by uncertainty-based gradient matching. In *The Twelfth International Conference on Learning Representations*, 2024. URL https://openreview.net/forum?id=D7KJmfEDQP.

Rahim Entezari, Hanie Sedghi, Olga Saukh, and Behnam Neyshabur. The role of permutation invariance in linear mode connectivity of neural networks. *arXiv preprint arXiv:2110.06296*, 2021.

Jonathan Frankle and Michael Carbin. The lottery ticket hypothesis: Finding sparse, trainable neural networks. In *International Conference on Learning Representations*, 2019.

Jonathan Frankle, Gintare Karolina Dziugaite, Daniel Roy, and Michael Carbin. Linear mode connectivity and the lottery ticket hypothesis. In *International Conference on Machine Learning*, pages 3259–3269. PMLR, 2020.

Timur Garipov, Pavel Izmailov, Dmitrii Podoprikhin, Dmitry P Vetrov, and Andrew G Wilson. Loss surfaces, mode connectivity, and fast ensembling of dnns. *Advances in neural information processing systems*, 31, 2018.

Charles Goddard, Shamane Siriwardhana, Malikeh Ehghaghi, Luke Meyers, Vlad Karpukhin, Brian Benedict, Mark McQuade, and Jacob Solawetz. Arcee's mergekit: A toolkit for merging large language models. *arXiv preprint arXiv:2403.13257*, 2024.

Chengcheng Guo, Bo Zhao, and Yanbing Bai. Deepcore: A comprehensive library for coreset selection in deep learning. In *International Conference on Database and Expert Systems Applications*, pages 181–195. Springer, 2022.

Ziyao Guo, Kai Wang, George Cazenavette, Hui Li, Kaipeng Zhang, and Yang You. Towards lossless dataset distillation via difficulty-aligned trajectory matching. *arXiv preprint arXiv:2310.05773*, 2023.

Jonathan J. Hull. A database for handwritten text recognition research. *IEEE Transactions on pattern analysis and machine intelligence*, 16(5):550–554, 1994.

Keller Jordan, Hanie Sedghi, Olga Saukh, Rahim Entezari, and Behnam Neyshabur. Repair: Renormalizing permuted activations for interpolation repair. *arXiv preprint arXiv:2211.08403*, 2022.

James Kirkpatrick, Razvan Pascanu, Neil Rabinowitz, Joel Veness, Guillaume Desjardins, Andrei A Rusu, Kieran Milan, John Quan, Tiago Ramalho, Agnieszka Grabska-Barwinska, et al. Overcoming catastrophic forgetting in neural networks. *Proceedings of the national academy of sciences*, 114(13):3521–3526, 2017.

Alex Krizhevsky, Geoffrey Hinton, et al. Learning multiple layers of features from tiny images. 2009.

Yann LeCun, Léon Bottou, Yoshua Bengio, and Patrick Haffner. Gradient-based learning applied to document recognition. *Proceedings of the IEEE*, 86(11):2278–2324, 1998.

Mikhail Iu Leontev, Viktoriia Islenteva, and Sergey V Sukhov. Non-iterative knowledge fusion in deep convolutional neural networks. *Neural Processing Letters*, 51(1):1–22, 2020.

Margaret Li, Suchin Gururangan, Tim Dettmers, Mike Lewis, Tim Althoff, Noah A Smith, and Luke Zettlemoyer. Branch-train-merge: Embarrassingly parallel training of expert language models. *arXiv preprint arXiv:2208.03306*, 2022.

Arun Mallya and Svetlana Lazebnik. Packnet: Adding multiple tasks to a single network by iterative pruning. In *Proceedings of the IEEE conference on Computer Vision and Pattern Recognition*, pages 7765–7773, 2018.

Michael S Matena and Colin A Raffel. Merging models with fisher-weighted averaging. *Advances in Neural Information Processing Systems*, 35:17703–17716, 2022.

Brendan McMahan, Eider Moore, Daniel Ramage, Seth Hampson, and Blaise Aguera y Arcas. Communication-efficient learning of deep networks from decentralized data. In *Artificial intelligence and statistics*, pages 1273–1282. PMLR, 2017.

Baharan Mirzasoleiman, Jeff Bilmes, and Jure Leskovec. Coresets for data-efficient training of machine learning models. In *International Conference on Machine Learning*, pages 6950–6960. PMLR, 2020.

Behnam Neyshabur, Hanie Sedghi, and Chiyuan Zhang. What is being transferred in transfer learning? In H. Larochelle, M. Ranzato, R. Hadsell, M.F. Balcan, and H. Lin, editors, *Advances in Neural Information Processing Systems*, volume 33, pages 512–523, 2020.

Timothy Nguyen, Roman Novak, Lechao Xiao, and Jaehoon Lee. Dataset distillation with infinitely wide convolutional networks. *Advances in Neural Information Processing Systems*, 34:5186–5198, 2021.

Robert E Schapire. A brief introduction to boosting. In *International Joint Conference on Artificial Intelligence*, volume 99, pages 1401–1406. Citeseer, 1999.

Daniel L Silver, Qiang Yang, and Lianghao Li. Lifelong machine learning systems: Beyond learning algorithms. In *2013 Association for the Advancement of Artificial Intelligence spring symposium series*, 2013.

Sidak Pal Singh and Martin Jaggi. Model fusion via optimal transport. *Advances in Neural Information Processing Systems*, 33:22045–22055, 2020.

George Stoica, Daniel Bolya, Jakob Bjorner, Taylor Hearn, and Judy Hoffman. Zipit! merging models from different tasks without training. *arXiv*, 2023.

David H Wolpert. Stacked generalization. *Neural networks*, 5(2):241–259, 1992.

Han Xiao, Kashif Rasul, and Roland Vollgraf. Fashion-mnist: a novel image dataset for benchmarking machine learning algorithms, 2017.

Bo Zhao, Konda Reddy Mopuri, and Hakan Bilen. Dataset condensation with gradient matching. In *International Conference on Learning Representations*, 2021.

Appendix A. Experimental Details

A.1. Dataset Condensation

For MNIST, RMNIST, FMNIST, and USPS we condensed the dataset using Gradient Matching (Zhao et al., 2021). The setup for creating the condensed dataset was the same architecture and the same data preprocessing as used for training. Condensation was performed in two cases: 1 per label and 10 per label. In CIFAR10, we used a more sophisticated dataset condensation (Nguyen et al., 2021). Since compressed datasets were publicly available[10], we used them.

A.2. Setup in Fig. 1d

Can we find the effective permutation for model merging without data? To answer this question, we generated a variety of permutations and plotted the correlations between test loss on the mixed dataset and neuronal permutation criteria in Fig. 1d. The datasets used were MNIST and RMNIST-90. To produce permutation variations, we used 25 patterns of FWM β from 0 to 1 and max iteration of WM search from $[2, 5, 300]$ and random number seed $[0, 1, 2, 3, 4]$. Of the 375 permutations generated, 30 are unique.

A.3. Setup of Tab. 2

To test the stability of the model merging method, we loaded the checkpoints of the trained Models A and B and experimented with different random number seeds. We merge the models five times to show the average test accuracy. The error bars are small enough to be omitted.

10. https://storage.cloud.google.com/kip-datasets/kip/cifar10/ConvNet_ssize500_nozca_nol_noaug_ckpt11500.npz