LEARNING TO PREDICT PARAMETER FOR UNSEEN DATA

Anonymous authors
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ABSTRACT

Typical deep learning models depend heavily on large amounts of training data and resort to an iterative optimization algorithm (e.g., SGD or Adam) for learning network parameters, which makes the training process very time- and resource-intensive. In this paper, we propose a new training paradigm and formulate network parameter training into a prediction task: given a network architecture, we observe there exists correlations between datasets and their corresponding optimal network parameters, and explore if we can learn a hyper-mapping between them to capture the relations, such that we can directly predict the parameters of the network for a new dataset never seen during the training phase. To do this, we put forward a new hypernetwork with the purpose of building a mapping between datasets and their corresponding network parameters, and then predict parameters for unseen data with only a single forward propagation of the hypernetwork. At its heart, our model benefits from a series of GRU sharing weights to capture the dependencies of parameters among different layers in the network. Extensive experimental studies are performed and experimental results validate our proposed method achieves surprisingly good efficacy. For instance, it takes 119 GPU seconds to train ResNet-18 using Adam from scratch and obtain a top-1 accuracy of 74.56%, while our method costs only 0.5 GPU seconds to predict the network parameters of ResNet-18 achieving comparable performance (73.33%), more than 200 times faster than the traditional training paradigm.

1 INTRODUCTION

Deep learning has yielded superior performance in a variety of fields in the past decade, such as computer vision (Kendall & Gal, 2017; Zhao et al., 2019), natural language processing (Devlin et al., 2019; Liu et al., 2017), reinforcement learning (Zheng et al., 2018; Fujimoto et al., 2018), etc. One of the keys to success for deep learning stems from huge amounts of training data used to learn a deep network. In order to optimize the network, the traditional training paradigm takes advantage of an iterative optimization algorithm (e.g., SGD) to train the model in a mini-batch manner, leading to huge time and resource consumption. For example, when training RestNet-101 (He et al., 2016) on the ImageNet (Deng et al., 2009) dataset, it often takes several days or weeks for the model to be well optimized with GPU involved. Thus, how to accelerate the training process of the network is an emergent topic in deep learning.

Nowadays, many methods for accelerating training of deep neural networks have been proposed (Kingma & Ba, 2015; Ioffe & Szegedy, 2015; Chen et al., 2018). The representative works include optimization based techniques by improving the stochastic gradient descent (Kingma & Ba, 2015; Yong et al., 2020; Anil et al., 2020), normalization based techniques (Ioffe & Szegedy, 2015; Salimans & Kingma, 2016; Ba et al., 2016), parallel training techniques (Chen et al., 2018; Kim et al., 2019), et. Although these methods have showed promising potential to speed up the training of the network, they still follow the traditional iterative-based training paradigm.

In this paper, we investigate a new training paradigm for deep neural networks. In contrast to previous works accelerating the training of the network, we formulate the parameter training problem into a prediction task: given a network architecture, we attempt to learn a hyper-mapping between datasets and their corresponding optimal network parameters, and then leverage the hyper-mapping to directly predict the network parameters for a new dataset unseen during training. A basic

assumption behind the above prediction task is that there exists correlations between datasets and their corresponding parameters of a given network. In order to demonstrate the rationality of this assumption, we perform the following experiment: for a dataset, we first randomly sample 3000 images to train a 3-layer convolutional neural network until convergence. Then we conduct the average pooling operation to the original inputs as a vector representation of the training data. We repeat the above experiment 1000 times, and thus obtain 1000 groups of representations and the corresponding network parameters. Finally, we utilize Canonical Correlation Analysis (CCA) (Weenink, 2003) to evaluate the correlations between training data and the network parameters by the above 1000 groups of data. Figure 1 shows the results, which illustrates there are indeed correlations between training datasets and their network parameters for a given network architecture.

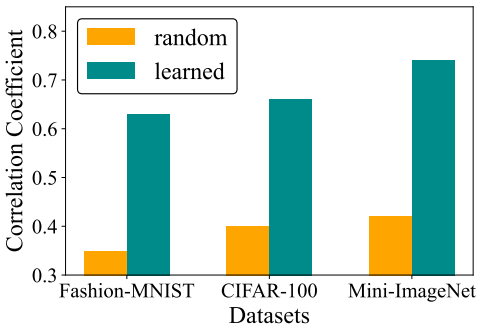

Figure 1: Correlation coefficients between training datasets and the network parameters on the Fashion-MNIST (Xiao et al., 2017), CIFAR-100 (Krizhevsky et al., 2009), Mini-ImageNet (Vinyals et al., 2016) datasets, respectively.'learned' depicts correlations between training datasets and the corresponding optimal network parameters. 'random' denotes correlations between training datasets and the network parameters selected randomly from 1000 groups.

In light of this, we propose a new hypernetwork, called PudNet, to learn a hyper-mapping between datasets and network parameters. Specifically, PudNet first summarizes the characters of datasets by compressing them into different vectors as their sketch. Then, PudNet extends the traditional hypernetwork (Ha et al., 2017) to predict network parameters of different layers based on these vectors. Considering that parameters among different layers should be dependent, we incorporate Gate Recurrent Unit (GRU) (Cho et al., 2014) into PudNet to capture the relations among them, so as to improve the performance of PudNet. Finally, it is worth noting that for training PudNet, it is infeasible if we prepare thousands of datasets and train networks on these datasets to obtain the corresponding optimal parameters respectively. Instead, we adopt a meta-learning based approach (Finn et al., 2017; Vinyals et al., 2016) to train the hypernetwork.

Extensive experiments demonstrate the surprising effectiveness of our PudNet. For example, it takes around 54, 119, 140 GPU seconds to train ResNet-18 using Adam from scratch and obtain top-1 accuracies of 99.91%, 74.56%, 71.84% on the Fashion-MNIST (Xiao et al., 2017), CIFAR-100 (Krizhevsky et al., 2009), Mini-ImageNet (Vinyals et al., 2016), respectively. While our method costs only around 0.5 GPU seconds to predict the parameters of ResNet-18 and still achieves 96.24%, 73.33%, 71.57% top-1 accuracies on the three datasets respectively, at least 100 times faster than the traditional training paradigm.

Our contributions are summarized as follows: 1) We find there are correlations between datasets and their corresponding parameters of a given network, and propose a general training paradigm for deep networks by formulating network training into a parameter prediction task. 2) We extend hypernetwork to learn the correlations between datasets and their corresponding network parameters, such that we can directly generate parameters for arbitrary unseen data with only a single forward propagation. 3) Our method achieves surprisingly good performance for unseen data, which is expected to motivate more researchers to explore along with this research direction.

2 Related Work

2.1 Hypernetworks

The core idea of hypernetworks is to use one network to predict parameters for another network (Ha et al., 2017; Knyazev et al., 2021). The original goal of hypernetwork is to decrease the number of training parameters (Ha et al., 2017), by training a hypernetwork with a smaller size to generate the parameters of another network with a larger size. Because of its promising performance, hypernetwork has been gradually applied to various tasks (Krueger et al., 2017; Zhang et al., 2019; von Oswald et al., 2020; Li et al., 2020; Shamsian et al., 2021). von Oswald et al. (2020) proposes a

task-conditioned hypernetwork to overcome catastrophic forgetting in continual learning. It learns an embedding for each task and utilizes the task embedding to generate corresponding parameters for each task. Bayesian hypernetwork (Krueger et al., 2017) is proposed to approximate Bayesian inference in neural networks. GHN (Knyazev et al., 2021) attempts to predict network parameters for unseen architectures, given a fixed dataset. Our work is orthogonal to GHN, since we aim to predict parameters for unseen data with a fixed network architecture.

2.2 Acceleration of Network Training

Many works have been proposed to speed up the training process of deep neural networks in the past decade, including optimization based methods (Kingma & Ba, 2015; Yong et al., 2020; Anil et al., 2020), normalization based methods (Ioffe & Szegedy, 2015; Salimans & Kingma, 2016; Ba et al., 2016), parallel training methods (Chen et al., 2018; Kim et al., 2019), etc. Optimization based methods mainly aim to improve the stochastic gradient descent. For instance, Yong et al. (2020) proposes a gradient centralization method that centralizes gradient vectors to improve the Lipschitzness of the loss function. Normalization based methods intend to propose good normalization methods to speed up the training process. The representative work is the batch normalization (Ioffe & Szegedy, 2015) that can make the optimization landscape smooth and lead to fast convergence (Santurkar et al., 2018). Parallel training methods usually stack multiple hardwares to conduct parallel training, which can reduce the training time by dispersing calculation amounts to distributed devices. However, these methods still follow the traditional iterative based training paradigm. Different from them, we attempt to explore a new training paradigm, and transform the training of neural network into a parameter prediction task.

3 Proposed Method

In this section, we will introduce our PudNet in detail. For better illustration, we first give preliminaries and our problem formulation, and then elaborate the details of our method.

3.1 Preliminaries

Notation We denote H_θ as our hypernetwork parameterized by θ. Let $\mathcal{D}^{train} = \{D_i\}_{i=1}^{\mathcal{N}}$ be the set of training datasets, where D_i is the ith dataset and $\mathcal{N}$ is the number of training datasets. Each sample $x_j \in D_i$ has a label $y_j \in \mathcal{C}_i^{tr}$, where $\mathcal{C}_i^{tr}$ is the class set of D_i. We use $\mathcal{C}^{tr} = \bigcup_{i=1}^{\mathcal{N}} \mathcal{C}_i^{tr}$ to denote the whole label set of training datasets. Similarly, we define $\mathcal{D}^{test}$ as the set of unseen datasets used for testing and $\mathcal{C}^{te}$ as the set containing all labels in $\mathcal{D}^{test}$.

Problem Formulation In contrast to traditional iterative-based training paradigm, we attempt to explore a new training paradigm, and formulate the network training into a parameter prediction task. To this end, we propose the following objective function:

$$\arg\min_{\theta} \sum_{i=1}^{\mathcal{N}} \mathcal{L}(\mathcal{F}(D_i, \Omega; H_\theta), \mathcal{M}_i^{\Omega}), \tag{1}$$

where $\mathcal{F}(D_i, \Omega; H_\theta)$ denotes a forward propagation of our hypernetwork H_θ. The input of the forward propagation is the dataset D_i and its output is the predicted parameters of network Ω by H_θ. Note that the architecture of Ω is always fixed during training and testing, e.g., ResNet-18. This makes sense because we often apply a representative deep model to data of different domains. Thus, it is obviously meaningful if we can predict the network parameters for unseen data using an identical network architecture. $\mathcal{M}^{\Omega} = \{\mathcal{M}_i^{\Omega}\}_{i=1}^{\mathcal{N}}$ denotes the ground-truth parameter set of network Ω corresponding to datasets $\mathcal{D}^{train}$, where $\mathcal{M}_i^{\Omega}$ is the ground-truth parameters for the dataset D_i. $\mathcal{L}$ is a loss function, measuring the difference between the ground-truth parameters $\mathcal{M}_i^{\Omega}$ and the predicted parameters.

The core idea in (1) is to learn a hyper-mapping H_θ between datasets $\mathcal{D}^{train}$ and the network parameter set $\mathcal{M}^{\Omega}$, on the basis of our finding that there are correlations between datasets and the network parameters, as shown in Figure 1. However, it is prohibitive if preparing thousands of datasets D_i

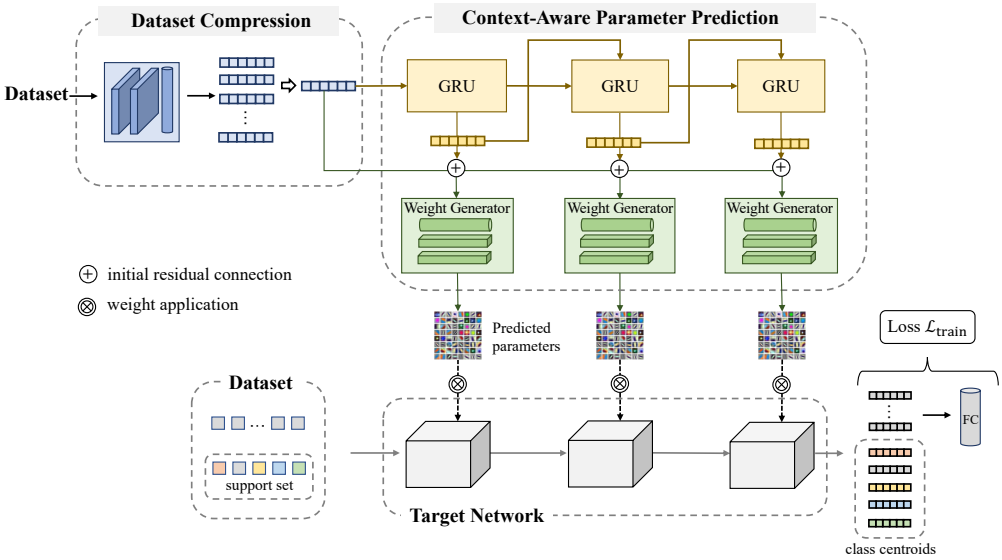

Figure 2: Overview of our proposed PudNet. PudNet first compresses each dataset into a sketch with a fixed size, and then utilizes the hypernetwork to generate parameters of a target network based on the sketch. Finally, PudNet is optimized based on a support set in a meta-learning based manner.

and training network Ω on D_i to obtain the corresponding ground-truth parameters $\mathcal{M}_i^{\Omega}$ respectively. To alleviate this problem, we adopt a meta-learning based (Vinyals et al., 2016) approach to train the hypernetwork H_θ, and propose another objective function as:

$$\arg\min_{\theta} \sum_{i=1}^{\mathcal{N}} \sum_{x_j \in D_i} \mathcal{L}(x_j, y_j; \mathcal{F}(D_i, \Omega; H_\theta)), \tag{2}$$

Instead of optimizing H_θ by directly matching the predicted parameters $\mathcal{F}(D_i, \Omega; H_\theta)$ with the ground-truth parameters $\mathcal{M}_i^{\Omega}$, we can adopt a typical loss, e.g., cross-entropy, to optimize H_θ, where each dataset D_i can be regarded as a task in meta-learning (Vinyals et al., 2016). By learning on multiple tasks, the parameter predictor H_θ is gradually able to learn to predict performant parameters for training datasets $\mathcal{D}^{train}$. During testing, we can utilize $\mathcal{F}(D, \Omega; H_\theta)$ to directly predict the parameters for a testing dataset D never seen in $\mathcal{D}^{train}$ with only a single forward propagation.

3.2 Overview of Our Framework

Our goal is to learn a hypernetwork H_θ, so as to directly predict the network parameters for an unseen dataset by H_θ. However, there remains two issues that are not solved: First, the sizes of different D_i may be different and the dataset sizes may be large, which makes H_θ hard to be trained; Second, there may be correlations among parameters of different layers in a network. However, how to capture such context relations among parameters has not been fully explored so far.

To this end, we propose a novel framework, PudNet, as shown in Figuire 2, PudNet first introduces a dataset compression module to compress each dataset D_i into a small size sketch $\boldsymbol{s}_i \in \mathbf{R}^{l \times m}$ to summarize the major characteristics of D_i, where l and m are the size and dimension of the sketch, respectively. Then, our context-aware parameter prediction module takes the sketch $\boldsymbol{s}_i$ as input, and outputs the predicted parameters of the target network, e.g., ResNet-18. At its heart, multiple GRUs sharing weights are constructed to capture the dependencies of parameters among different layers in the network. Finally, PudNet is optimized based on a support set in a meta-learning based manner.

3.3 Dataset Compression

To solve the issue of different sizes of training datasets, we first compress each dataset into a sketch with a fixed size. In recent years, many data compression methods have been proposed, such as

matrix sketching (Qian et al., 2015; Song et al., 2019), random projection (Sarlos, 2006; Liberty et al., 2007), etc. In principle, these methods can be applied to our data compression module. For simplification, we leverage a deep neural network to extract a feature vector as the representation of each sample, and then conduct the average pooling operation to generate a final vector as the sketch of the dataset. The sketch $\boldsymbol{s}_i$ for the dataset D_i can be calculated as:

$$\boldsymbol{s}_i = \frac{1}{|D_i|} \sum_{x_j \in D_i} T_\phi(x_j), \tag{3}$$

where $T_\phi(\cdot)$ denotes a feature extractor parameterized by ϕ, and $|D_i|$ is the size of the dataset D_i. In future work, more efforts could be made to explore more on-the-fly solutions to summarize the information of a dataset.

3.4 Context-Aware Parameter Prediction

After obtaining the sketches for all training datasets, we will feed them into the context-aware parameter prediction module, i.e., our hypernetwork, as shown in Figure 2. In the followings, we will introduce this module in detail.

Capturing Context Relations via GRU Since an input of a neural network would sequentially pass forward the layers of this network, the parameters of different layers should be not independent. If we ignore the context relations among parameters of different layers, the solution may be sub-optimal. Thus, we utilize GRU (Cho et al., 2014) to capture the context-aware parameter relations as shown in Figure 3. Note that we have two changes compared to conventional GRU: 1) conventional GRU utilizes the randomly initialized hidden state $\boldsymbol{h}_0$. Different from this, we set the dataset sketch embedding as the initial hidden state: $\boldsymbol{h}_0 = \boldsymbol{s}_i$, so as to provide dataset information for predicting corresponding structure parameters; 2) In each recurrent step, conventional GRU usually takes the next word as input in natural language process field (Cho et al., 2014). Instead of that, we exploit the predicted structure parameters of previous layer as input, enabling the information of shallower layer parameters memorized in GRU to help the prediction of parameters in the deeper layer. By this way, the dependency relations among parameters of different layers can be well captured.

The following comes a formal description:

$$\begin{aligned}
\boldsymbol{r}_t &= \sigma(\boldsymbol{W}_r \cdot [\boldsymbol{h}_{t-1}, \boldsymbol{a}_{t-1}]), \\
\boldsymbol{z}_t &= \sigma(\boldsymbol{W}_z \cdot [\boldsymbol{h}_{t-1}, \boldsymbol{a}_{t-1}]), \\
\tilde{\boldsymbol{h}}_t &= tanh(\boldsymbol{W}_h \cdot [\boldsymbol{r}_t * \boldsymbol{h}_{t-1}, \boldsymbol{a}_{t-1}]), \\
\boldsymbol{h}_t &= (1 - \boldsymbol{z}_t) * \boldsymbol{h}_{t-1} + \boldsymbol{z}_t * \tilde{\boldsymbol{h}}_t, \\
\boldsymbol{a}_t &= \sigma(\boldsymbol{W}_o \cdot \boldsymbol{h}_t),
\end{aligned}$$

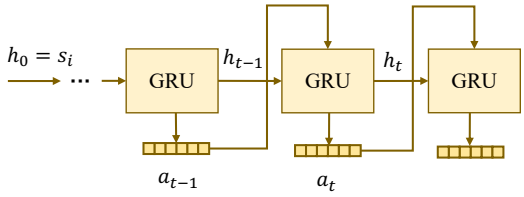

Figure 3: An illustration of capturing context relations via GRU.

where $\boldsymbol{h}_t$ could transfer dataset related information. $\boldsymbol{a}_t$ is a latent vector encoding the context information. $\boldsymbol{W}_r, \boldsymbol{W}_z, \boldsymbol{W}_h, \boldsymbol{W}_o$ are the learnable parameters. As in GRU, the reset gate $\boldsymbol{r}_t$ decides how much information in the hidden state $\boldsymbol{h}_{t-1}$ needs to be reset. $\tilde{\boldsymbol{h}}_t$ is a new memory, which absorbs the information of $\boldsymbol{h}_{t-1}$ and $\boldsymbol{a}_{t-1}$. $\boldsymbol{z}_t$ is an update gate, which regulates how much information in $\tilde{\boldsymbol{h}}_t$ to update and how much information in $\boldsymbol{h}_{t-1}$ to forget. The context-aware output $\boldsymbol{a}_t$ is taken as input to the weight generator to predict parameters of the t-th layer of the target network Ω.

Initial Residual Connection To ensure that the final context-aware output contains at least a fraction of the initial dataset information, we additionally implement an initial residual connection between dataset sketch embedding $\boldsymbol{s}_i$ and $\boldsymbol{a}_t$ as:

$$\hat{\boldsymbol{a}}_t = \boldsymbol{a}_t \times (1 - \eta) + \boldsymbol{s}_i \times \eta, \tag{4}$$

where η is the hyperparameter. After obtaining $\hat{\boldsymbol{a}}_t$, we put $\hat{\boldsymbol{a}}_t$ into a weight generator used to generate the parameters of Ω.

Weight Generator Since the target network Ω usually has different sizes and dimensions in different layers, we construct a weight generator g_{ψ_t} to transform $\hat{\boldsymbol{a}}_t$ of a fixed dimension to network parameter tensor $\boldsymbol{w}_t$ with variable dimensions. Here g_{ψ_t} denotes the weight generator of the t-th layer, ψ_t is the learnable parameters of g_{ψ_t}, $\boldsymbol{w}_t$ is the predicted parameter of t-th layer in Ω. We can derive the predicted parameter of the t-th layer as:

$$\boldsymbol{w}_t = g_{\psi_t}(\hat{\boldsymbol{a}}_t) \tag{5}$$

where g_{ψ_t} consists of one linear layer and two 1×1 convolutional Layers. More detail can be found in Appendix A.1. When the parameters $\boldsymbol{w}_t$ of each layer are predicted, we can use these parameters as the final parameters of Ω.

3.5 Optimization of Our Framework

In this section, we introduce how to optimize our PudNet. In contrast to traditional classification tasks where training data and testing data have the identical label space. In our task, the label spaces between training and testing can be different, even not overlapped. Thus, training a classification head on the training data can not be used to predict labels of testing data. Motivated by several metric learning methods (Chen et al., 2021; Oreshkin et al., 2018), we introduce a parameter-free classification method to solve the above issue.

Similar to Chen et al. (2021), we obtain a metric-based category prediction on class c_k as:

$$p(y = c_k | x_j, \Omega, D_i; H_\theta) = \frac{exp(\tau \cdot < f(x_j; \mathcal{F}(D_i, \Omega; H_\theta)), \boldsymbol{u}_k >)}{\sum_c exp(\tau \cdot < f(x_j; \mathcal{F}(D_i, \Omega; H_\theta)), \boldsymbol{u}_c >)}, \tag{6}$$

where $\boldsymbol{u}_k$ is the centroid of class c_k, which is the average output of the predicted network Ω over samples belonging to class c_k in the support set, as in Snell et al. (2017). $< \cdot, \cdot >$ denotes the cosine similarity of two vector, and τ is a learnable temperature parameter. $f(x_j; \mathcal{F}(D_i, \Omega; H_\theta))$ is the output of the target neural network Ω based on the input x_j.

Then, the parameter-free classification loss can be defined as:

$$\mathcal{L}_1 = \sum_{i=1}^{\mathcal{N}} \sum_{x_j \in D_i} \mathcal{L}(p(y|x_j, \Omega, D_i; H_\theta), y_j), \tag{7}$$

where y_j is the true label of x_j, $\mathcal{L}$ is the cross-entropy loss.

To further improve the performance of the model, we introduce an auxiliary task for training our hypernetwork, by adding a full classification head $\mathcal{Q}_\varphi$ parameterized by φ. The classification head aims to map the output of the target network Ω to probabilities of the whole classes $\mathcal{C}^{tr}$ from $\mathcal{D}^{train}$. The full classification loss is defined as:

$$\mathcal{L}_2 = \sum_{i=1}^{\mathcal{N}} \sum_{x_j \in D_i} \mathcal{L}(\mathcal{Q}_\varphi(f(x_j; \mathcal{F}(D_i, \Omega; H_\theta))), y_j). \tag{8}$$

Moreover, to make parameter-free based prediction and full classification based prediction consistent, we introduce a Kullback-Leibler Divergence loss to encourage their predicted probabilities to be matched:

$$\mathcal{L}_3 = \sum_{i=1}^{\mathcal{N}} \sum_{x_j \in D_i} KL(q(y|x_j) || p(y|x_j)), \tag{9}$$

where KL is the Kullback-Leibler Divergence. $p(y|x_j)$ and $q(y|x_j)$ are the predicted probabilities of x_j of parameter-free based and full classification based methods, respectively. The probabilities of the corresponding classes in $p(y|x_j)$ are padding with zero to match the dimension of $q(y|x_j)$.

Finally, we give the overall multi-task loss as:

$$\mathcal{L}_{total} = \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3. \tag{10}$$

where D_i can be regarded as a task similar to that in meta-learning. By minimizing (10), our hypernetwork can be well trained. For an unseen data in testing, we utilize our hypernetwork to directly predict its network parameters, and use the parameter-free based method for classification. The training procedure of our PudNet is in Appendix A.4.

4 EXPERIMENT

4.1 DATASET CONSTRUCTION

In the experiment, we construct numerous datasets for evaluating our method based on Four publicly available datasets: Fashion-MNIST (Xiao et al., 2017), CIFAR-100 (Krizhevsky et al., 2009), Mini-ImageNet (Vinyals et al., 2016), Animals-10 (Gupta & Brown, 2022). The constructed datasets are summarized as:

Fashion-set: We randomly select 6 classes from Fashion-MNIST to construct training datasets and the remaining 4 classes for constructing testing datasets. We construct 2000 groups of datasets from the 6-category training set to train PudNet. To verify PudNet's ability to directly generate parameters, we construct 500 groups of datastes from the 4-category testing set to generate 500 groups of network parameters. For each group of network parameters, we also construct another dataset having identical labels but not overlapped samples with the dataset used for generating parameters, in order to test the performance of the predicted network parameters. Each dataset contains 600 randomly sampled images with 2 randomly sampled classes.

CIFAR100-set: We randomly choose 80 classes from CIFAR-100 for constructing training datasets and 20 classes not overlapped with the above 80 classes to construct testing datasets. We sample 100000 groups of datasets for training PudNet. Similar to Fashion-set, we construct 500 groups of datastes to directly generate their network parameters by PudNet, and create another 500 groups of datasets for testing the performance of the predicted parameters. Each datasets consists of 500 images with 5 classes randomly selected.

ImageNet-set: Similar to CIFAR100-set, the mini-Imagenet dataset is randomly split into 80 classes for creating training datasets and 20 classes for creating testing datsets. We sample 50000 groups of datasets for training PudNet. Similar to Fashion-set, we use 500 groups of datastes to generate their network parameters, and construct another 500 groups of datasets for testing. There are 500 images with 5 classes selected randomly in each dataset.

CIFAR100→Animals10: To further verify the generalization of our PudNet, we construct a cross-domain dataset. We use CIFAR-100 to construct training datasets, and Animals-10 for testing datasets. There are 100000 groups of datasets from CIFAR-100 to train PudNet. We randomly split Animals-10 into two not overlapped subsets: one is used to generate parameters, and the other for testing.

4.2 BASELINES

We compare our method with traditional iterative based training paradigm including training from scratch and one training acceleration method, GC (Yong et al., 2020). We also take the pretrained model as a baseline. In addition, we also compare with metric-based meta-learning methods, including MatchNet (Vinyals et al., 2016), ProtoNet (Snell et al., 2017), Meta-Baseline (Chen et al., 2021), Meta-DeepDBC (Xie et al., 2022). We use two kinds of architectures as our target network Ω: a 3-layer CNN, ConvNet-3, and a 18-layer residual network, Resnet-18. To ensure a fair comparison, we use all training datasets for training meta-learning methods and the pretrained model. For all experiments, we use ACC (Top-1 Accuracy) metric to evaluate the classification performance.

4.3 IMPLEMENTATION DETAILS

We perform the experiments using GeForce RTX 3090 Ti GPU. We set the learning rate as 0.001. For the target network ConvNet-3, we set the hyperparameter η as 0.2,0.1,0.3,0.1 for Fashion-set, CIFAR100-set, ImageNet-set, CIFAR100→Animals10 respectively. For the target network ResNet-18, we set the hyperparameter η as 0.2,0.5,0.5,0.5 for Fashion-set, CIFAR100-set, ImageNet-set, CIFAR100→Animals10 respectively. More details could be found in Appendix A.1 and A.2.

4.4 RESULT AND ANALYSIS

General Performance Analysis Table 1 and Table 2 show the general results of our method. It can be observed that our method consistently outperforms the metric-based meta-learning methods

Table 1: Results of different methods in terms of the target network ConvNet-3 on the Fashion-set, CIFAR100-set, ImageNet-set datasets.

Method		Fashion-set		CIFAR100-set		ImageNet-set	
		ACC(%)	time (sec.)	ACC	time (sec.)	ACC	time (sec.)
MatchNet		89.93±0.65	-	47.75±0.73	-	43.83±0.83	-
ProtoNet		92.32±0.37	-	51.96±0.57	-	49.59±0.88	-
Meta-Baseline		94.85±0.31	-	57.69±0.38	-	54.97±0.75	-
Meta-DeepDBC		95.76±0.39	-	60.52±0.41	-	55.36±0.73	-
Pretrained		94.12±0.63	-	58.35±0.61	-	53.28±0.67	-
PudNet		**96.64**±0.34	0.03	**64.09**±0.40	0.03	**59.31**±0.64	0.03
Adam Scratch	1 epochs	91.07±1.11	0.87	49.11±1.03	0.99	41.53±1.20	2.67
	30 epochs	99.97±0.02	25.99	64.54±0.40	28.37	64.33±0.83	77.08
	50 epochs	99.96±0.03	43.36	70.68±0.53	49.02	67.25±0.69	133.48
GC	1 epochs	92.36±1.20	0.88	50.23±1.23	0.99	40.74±1.32	2.67
	30 epochs	99.98±0.01	26.01	66.76±0.54	29.83	65.45±0.89	77.12
	50 epochs	99.97±0.02	43.42	71.56±0.63	50.22	69.44±0.77	133.69

Table 2: Results of different methods in terms of the target network ResNet-18 on the Fashion-set, CIFAR100-set, ImageNet-set datasets.

Method		Fashion-set		CIFAR100-set		ImageNet-set	
		ACC(%)	time (sec.)	ACC	time (sec.)	ACC	time (sec.)
MatchNet		90.16±0.53	-	56.23±0.71	-	53.17±0.91	-
ProtoNet		93.64±0.47	-	60.29±0.59	-	58.95±0.83	-
Meta-Baseline		95.35±0.29	-	67.51±0.55	-	67.16±0.70	-
Meta-DeepDBC		94.28±0.31	-	69.54±0.49	-	68.48±0.60	-
Pretrained		93.76±0.47	-	64.58±0.59	-	65.67±0.73	-
PudNet		**96.24**±0.39	0.50	**73.33**±0.54	0.49	**71.57±0.71**	0.50
Adam Scratch	1 epochs	93.98±1.21	1.83	52.82±1.01	3.96	46.43±1.18	4.81
	30 epochs	99.91±0.05	54.22	74.56±0.45	118.87	71.84±0.69	140.37
	50 epochs	99.87±0.11	91.19	79.85±0.47	198.12	75.98±0.71	231.63
GC	1 epochs	94.11±1.25	1.88	53.21±1.23	4.01	47.55±1.33	4.82
	30 epochs	99.94±0.05	54.93	75.74±0.59	119.03	72.89±0.73	140.98
	50 epochs	99.96±0.03	91.73	79.98±0.55	199.61	76.73±0.87	232.57

Table 3: Results of different methods on the cross-domain datasets CIFAR100→Animals10.

Method	ConvNet-3		ResNet-18	
	ACC (%)	time (sec.)	ACC (%)	time (sec.)
Pretrained	16.43±0.73	-	33.36±0.75	-
Meta-DeepDBC	31.93±0.81	-	40.50±0.64	-
ours	**35.15**±0.77	0.03	**43.21**±0.69	0.49
Adam(1 epochs)	18.33±0.57	21.37	22.09±0.58	31.29
Adam(5 epochs)	38.71±0.31	103.25	49.12±0.08	156.56
Adam(10 epochs)	53.62±0.18	203.64	66.44±0.37	311.74
Adam(final epochs)	64.22±0.43	447.74	79.76±0.34	620.63

and the pretrained method. This demonstrates that learning a hyper-mapping between datasets and corresponding network parameters is effective. To demonstrate the time consumption our method could save, we also provide the time of training the model from scratch by a widely-used optimizer Adam (Kingma & Ba, 2015) and the training acceleration technique, GC. We could find that it takes around 55, 119, 140 GPU seconds to train ResNet-18 using the accelerated method GC and obtain top-1 accuracies of 99.94%, 75.74%, 72.89% on the Fashion-set, CIFAR-set, ImageNet-set respectively. While our method costs only around 0.5 GPU seconds to predict the parameters of ResNet-18 and still achieves a comparable performance (96.24%, 73.33%, 71.57% top-1 accuracies) on the three datasets respectively, at least 100 times faster than the accelerated method.

Performance on Cross-domain Datasets We further evaluate our method on the cross-domain datasets, CIFAR100→Animals10. Since Meta-DeepDBC generally achieves better performance among all meta-learning methods based on Table 1 and 2, here we only report the results of Meta-DeepDBC. Table 3 shows the results on the CIFAR100→Animals10 dataset. Our model still outperforms meta-DeepDBC in a large margin, especially when compared with the pretrained method.

Table 4: Ablation study of our method.

	ConvNet-3			ResNet-18		
Setting	Fashion-set	CIFAR100-set	ImageNet-set	Fashion-set	CIFAR100-set	ImageNet-set
PudNet-w.o.-Context	93.13±0.36	59.51±0.42	54.36±0.67	93.08±0.44	65.35±0.51	61.42±0.70
PudNet-Random	90.51±0.32	57.26±0.39	52.88±0.59	89.09±0.40	60.56±0.50	55.93±0.70
PudNet-w.o.-initRes	95.46±0.35	61.56±0.40	57.81±0.66	95.42±0.44	71.06±0.51	68.98±0.73
PudNet-metric	95.31±0.45	60.97±0.53	50.15±0.87	94.75±0.44	68.60±0.61	61.28±0.85
PudNet-w.o.-kl	95.92±0.34	61.29±0.41	57.64±0.62	95.44±0.38	70.27±0.54	67.53±0.73
PudNet	**96.64**±0.34	**64.09**±0.40	**59.31**±0.64	**96.24**±0.39	**73.33**±0.54	**71.57**±0.71

In addition, we can obtain comparable accuracy when training the model from scratch at around 5 epochs, while our method is at least 300 times faster than the traditional training methods. We expect that such a result could motivate more researchers to explore along this direction.

Ablation Study We design a variant of our method to analyse the effect of the context relation information. PudNet-w.o.-Context denotes our method directly feeds the dataset sketch into the weight generator without using GRU. The results are listed in Table 4. Our PudNet outperforms PudNet-w.o.-Context in a large margin, demonstrating the effectiveness of capturing dependencies among parameters of different layers.

Moreover, we design two variants of our method to further study the contribution of the dataset information. PudNet-Random denotes our method randomly initializes the hidden state of GRU. PudNet-w.o.-initRes denotes our method does not utilize initial residual connection for initial dataset information complementary. As shown in Table 4, the performance of our method decreases when randomly initializing the hidden state of GRU. It indicates that exploiting the initialization of the hidden state to deliver the information of datasets is effective. Moreover, PudNet is better than PudNet-w.o.-initRes, illustrating the effectiveness of the initial residual connection.

Finally, we design another two variants of our methods to study the impact of the auxiliary task. PudNet-metric means our method only using the parameter-free loss. PudNet-w.o.-kl means out method without using the KL Divergence. As shown in Table 4, PudNet-w.o.-kl has better performance than PudNet-metric, demonstrating it is effective for the auxiliary full classification task. PudNet outperforms PudNet-w.o.-kl. This illustrates it is effective to encourage the predicted probability distribution of parameter-free method and full classification method to be matched.

Fine-tuning Predicted Parameters Since a typical strategy for applying a pretrained model to a new dataset is to fine-tune the model. Thus, we intend to evaluate the performance of fine-tuning our method and baselines on the CIFAR-set dataset. To do this, we first incorporate an additional linear classification layer to our method and baselines, except 'From scratch'. Then, we randomly select 10000 samples from 20 classes for fine-tuning the models, and use the remaining 2000 samples for testing. Table 5 shows the results. Here 'From Scratch' means directly training the target network with random initialized parameters from scratch. Our method achieves the best performance. This indicates the predicted parameters by our PudNet can well serve as a pretrained model.

Table 5: Performance of finetuning all methods using 50 epochs.

Method	ConvNet-3	ResNet-18
From Scratch	44.85±0.23	48.25±0.30
Pretrained	49.40±0.17	59.75±0.24
Meta-DeepDBC	50.05±0.21	61.35±0.28
ours	**55.21**±0.19	**65.19**±0.22

5 Conclusion

In this paper, we found there are correlations among datasets and the corresponding parameters of a given network, and explored a new training paradigm for deep neural networks. We proposed a new hypernetwork, PudNet, which can directly predict the network parameters for an unseen data with only a single forward propagation. Essential to our hypernetwork is the construction of a series of GRU, to capture the relations among parameters of different layers in a network. Extensive experimental results demonstrated the effectiveness and efficiency of our method.

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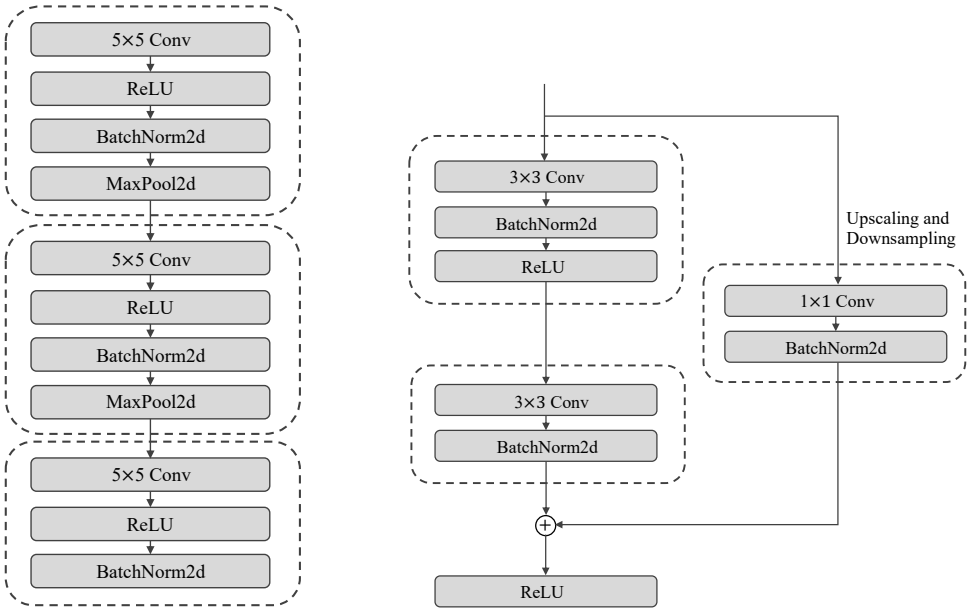
A APPENDIX

A.1 ARCHITECTURE DETAILS

Dataset Compression Module Details. A block in this module is consists of: a 5×5 convolutional layer, a leakyReLU function, a batch normalization layer. We call this block as extractor block. The feature extractor is composed of several extractor blocks and a linear layer. We stack one extractor block when the target network is set as ConvNet-3. We stack three extractor blocks when the target network is set as ResNet-18.

Context-Aware Parameter Prediction Module Details. We utilize ConvNet-3 and ResNet-18 as target networks, and devise a context-aware parameter prediction module to predict parameters for these two target network. We first introduce the architecture of these two target network. As shown in Figure 4(a), ConvNet-3 consists of two repeated Conv-ReLU-BatchNorm2d-MaxPool2d blocks, followed by one Conv-ReLU-BatchNorm2d block. ResNet-18 feature extractor includes one Conv-BatchNorm2d-Relu block and 8 Residual Blocks, followed by a global max-pool. Figure 4(b) shows the structure of Residual Block. Note that only the third, fifth and seventh Residual Blocks have the upscaling and downsampling branch, the rest of Residual Blocks utilize the identical feature output by previous Residual Block to conduct residual connection.

Figure 5 gives the case of predicting the parameters of target network with Residual Block. Since ResNet-18 includes more convoluted parameters than ConvNet-3, we leverage stacked GRU to model the complex structural parameter information for ResNet-18. We exploit GRU in upper layer to capture the lower-level context-aware structural parameter features and GRU in lower layer to capture the higher-level context-aware structural parameter features. As in Figure 5, the dataset sketch embedding acquired by dataset compression Module is split into two parts to serve as the inputs of the two-layer stacked GRUs. The stacked GRUs gradually take in structural parameter feature of previous layer and output the parameter for each layer. The initial residual connection of dataset sketch embedding is conducted on the parameter feature to get desired structural parameter vectors. Then the weight generator absorbs the structural parameter vectors of fixed dimension to predict parameters of the corresponding dimension for each layer of Residual Block.



(a) ConvNet-3 (b) Residual Block

Figure 4: The Structure of Target Network.

Figure 6 shows the details of weight generator. Here we take an example of predicting the parameters tensor with size $d_{out} \times d_{in} \times f \times f$ for $f \times f$convolutional layer. The structural parameter vector with

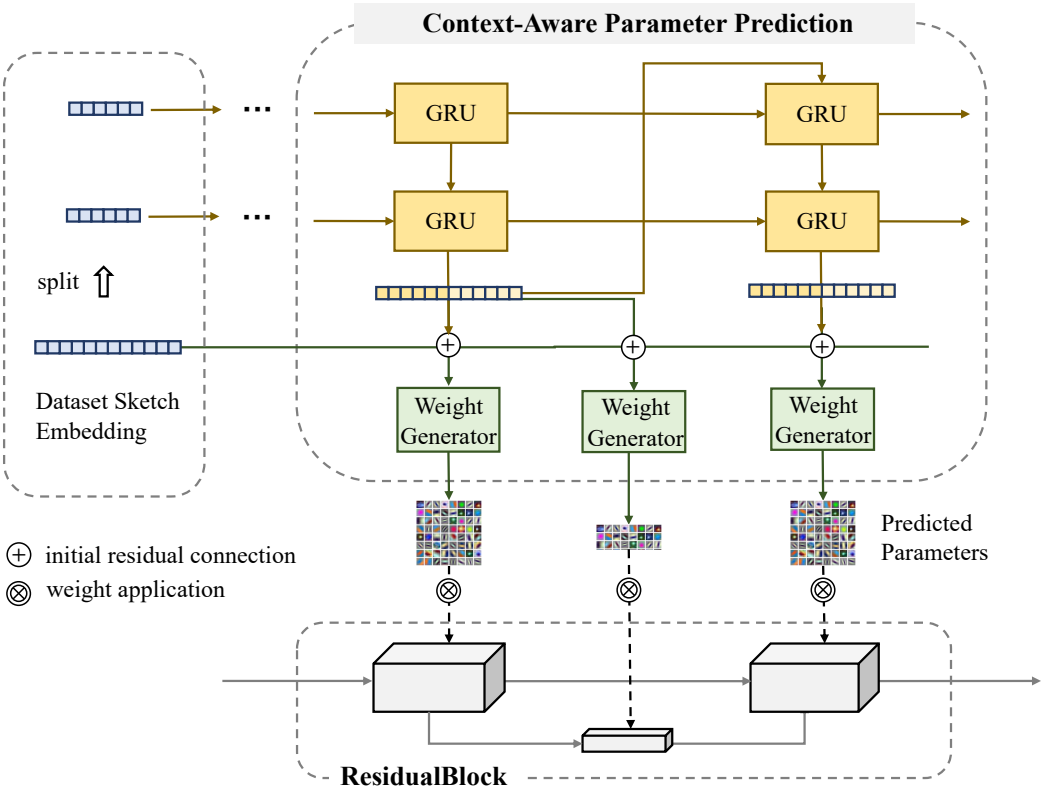


Figure 5: Parameter Prediction with Residual block.

dimension d_a is fed to weight generator to be first transformed into hidden vector with dimension $d_h \times f \times f$. Then we resize the hidden vector and expand the channel dimension of the hidden vector with 1×1 convolutional layer to $2d_h \times f \times f$. Next, a final 1×1 convolutional layer is followed to predict the desired parameters with dimension $d_{out} \times d_{in} \times f \times f$.

A.2 Additional Implementation Details

For all experiments, we use ACC (Top-1 Accuracy) metric to evaluate the classification performance. All experiments are optimized by Adam optimizer. We set learning rate to 0.001 and train PudNet until convergence. In metric-based learning process, following Chen et al. (2021), the temperature $\tau = 10$ in Eq.(6) is fixed. 10 labeled samples per class are used as support sets to deduce the class centroid. As mentioned in the main paper, we introduce auxiliary tasks to assist optimization. We add an full classification linear layer (e.g. 80-way linear head in CIFAR-100) to maintain static class set during training. We also introduce a consistency loss, while the dimension between logits deduced by metric-based classification (e.g.5-dimensional in CIFAR-100) and the logits produced

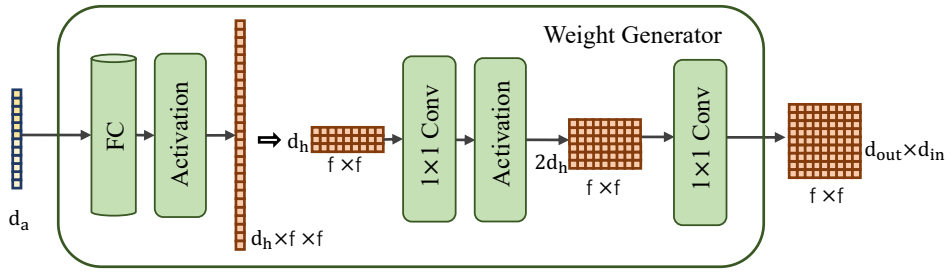


Figure 6: The Details of Weight Generator.

Table 6: Results of different methods on new dataset CIFAR-100→CIFAR-10.

Method	ConvNet-3		ResNet-18	
	ACC(%)	time (sec.)	ACC (%)	time (sec.)
Pretrained	34.32±0.61	-	40.93±0.48	-
Meta-DeepDBC	41.28±0.59	-	47.15±0.63	-
ours	**43.76**±0.64	0.05	**51.05**±0.56	0.56
Adam(1 epochs)	19.98±0.63	51.57	21.37±0.71	60.79
Adam(5 epochs)	44.67±0.42	253.16	33.76±0.44	310.29
Adam(10 epochs)	48.69±0.48	506.63	48.21±0.25	621.75
Adam(15 epochs)	56.74±0.39	763.85	59.89±0.47	932.46
Adam(final epochs)	63.93±0.54	1370.39	84.11±0.60	9305.03

Table 7: Effect of different number of training classes with varying groups on CIFAR100-set.

Groups	50	100	500	1000	5000	10000	50000
Train-C20	45.77±0.33	49.25±0.31	51.31±0.28	51.11±0.28	50.93±0.29	51.02±0.22	51.10±0.19
Train-C80	45.37±0.54	51.99±0.47	58.98±0.44	60.44±0.45	62.42±0.39	62.84±0.41	64.09±0.40

by full linear head (e.g.80-dimensional in CIFAR-100) are not matching, thus we transpose the 5-dimensional logit to 80-dimensional logit, by padding the rest values with zero. We search η from $\{0, 0.1, 0.2, 0.3, \cdots, 0.9\}$. For target network ConvNet-3, we set $\eta = 0.2$ for Fashion-set, $\eta = 0.1$ for CIFAR100-set, $\eta = 0.3$ for ImageNet-set, $\eta = 0.1$ for CIFAR100→Animals10. For target network ResNet-18, we set $\eta = 0.2$ for Fashion-set, $\eta = 0.5$ for CIFAR100-set and ImageNet-set, $\eta = 0.5$ for CIFAR100→Animals10.

A.3 Additional Experiments

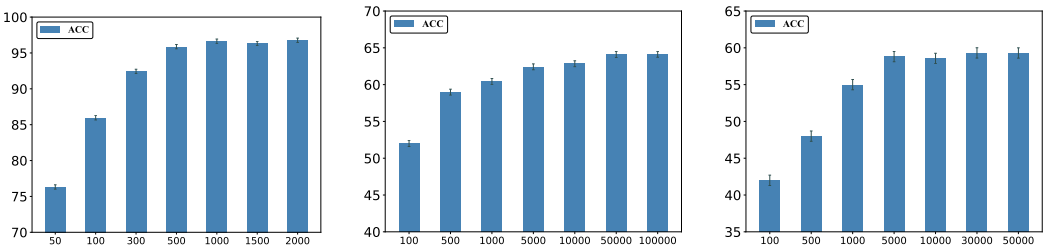
Performance on Other Full Dataset Analysis Here we utilze CIFAR100-set to train the model and evaluate the performance on CIFAR-10. Note that the classes in CIFAR-10 (Krizhevsky et al., 2009) are mutually exclusive with the classes in CIFAR-100. Since Meta-DeepDBC achieves better performance among all meta-learning methods based on Table 1 and 2, here we only report the results of Meta-DeepDBC and pretrained model for clarity. Table 6 shows the results on CIFAR-100→CIFAR-10. We observe that our model outperforms the Pretrained and Meta-DeepDBC competitors. This further verifies the effectiveness of our method. We also provide the time consumption of training the target network from scratch with Adam optimizer on CIFAR-10. It worth noting that it takes around 622 GPU seconds to train ResNet-18 using Adam from scratch and obtain top-1 accuracy of 48.21% on CIFAR-10. While our method costs only around 0.56 GPU seconds to predict the parameters of ResNet-18 and still achieves 51.05% top-1 accuracy, which is 1000 times faster than the training from scratch method.

Effect of Different Number of Training Classes with Varying Groups Here we analyze the effect of different number of classes on training set. We utilize PudNet to predict parameters for ConvNet-3. The results are shown in Table 7. Train-C20 denotes that the training set involving 50000 groups of datasets contains 20 classes in total. Similarly, Train-C80 denotes that the training set involving 50000 groups of datasets owns 80 classes. We find that with more classes included in training set, our PudNet achieves better performance as the number of dataset groups increase. This is because with larger number of classes occurred on training period to learn the mapping relation, our PudNet could obtain better generalization ability.

Effect of Different Layers of Stacked GRU Analysis We exploit the stacked GRU to transfer the context-aware information of parameters for ResNet-18 in Parameter Prediction Module, as illustrated in Appendix A.1. We conduct experiments to investigate the effect of different number

Table 8: Effect of different layers of stacked GRU.

Stacked GRU	Target Network	num_layers=1	num_layers=2	num_layers=4	num_layers=6	num_layers=8
CIFAR100-set	ResNet-18	68.89±0.52	**73.33**±0.54	71.78±0.57	70.15±0.49	70.81±0.50
ImageNet-set	ResNet-18	67.81±0.77	68.13±0.69	**71.57**±0.71	70.54±0.74	69.26±0.71



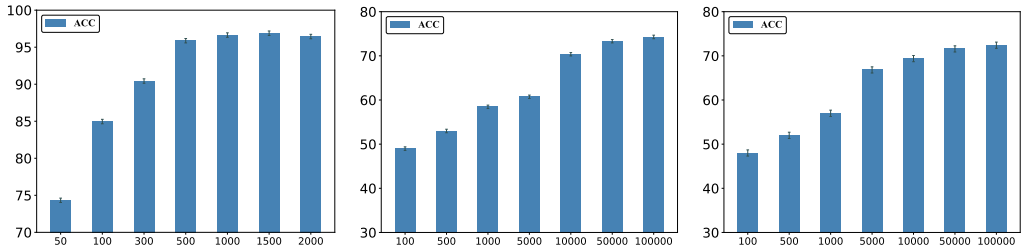
(a) Fashion-set (b) CIFAR100-set (c) ImageNet-set

Figure 7: Effect of Different Groups of Datasets for Training to Predict Parameters for ConvNet-3.

of layers in stacked GRU and report the results in Table 8. Since PudNet of single GRU gives decent performance for Fashion-set, here we utilize CIFAR100-set and ImageNet-set to study the effect. We can observe that the best results on ResNet-18 are achieved when the number of layers in stacked GRU is greater than one. We attribute the performance boost to the fact that the stacked GRU can capture both the lower-level and high-level structural parameter information.

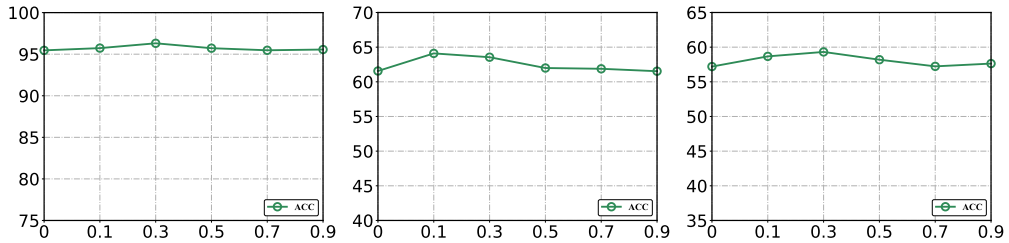
Effect of Different Groups of Datasets Here we analyze the effect of different groups of datasets for training. The results of utilizing PudNet to predict parameters for ConvNet-3 are shown in Figure 7. For the target network ConvNet-3, we construct 2000, 100000, 50000 groups of datasets for training PudNet on Fashion-set, CIFAR100-set, Imagenet-set respectively. Figure 8 reports the results of exploiting PudNet to predict parameters for ResNet-18. We construct 2000, 100000, 100000 groups of datasets for training our PudNet on Fashion-set, CIFAR100-set, Imagenet-set respectively. We find that with more datasets for training, our PudNet could obtain better performance. This is because with larger groups of datasets to learn the hyper-mapping relation, our PudNet could obtain better generalization ability. However, when the number of group becomes large, the performance increase becomes slow.

Effect of Hyper-parameter η Analysis Here we analyze the effect of different hyper-parameter η. Recall that η controls the percent of dataset complementary information in the initial residual connection. Figure 9(a)(b)(c) show the results for utilizing our PudNet to predict parameters of ConvNet-3, and Figure 9(d)(e)(f) give the results for utilizing our PudNet to predict parameters of

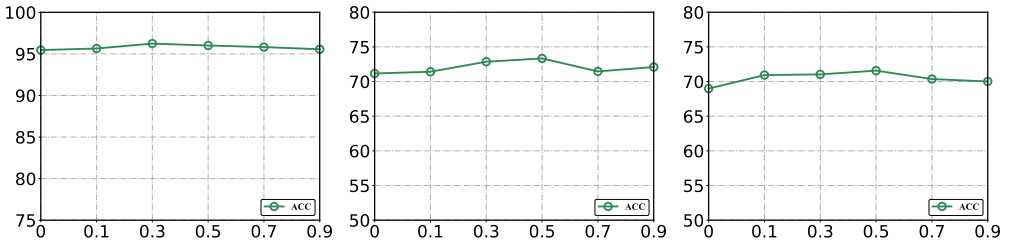


(a) Fashion-set (b) CIFAR100-set (c) ImageNet-set

Figure 8: Effect of Different Groups of Datasets for Training to Predict Parameters for ResNet-18.



(a) Fashion-set with ConvNet-3 (b) CIFAR100-set with ConvNet-3 (c) ImageNet-set with ConvNet-3



(d) Fashion-set with ResNet-18 (e) CIFAR100-set with ResNet-18 (f) ImageNet-set with ResNet-18

Figure 9: Sensitivity Analysis of Hyper-parameter η.

ResNet-18. We observe that our model obtain better performance when $\eta > 0$ in general. Additionally, η is relatively stable in the selected wide range of values.

Convergence Analysis We discuss the convergence property of the proposed method by plotting the loss curves with increasing iteration. Here we utilize PudNet to predict parameters for ConvNet-3, based on Fashion-set, CIFAR100-set and ImageNet-set respectively. As shown in Figure 10, the training metric-based loss and training total loss first decrease rapidly as the number of iterations increases, and then gradually decreases to convergence.

A.4 Algorithm Pseudo-code

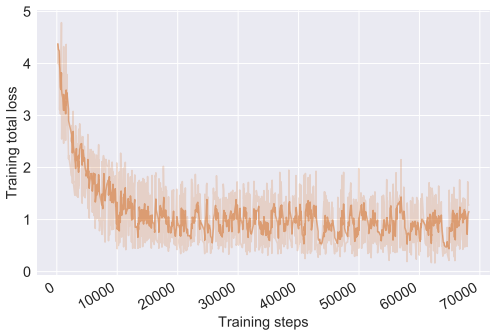
Here, we provide training procedure of our PudNet as listed in Algorithm 1. For each training dataset $D_i \in \mathcal{D}^{train}$, we first derive the skecth $\boldsymbol{s}_i$ of dataset D_i and set the initial hidden state $\boldsymbol{h}_0 = \boldsymbol{s}_i$ in GRU. Then, we predict the parameters of each layer in the target network Ω. Finally, we optimize the the learnable parameters θ, φ by the the overall multi-task loss $\mathcal{L}_{total}$.

Algorithm 1 The Training of PudNet

Input: a set of training datasets $\mathcal{D}^{train} = \{D_i\}_{i=1}^{\mathcal{N}}$, target network architecture Ω.
Initialize the learnable parameter θ of H_θ.
Initialize the learnable parameter φ of the auxiliary full classification.
while *not converged* **do**
  for $i \in \{1, \cdots, \mathcal{N}\}$ **do**
    Obtain a skecth $\boldsymbol{s}_i$ of dataset D_i via the dataset compression module;
    Initialize the hidden state $\boldsymbol{h}_0 = \boldsymbol{s}_i$;
    for *each layer* t *in* Ω **do**
      Predict the parameters w_t of the t-th layer by (5);
      Fix the predicted parameters w_t to Ω;
    for *each batch* b *in* D_i **do**
      Compute the parameter-free loss $\mathcal{L}_1$ with a batch size of b;
      Compute the full classification loss $\mathcal{L}_2$ and consistency loss $\mathcal{L}_3$ with a batch size of b;
      Update the learnable parameters θ, φ by the overall multi-task loss $\mathcal{L}_{total}$ in (10);

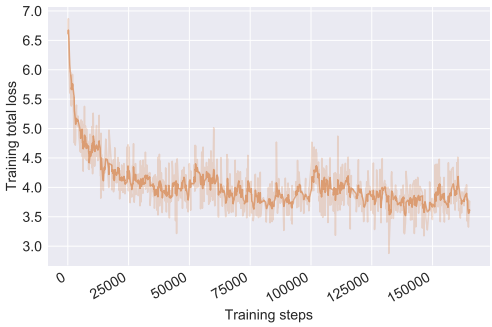
Output: The PudNet H_θ.

(a) metric-based loss on Fashion-set



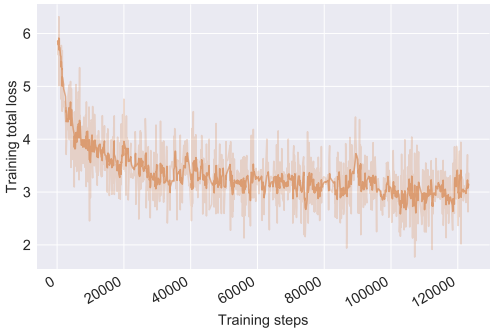
(b) total loss on Fashion-set

(c) metric-based loss on CIFAR100-set



(d) total loss on CIFAR100-set

(e) metric-based loss on ImageNet-set



(f) total loss on ImageNet-set

Figure 10: Training Loss of PudNet.