MAHINET: A NEURAL NETWORK FOR MANY-CLASS FEW-SHOT LEARNING WITH CLASS HIERARCHY

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ABSTRACT

We study many-class few-shot (MCFS) problem in both supervised learning and meta-learning scenarios. Compared to the well-studied many-class many-shot and few-class few-shot problems, MCFS problem commonly occurs in practical applications but is rarely studied. MCFS brings new challenges because it needs to distinguish between many classes, but only a few samples per class are available for training. In this paper, we propose "memory-augmented hierarchical-classification network (MahiNet)" for MCFS learning. It addresses the "many-class" problem by exploring the class hierarchy, e.g., the coarse-class label that covers a subset of fine classes, which helps to narrow down the candidates for the fine class and is cheaper to obtain. MahiNet uses a convolutional neural network (CNN) to extract features, and integrates a memory-augmented attention module with a multi-layer perceptron (MLP) to produce the probabilities over coarse and fine classes. While the MLP extends the linear classifier, the attention module extends a KNN classifier, both together targeting the "few-shot" problem. We design different training strategies of MahiNet for supervised learning and meta-learning. Moreover, we propose two novel benchmark datasets "*mcfs*ImageNet" (as a subset of ImageNet) and "*mcfs*Omniglot" (re-splitted Omniglot) specifically for MCFS problem. In experiments, we show that MahiNet outperforms several state-of-the-art models on MCFS classification tasks in both supervised learning and meta-learning scenarios.

1 INTRODUCTION

The representation power of deep neural networks (DNN) has dramatically improved in recent years, as deeper, wider and more complicated DNN architectures (He et al., 2016; Huang et al., 2017) have emerged to match the increasing computation power of new hardwares. Although this brings hope for complex tasks that could be hardly solved by previous shallow models, more training data is usually required. Hence, the scarcity of annotated data has become a new bottleneck for training more powerful DNNs. For example, in image classification, the number of candidate classes can easily range from hundreds to tens of thousands (i.e., many-class), but the training samples available for each class can be less than 100 (i.e., few-shot). Additionally, in life-long learning, models are always updated once new training data becomes available, and those models are expected to quickly adapt to new classes with a few training samples. This "many-class few-shot" problem is very common in various applications, such as image search, robot navigation and video surveillance.

Although enormous previous works have shown the remarkable power of DNN when "many-class many-shot" training data is available, their performance degrades dramatically when each class only has a few samples available for training. In practical applications, acquiring samples of rare species is usually difficult and often expensive. In these few-shot scenarios, the model's capacity cannot be fully utilized, and it becomes much harder to generalize the model to unseen data. Recently, several approaches have been proposed to address the few-shot learning problem. Most of them are based on the idea of "meta-learning", which trains a meta-learner that can generalize to different tasks. For classification, each task targets a different set of classes. Meta-learning can be categorized into two types: methods based on "learning to optimize", and methods based on metric learning. The former type adaptively modifies the optimizer (or some parts of it) applied to the training process. It includes methods that incorporate an RNN meta-learner (Andrychowicz et al., 2016; Li & Malik, 2017; Ravi & Larochelle, 2017), and model agnostic meta learning (MAML) methods aiming to learn a

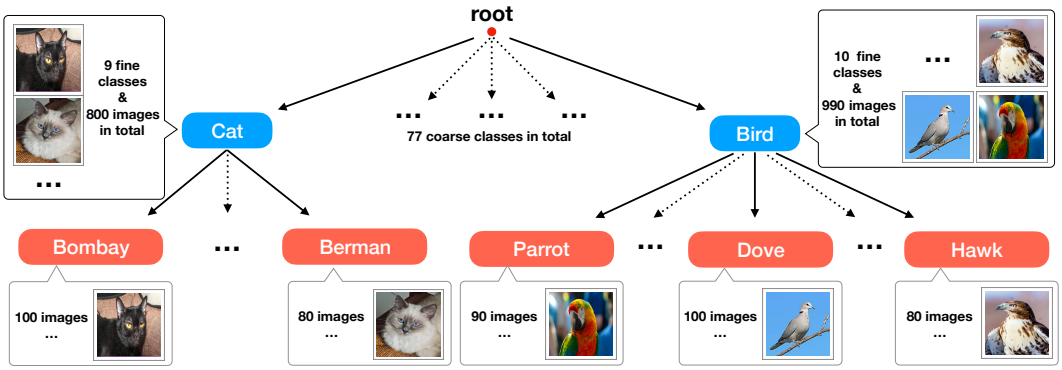

Figure 1: The MCFS problem with class hierarchy information. There are a few coarse classes (blue), but each coarse class contains a large number of fine classes (red), and the total number of fine classes is large. Only a few training samples are available for each fine class. The goal is to train a classifier to generate a prediction over all fine classes. In meta-learning, each task is an MCFS problem sampled from a certain distribution. The meta-learner's goal is to help train a classifier for any sampled task with better adaptation to few-shot data.

generally compelling initialization (Finn et al., 2017). The latter type learns a similarity/distance metric (Vinyals et al., 2016) or a support set of samples (Snell et al., 2017) that can be generally used to build KNN classifiers for different tasks.

Table 1: Targeted problems of different methods.

	many-class	few-class
few-shot	**MahiNet (ours)**	MAML, Matching Net, *etc.*
many-shot	ResNet, DenseNet, Inception, VGG, *etc.*	

Instead of using meta-learning, some other approaches, such as Douze et al. (2018), address the few-shot learning problem through data augmentation by generating artificial samples for each class. However, most existing few-shot learning approaches only focus on "few-class" case (e.g., 5 or 10) per task, and performance usually collapses when the number of classes grows to hundreds or thousands. This is because the samples per class no longer provide enough information to distinguish them from other possible samples within a large number of other classes. And, in real-world problems, tasks are usually complicated involving many classes.

Fortunately, in practice, class hierarchy is usually available or cheaper to obtain. As shown in Figure 1, coarse class labels might reveal the relationships among the targeted fine classes. Moreover, the samples per coarse class are sufficient to train a reliable coarse classifier, whose predictions are able to narrow down the candidates for fine classes. For example, a sheepdog with long hair could be easily mis-classified as mop when training samples of sheepdog are insufficient. However, if we could train a reliable dog classifier, it would be much simpler to predict an image as a sheepdog than a mop given a correct prediction of the coarse class as "dog". Hence, class hierarchy might provide weakly supervised information to help solve the "many-class few-shot (MCFS)" problem.

1.1 Our Approach

In this paper, we study how to explore the class hierarchy to solve MCFS problem in both traditional supervised learning and in meta-learning. We develop a DNN architecture "memory-augmented hierarchical-classification networks (MahiNet)" that can be applied to both learning scenarios. MahiNet uses a CNN, i.e., ResNet by He et al. (2016), as a backbone network to extract features from raw images. The CNN feeds features into coarse-class and fine-class classifiers, and the results are combined to produce the final prediction according to fine classes as probabilities. In this way, both the coarse-class and the fine-class classifiers mutually help each other within MahiNet: the former helps to narrow down the candidates for the latter, while the latter provides multiple attributes per coarse class that can regularize the former. This design leverages the relationship between fine classes, and mitigates the difficulty caused by "many class" problem.

To address the "few-shot" problem, we apply two types of classifiers in MahiNet, i.e., MLP and K-nearest neighbor (KNN), which have advantages in many-shot and few-shot situations, respectively. We always use MLP for coarse classification, and KNN for fine classification. With a sufficient amount of data in supervised learning, MLP is combined with KNN for fine classification; and in meta-learning when less data is available, we also use KNN for coarse classification to assist MLP.

In Table 1, we provide a brief comparison of MahiNet with other popular models on the learning scenarios they excel.

To make the KNN learnable and more adaptive to classes with few-shot data, we use an attention module to optimize the similarity/distance metric used in KNN, and a budget of re-writable memory to store and update KNN support set during training. In supervised learning, it is necessary to maintain and update a relatively small memory by selecting a few samples, because conducting a KNN search over all available training samples is too computationally expensive in computation. In meta-learning, the attention module can be treated as a meta-learner that learns a universal similarity metric for different tasks.

To test the performance of our approach against existing methods on MCFS problem, we extract a large subset of ImageNet (Deng et al., 2009), "*mcfs*ImageNet", which covers 77 non-overlapping coarse classes, and randomly sampled 754 fine classes, each only belonging to one of the 77 coarse classes. *mcfs*ImageNet contains 139,346 images in total, so each fine class has only ~ 180 images. Some imbalance between the different classes was retained to reflect the types of dataset commonly encountered in practical problems. We will make *mcfs*ImageNet publicly available later.

We experimented on "*mcfs*ImageNet" and '*mcfs*Omniglot". MahiNet outperforms the widely used ResNet (He et al., 2016) in supervised learning. In meta-learning scenario with many classes per task, it also shows much better results compared to existing few-shot methods.

2 Memory-Augmented Hierarchical-Classification Network

2.1 Problem Formulation

We study supervised learning and meta-learning given a training set of n samples $\mathbb{D} = \{(x_i, y_i, z_i)\}_{i=1}^n$, where each sample $x_i \in \mathcal{X}$ is associated with a fine-class label $y_i \in \mathcal{Y}$ and a coarse-class label $z_i \in \mathcal{Z}$, and is sampled from a data distribution $\mathcal{D}$, i.e., $(x_i, y_i, z_i) \sim \mathcal{D}$. Here, $\mathcal{Y}$ denotes the set of all the fine classes, and $\mathcal{Z}$ denotes the set of all the coarse classes. To define a class hierarchy for $\mathcal{Y}$ and $\mathcal{Z}$, we further assume that each coarse class $z \in \mathcal{Z}$ covers a subset of fine classes $\mathcal{Y}_z$, and that distinct coarse classes are associated with disjoint subsets of fine classes, i.e., for any $z_1,\ z_2 \in \mathcal{Z}$, we have $\mathcal{Y}_{z_1} \cap \mathcal{Y}_{z_2} = \emptyset$. Our goal is fine-class classification by using the class hierarchy information. In particular, the supervised learning in this case can be formulated as:

$$\min_{\Theta} \mathbb{E}_{(x,y,z)\sim\mathcal{D}} - \log \Pr(y|x;\Theta), \tag{1}$$

where Θ is the model parameters. In practice, we solve the corresponding empirical risk minimization (ERM) during training, i.e.,

$$\min_{\Theta} \sum_{i=1}^{n} - \log \Pr(y_i|x_i;\Theta). \tag{2}$$

In contrast, meta-learning aims to maximize the expectation of the prediction likelihood of a task drawn from a distribution of tasks. Specifically, we assume that the subset of fine classes T for each task is sampled from a distribution $\mathcal{T}$, and the problem is formulated as

$$\min_{\Theta} \mathbb{E}_{T\sim\mathcal{T}} \left[\mathbb{E}_{(x,y,z)\sim\mathcal{D}_T} - \log \Pr(y|x;\Theta) \right], \tag{3}$$

where $\mathcal{D}_T$ refers to the distribution of samples with label $y_i \in T$. The corresponding ERM is

$$\min_{\Theta} \sum_{T} \left[\sum_{i\in\mathbb{D}_T} - \log \Pr(y_i|x_i;\Theta) \right], \tag{4}$$

where T is a task (defined by a subset of fine classes) sampled from distribution $\mathcal{T}$, and $\mathbb{D}_T$ is a training set sampled from $\mathcal{D}_T$.

To leverage the coarse class information of z, we write $\Pr(y|x;\Theta)$ in Eq. (1) and Eq. (3) as

$$\Pr(y|x;\Theta) = \sum_{z\in\mathcal{Z}} \Pr(y|z,x;\Theta_f) \Pr(z|x;\Theta_c), \tag{5}$$

where Θ_f and Θ_c are the model parameters for fine classifier and coarse classifier, respectively[1]. Accordingly, given a specific sample (x_i, y_i, z_i) with its ground truth labels for coarse and fine

[1]For simplicity, we neglect model parameters θ^{CNN} for feature extraction here. The complete form of $\Pr(y|z,x;\Theta_f)$ and $\Pr(z|x;\Theta_c)$ should be $\Pr(y|z,x;\theta^{CNN},\Theta_f)$ and $\Pr(z|x;\theta^{CNN},\Theta_c)$, respectively.

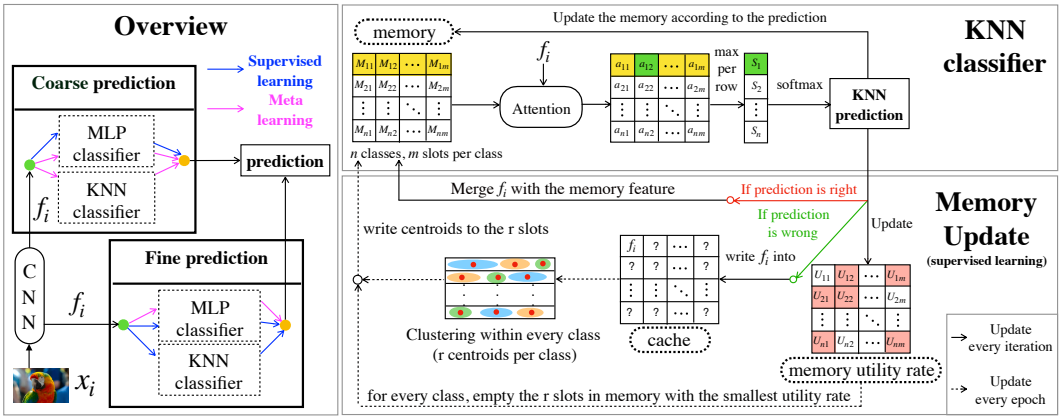

Figure 2: **Left:** MahiNet. The final fine-class prediction combines predictions based on both fine classes and coarse classes, each of which is produced by an MLP classifier or/and an attention-based KNN classifier. **Top right:** The attention-based KNN classifier. The "Attention" block computes the similarity $a_{i,j}$ between the input sample and each representative sample stored in memory (in the feature space learned by the CNN). **Bottom right:** The memory update mechanism. In meta-learning, the memory stores features extracted the training samples for each task and does not change during training. In supervised learning, the memory is updated during training. In each epoch, if the KNN classifier predicts correctly on one sample, the feature of this sample will be merged into the feature vectors in memory; if wrong, the sample's feature vector is written into a "cache". At the end of one epoch, we cluster the samples of each class in the cache, and replace the r slots of the memory having the smallest utility rate with the r clustering centroids.

classes, we can write $\Pr(y_i|x_i;\Theta)$ in Eq. (2) and Eq. (4) as follows.

$$\Pr(y_i|x_i;\Theta) = \Pr(y_i|z_i,x_i;\Theta_f)\Pr(z_i|x_i;\Theta_c). \tag{6}$$

Suppose that a DNN model already produces a logit a_y for each fine class y, and a logit b_z for each coarse class z, the two probabilities in the right hand side of Eq. (6) are computed by applying softmax function to the logit values in the following way.

$$\Pr(y_i|z_i,x_i;\Theta_f) = \frac{\exp(a_{y_i})}{\sum_{y\in\mathcal{Y}_{z_i}}\exp(a_y)}, \quad \Pr(z_i|x_i;\Theta_c) = \frac{\exp(b_{z_i})}{\sum_{z\in\mathcal{Z}}\exp(a_z)}. \tag{7}$$

Therefore, we integrate both the fine-class label and coarse-class label in an ERM, whose goal is to maximize the likelihood of the ground truth fine-class label. Given a DNN that can produce two logit vectors a and b for fine class and coarse class, we can train it for supervised learning or meta-learning by solving the ERM problems in Eq. (2) or Eq. (4) (with Eq. (6) and Eq. (7) plugged in).

2.2 Network Architecture

To address the MCFS problem in both supervised learning and meta-learning scenarios, we developed a universal model, MahiNet, as in Figure 2. MahiNet uses a CNN to extract features from raw inputs, and then applies two modules to produce coarse-class prediction and fine-class prediction, respectively. Each module includes one or two classifiers: either an MLP or an attention-based KNN classifier or both. Intuitively, MLP performs better when data is sufficient, while the KNN classifier is more stable in few-shot scenario. Hence, we always apply MLP to coarse prediction, and apply KNN to fine prediction. In addition, we use KNN to assist MLP for coarse module in meta-learning, and use MLP to assist KNN for fine module in supervised learning.

In the attention-based KNN classifier, an attention module is trained to compute the similarity between two samples, and a re-writable memory is maintained with a highly representative support set for KNN prediction. We illustrate the structure of these two mechanisms in the **right part** of Figure 2, and will introduce their details in Sec. 2.3 and Sec. 2.4.

Our method for learning a KNN classifier combines the ideas from two popular meta-learning methods, i.e., matching networks (Vinyals et al., 2016) that aims to learn a similarity metric, and prototypical networks (Snell et al., 2017) that aims to find a representative center per class for NN search. However, our method relies on an augmented memory rather than a bidirectional RNN for retrieving of NN in matching networks. In contrast to prototypical networks, that only have one prototype per class, we allow multiple prototypes as long as they can fit in the memory budget. Together these two mechanisms prevent the confusion caused by subtle differences between classes in many-class

Algorithm 1 Training of MahiNet for Supervised Learning

Input: Training set $\mathbb{D} = \{(\boldsymbol{x}_i, y_i, z_i)\}_{i=1}^n$;
Randomly initialized θ_f^{KNN}, pre-trained θ^{CNN}, θ_c^{MLP} and θ_f^{MLP};
Hyper-parameters: memory update parameters r, γ, μ and η; learning rate and its scheduler;

```
while no converge do
    for mini-batch {(x_i, y_i, z_i)}_{i∈B} in D do
        Compute fine-class logits a and coarse-class logits b from the outputs of MLP/KNN classifiers;
        Apply one step of mini-batch SGD for ERM in Eq. (2) (with Eq. (6) and Eq. (7) plugged in);
        for sample in the mini-batch do
            Update the memory M according to Eq. (11);
            Update the utility rate U according to Eq. (13);
            Expand the feature cache ℂ according to Eq. (12);
        end for
    end for
    for each fine class j in 𝒴 do
        Fine the indexes of the r smallest values in U_j, denoted as {k_1, k_2, ..., k_r};
        Clustering of the feature vectors within cache ℂ_j to r clusters with centroids {c_1, c_2, ..., c_r};
        Replace the r memory slots by centroids: M_{j,k_i} = c_i for i ∈ [r];
    end for
end while
```

scenario. Notably, MahiNet can also be extended to "life-long learning" given this memory updating mechanism. We do not adopt the architecture used in Mishra et al. (2018) since it requires the representations of all historical data to be stored.

2.3 Learning a KNN Similarity Metric with an Attention Module

In MahiNet, we train an attention module to compute the similarity used in the KNN classifier. The attention module learns a distance metric between the feature vector f_i of a given sample $\boldsymbol{x}_i$ and any feature vector from the support set stored in the memory. Specifically, we use the dot product attention similar to the one adopted in Vaswani et al. (2017) for supervised learning, and use an Euclidean distance based attention for meta-learning (which follows the instruction from Snell et al. (2017)). Given a sample $\boldsymbol{x}_i$, we compute a feature vector $\boldsymbol{f}_i \in \mathbb{R}^d$ by applying a backbone CNN to $\boldsymbol{x}_i$. In the memory, we maintain a support set of m feature vectors for each class, i.e., $\boldsymbol{M} \in \mathbb{R}^{C \times m \times d}$, where C is the number of classes. The KNN classifier produces the class probabilities of $\boldsymbol{x}_i$ by first calculating the attention scores between $\boldsymbol{f}_i$ and each feature vector in the memory, as follows.

$$a(\boldsymbol{f}_i, \boldsymbol{M}_{j,k}) = \frac{g(\boldsymbol{f}_i) \cdot h(\boldsymbol{M}_{j,k})}{\|g(\boldsymbol{f}_i)\| \|h(\boldsymbol{M}_{j,k})\|} \quad \text{or} \quad -\|g(\boldsymbol{f}_i) - h(\boldsymbol{M}_{j,k})\|_2, \ \ \forall j \in [C], \ k \in [m], \tag{8}$$

where g and h are learnable transformations for $\boldsymbol{f}_i$ and the feature vectors in the memory. We select the K nearest neighbors of $\boldsymbol{f}_i$ among the m feature vectors for each class j, and compute the sum of their similarity scores as the attention score of $\boldsymbol{f}_i$ to class j, i.e.,

$$s(\boldsymbol{f}_i, \boldsymbol{M}_j) = \max_{N \subseteq [m], |N| \leq K} \sum_{k \in N} a(\boldsymbol{f}_i, \boldsymbol{M}_{j,k}), \ \ \forall j \in [C]. \tag{9}$$

We usually find $K = 1$ is sufficient in practice. The predicted class probability is derived by applying a softmax function to the attention scores of $\boldsymbol{f}_i$ over all C classes, i.e.,

$$\Pr(y_i = j) \triangleq \frac{\exp\left(s(\boldsymbol{f}_i, \boldsymbol{M}_j)\right)}{\sum_{j'=1}^{C} \exp\left(s(\boldsymbol{f}_i, \boldsymbol{M}_{j'})\right)}, \ \ \forall j \in [C]. \tag{10}$$

2.4 Memory Mechanism updating Support Set of KNN

Ideally, the memory $\boldsymbol{M} \in \mathbb{R}^{C \times m \times d}$ can store all available training samples as the support set of the KNN classifier. In meta learning, in each episode, we sample a task with C classes and m training samples per class, and store them in the memory. Due to the small amount of training data for each task, we can store all data in the memory. In supervised learning, we only focus on one task, which is possible to have a large training set that cannot be entirely stored in the memory. Hence, we set up a budget hyper-parameter m for each class. m is the maximal number of feature vectors

Algorithm 2 Training of MahiNet for Meta-Learning

Input: Training set $\mathbb{D} = \{(\boldsymbol{x}_i, y_i, z_i)\}_{i=1}^n$ and fine class set $\mathcal{Y}$;
Parameters: randomly initialized θ^{CNN}, θ_c^{MLP}, θ_f^{MLP}, and θ_f^{KNN};
Hyper-parameters: learning rate, scheduler; for each class, number of queries n_s, support set size n_S;

```
while not converge do
    Sample a task T ~ 𝒯 as a subset of fine classes T ⊆ 𝒴.
    for class j in T do
        Randomly sample n_s data points of class j from 𝔻 to be the support set 𝕊_j of class j.
        Randomly sample n_q data points of class j from 𝔻\𝕊_j to be the query set ℚ_j of class j.
    end for
    for mini-batch from ℚ do
        Compute fine-class logits a and coarse-class logits b from the outputs of MLP/KNN classifiers;
        Apply one step of mini-batch SGD for ERM in Eq. (4) (with Eq. (6) and Eq. (7) plugged in);
    end for
end while
```

to be stored in the memory for one class. Moreover, we develop a memory update mechanism that maintains a small memory with diverse and representative feature vectors per class. Intuitively, it can choose to forget or merge feature vectors that are no longer representative, and select new important feature vectors into memory.

During training, for the data that can be correctly predicted by the KNN classifier, we merge its feature with corresponding slots in the memory by computing their convex combination, i.e.,

$$\boldsymbol{M}_{j,k} = \begin{cases} \gamma \times \boldsymbol{M}_{j,k} + (1-\gamma) \times \boldsymbol{f}_i, & \text{if } \hat{y}_i = y_i \\ \boldsymbol{M}_{j,k}, & \text{otherwise} \end{cases}, \tag{11}$$

where y_i is the ground truth label, and $\gamma = 0.95$ is a combination weight that works well in most of our empirical studies; for input feature vector that cannot be correctly predicted, we write it to a cache $\mathbb{C} = \{\mathbb{C}_1, ..., \mathbb{C}_C\}$ that stores the candidates written into the memory for the next epoch, i.e.,

$$\mathbb{C}_j = \begin{cases} \mathbb{C}_j, & \text{if } \hat{y}_i = y_i \\ \mathbb{C}_j \cup \{\boldsymbol{f}_i\}, & \text{otherwise} \end{cases}, \tag{12}$$

Concurrently, we record the utility rate of the feature vectors in the memory, i.e., how many times each feature vector being selected into the K nearest neighbor during the epoch. The rates are stored in a matrix $\boldsymbol{U} \in \mathbb{R}^{C \times m}$, and we update it as follows.

$$\boldsymbol{U}_{j,k} = \begin{cases} \boldsymbol{U}_{j,k} \times \mu, & \text{if } \hat{y}_i = y_i \\ \boldsymbol{U}_{j,k} \times \eta, & \text{otherwise} \end{cases}, \tag{13}$$

where $\mu \in (1, 2)$ and $\eta \in (0, 1)$ are hyper-parameters.

At the end of each epoch, we cluster the feature vectors per class in the cache, and obtain r cluster centroids as the candidates for the memory update in the next epoch. Then, for each class, we replace r feature vectors in the memory that have the smallest utility rate with the r cluster centroids.

3 Training Strategies

As shown in the network structure in Figure 2, in supervised learning and meta learning, we use different combinations of MLP and KNN to produce fine-class and coarse-class predictions. The classifiers are combined by summing up their logits for each class, and a softmax function is used to generate the class probabilities. Assume the MLP classifiers for the coarse classes and the fine classes are $\phi(\cdot; \theta_c^{MLP})$ and $\phi(\cdot; \theta_f^{MLP})$, the KNN classifiers for the coarse classes and the fine classes are $\phi(\cdot; \theta_c^{KNN})$ and $\phi(\cdot; \theta_f^{KNN})$. In supervised learning, the model parameters are θ^{CNN}, $\Theta_c = \theta_c^{MLP}$ and $\Theta_f = \{\theta_f^{MLP}, \theta_f^{KNN}\}$; in meta-learning setting, the model parameters are θ^{CNN}, $\Theta_c = \{\theta_c^{MLP}, \theta_c^{KNN}\}$ and $\Theta_f = \theta_f^{KNN}$.

According to Sec. 2.1, we train MahiNet for supervised learning by solving the ERM problems in Eq. (2) and by solving Eq. (4) for meta-learning. As previously mentioned, the logits (for either fine classes or coarse classes) used in those ERM problems are obtained by summing up the logits produced by the corresponding combination of classifiers.

Training MahiNet for Supervised learning. In supervised learning, the memory update relies heavily on the clustering of the merged feature vectors in the cache. To achieve relatively high-

Table 2: Comparison of the statistics for *mcfs*ImageNet and previously used datasets. "#c" and "#f" denote the number of coarse classes and fine classes, respectively. "-" means "not applicable".

	Meta Learning						Supervised Learning				#image	image size
	Train		Val		Test		Train		Test			
	#c	#f	#c	#f	#c	#f	#c	#f	#c	#f		
ImageNet-1k	-	-	-	-	-	-	1	1000	1	1000	1.43M	224
*mini*ImageNet	1	64	1	16	1	20	-	-	-	-	0.06M	84
Omniglot	33	1028	5	172	13	423	-	-	-	-	0.03M	28
*mcfs*Omniglot	50	973	50	244	50	1624	-	-	-	-	0.03M	28
***mcfs*ImageNet**	77	482	61	120	68	152	77	754	77	754	0.14M	112

quality feature vectors, we firstly pre-train the backbone CNN together with MLP classifiers for both fine classes and coarse classes (without any KNN classifier or memory update), and then fine-tune the whole model (including the fine-class KNN classifier) with memory updates. The training procedure of the fine-tune stage is explained in Alg. 1.

Training MahiNet for Meta-learning. In meta learning, the memory is constant and stores features extracted from the support set for KNN classifier. The detailed training procedure can be found in Alg. 2. In summary, we sample each training task by randomly sampling a subset of fine classes, and then randomly sample a support set $\mathbb{S}$ and a query set $\mathbb{Q}$. We store the CNN feature vectors of $\mathbb{S}$ in the memory, and train MahiNet to produce correct predictions for the samples in $\mathbb{Q}$. When sampling the training/test tasks, we allow new fine classes that were not covered in any training task to appear as test tasks, but the ground set of the coarse classes is fixed for both training and test. Hence, every coarse class appearing in any test task has been seen in previous training, but the corresponding fine classes belonging to this coarse class in training and test tasks can vary.

4 EXPERIMENTS

We propose two benchmarks for MCFS Problem: *mcfs*ImageNet & *mcfs*Omniglot. We compares the statistics of *mcfs*ImageNet and *mcfs*Omniglot with several benchmark datasets in Table 2. More details can be found in Appendix A.

4.1 SUPERVISED LEARNING EXPERIMENTS

Experiments on *mcfc*ImageNet. We use ResNet18 (He et al., 2016) for the backbone CNN. The transformation functions g and h in the attention module are two fully connected layers followed by group normalization (Wu & He, 2018) with a residual connection. More detailed parameter choices can be found in Appendix B.

The results of the comparison of MahiNet with the supervised learning model (i.e., ResNet18) and meta learning model (i.e, prototypical networks) are provided in Table 3. The results show that MahiNet outperforms the specialized models, such as ResNet18 in the MCFS scenario. Prototypical networks is a meta-learning model designed to solve few-shot classification problems. We train it in a supervised learning manner (i.e., on a single task with many classes and relatively much more samples per class), and include it in the comparison to test its performance on MCFS problem. Prototypical network fails to solve the MCFS problem in the supervised learning scenario. To separately measure the contribution of the class hierarchy and the attention-based KNN classifier, we conduct an ablation study that removes the KNN classifier from MahiNet. The results show that MahiNet outperforms ResNet18 even when only using the extra coarse-label information during training, and that the using a KNN classifier further improves the performance.

Table 3: Different models' performance of supervised learning (test accuracy) on *mcfs*ImageNet.

Model	**Hierarchy**	**Accuracy**
Prototypical Net	N	2.7%
ResNet18	N	48.6%
MahiNet w/o KNN	Y	49.1%
MahiNet	Y	**49.9%**

Table 4: Comparison *w.r.t.* the accuracy (%) of different approaches in meta-learning scenario on *mcfs*ImageNet. Test accuracy is reported as the averaged over 600 test episodes along with the corresponding 95% confidence intervals are reported. In the first row, "n-k" represents n-way (class) k-shot. Mem-1, Mem-2, and Mem-3 indicate 3 different kinds of memory, respectively.

Model	**Hierarchy**	**5-10**	**20-5**	**20-10**	**50-5**	**50-10**
ResNet18 (He et al., 2016)	N	60.7	58.6	67.2	48.9	56.8
Prototypical Net (Snell et al., 2017)	N	78.48±0.66	67.78±0.37	70.11±0.38	57.74±0.24	62.12±0.24
MahiNet (Mem-1) w/o Attention & Hierarchy	N	79.04±0.67	68.46±0.38	71.13±0.38	58.09±0.24	62.18±0.22
MahiNet (Mem-2) w/o Attention & Hierarchy	N	77.41±0.71	66.89±0.40	71.72±0.37	55.25±0.23	59.38±0.23
MahiNet (Mem-2) w/o Hierarchy	N	76.85±0.67	66.43±0.41	70.01±0.38	55.13±0.23	59.22±0.23
MahiNet (Mem-3) w/o Hierarchy	N	78.27±0.68	67.03±0.41	71.20±0.37	57.98±0.24	62.40±0.23
MahiNet (Mem-1)	Y	80.64±0.64	68.99±0.40	72.78±0.37	58.56±0.25	62.70±0.24
MahiNet (Mem-3)	Y	**80.74**±0.66	**70.11**±0.41	**73.50**±0.36	**58.80**±0.24	**62.80**±0.24

Table 5: Comparison on *mcfs*Omniglot. Symbols and settings are the same as Table 4.

Model	**Hierarchy**	**5-5**	**20-5**	**50-5**	**100-5**
Prototypical Net (Snell et al., 2017)	N	99.10±0.15	98.84±0.11	97.94±0.08	96.67±0.09
Mahinet (Mem-1) w/o Hierarchy	N	99.17±0.16	98.82±0.11	97.96±0.09	96.62±0.09
Mahinet (Mem-3) w/o Hierarchy	N	99.31±0.18	98.89±0.11	97.93±0.09	96.58±0.09
MahiNet(Mem-3)	Y	**99.40**±0.15	**99.00**±0.16	**98.10**±0.17	**96.70**±0.17

4.2 META-LEARNING EXPERIMENTS

Experiments on *mcfc*ImageNet. We use the same backbone CNN, g, and h as in supervised learning. In each task, we sample the same number of classes for training and test, and follow the training procedure in Snell et al. (2017). More detailed parameters can be found in Appendix B.

Table 4 shows that MahiNet outperforms the supervised learning baseline (i.e., ResNet18) and the meta-learning baseline (i.e., prototypical networks). For ResNet18, we follow the fine-tune baseline in Finn et al. (2017). To evaluate the contributions of each component in MahiNet, we show results of several variants of MahiNet in Table 4. "Attention" indicates parametric functions for g and h, otherwise using identity mapping. "Hierarchy" indicates the assist of class hierarchy. For a specific task, "Mem-1" stores the average feature of all training samples for each class; "Mem-2" stores all features of the training samples; "Mem-3" is the union of "Mem-1" and "Mem-2". From Table 4, several conclusions can be made. (1) Class hierarchy information can incur steady performance across all tasks. (2) Using the union of "Mem-1" and "Mem-2" outperforms only using either of them. (3) "Attention" is helpful especially when "Mem-1" is used.

Experiments on *mcfs*Omniglot. We conduct experiments on the secondary benchmark *mcfs*ImageNet. We use the same training setting as for *mcfs*ImageNet. Following Santoro et al. (2016), *mcfs*Omniglot is augmented with rotations by multiples of 90 degrees. We do not use ResNet18 on *mcfs*Omniglot, since *mcfs*Omniglot is a 28×28 small dataset, which would be easy for ResNet18 to overfit. Therefore, we use four consecutive convolutional layers as the backbone CNN and compare MahiNet with prototypical networks as in Table 5. We do ablation study on MahiNet with/without hierarchy and MahiNet with different kinds of memory. "Mem-3", i.e., the union of "Mem-1" and "Mem-2", outperforms "Mem-1", and "Attention" mechanism can improve the performance. Additionally, MahiNet outperforms other compared methods, which indicates the class hierarchy assists to make more accurate predictions. In summary, experiments on the small-scale and large-scale datasets show that class hierarchy brings a stable improvement.

REFERENCES

Marcin Andrychowicz, Misha Denil, Sergio Gómez, Matthew W Hoffman, David Pfau, Tom Schaul, Brendan Shillingford, and Nando de Freitas. Learning to learn by gradient descent by gradient descent. In *Advances in Neural Information Processing Systems (NIPS)*, 2016.

Jia Deng, Wei Dong, Richard Socher, Li-Jia Li, Kai Li, and Li Fei-Fei. ImageNet: A Large-Scale Hierarchical Image Database. In *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2009.

Matthijs Douze, Arthur Szlam, Bharath Hariharan, and Hervé Jégou. Low-shot learning with large-scale diffusion. In *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2018.

Li Fei-Fei, Rob Fergus, and Pietro Perona. One-shot learning of object categories. *IEEE Transactions on Pattern Analysis and Machine Intelligence (T-PAMI)*, 2006.

Chelsea Finn, Pieter Abbeel, and Sergey Levine. Model-agnostic meta-learning for fast adaptation of deep networks. In *International Conference on Machine Learning (ICML)*, 2017.

Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. In *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2016.

Gao Huang, Zhuang Liu, Laurens Van Der Maaten, and Kilian Q Weinberger. Densely connected convolutional networks. In *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2017.

Sergey Ioffe and Christian Szegedy. Batch normalization: Accelerating deep network training by reducing internal covariate shift. In *International Conference on Machine Learning (ICML)*, 2015.

Diederik P Kingma and Jimmy Ba. Adam: A method for stochastic optimization. In *International Conference on Learning Representations (ICLR)*, 2015.

Gregory Koch, Richard Zemel, and Ruslan Salakhutdinov. Siamese neural networks for one-shot image recognition. In *International Conference on Machine Learning (ICML) Workshop*, 2015.

Brenden Lake, Ruslan Salakhutdinov, Jason Gross, and Joshua Tenenbaum. One shot learning of simple visual concepts. In *Proceedings of the Annual Meeting of the Cognitive Science Society (CogSci)*, 2011.

Brenden M Lake, Ruslan R Salakhutdinov, and Josh Tenenbaum. One-shot learning by inverting a compositional causal process. In *Advances in Neural Information Processing Systems (NIPS)*, 2013.

Brenden M Lake, Ruslan Salakhutdinov, and Joshua B Tenenbaum. Human-level concept learning through probabilistic program induction. *Science*, 2015.

Ke Li and Jitendra Malik. Learning to optimize. In *International Conference on Learning Representations (ICLR)*, 2017.

Nikhil Mishra, Mostafa Rohaninejad, Xi Chen, and Pieter Abbeel. A simple neural attentive meta-learner. In *International Conference on Learning Representations (ICLR)*, 2018.

Devang K Naik and RJ Mammone. Meta-neural networks that learn by learning. In *International Joint Conference on Neural Networks (IJCNN)*, 1992.

Sachin Ravi and Hugo Larochelle. Optimization as a model for few-shot learning. In *International Conference on Learning Representations (ICLR)*, 2017.

Adam Santoro, Sergey Bartunov, Matthew Botvinick, Daan Wierstra, and Timothy Lillicrap. Meta-learning with memory-augmented neural networks. In *International Conference on Machine Learning (ICML)*, 2016.

Jurgen Schmidhuber. *Evolutionary principles in self-referential learning, or on learning how to learn: the meta-meta-... hook*. PhD thesis, Institut f. Informatik, Tech. Univ. Munich, 1987.

Jake Snell, Kevin Swersky, and Richard Zemel. Prototypical networks for few-shot learning. In *Advances in Neural Information Processing Systems (NIPS)*, 2017.

Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N Gomez, Łukasz Kaiser, and Illia Polosukhin. Attention is all you need. In *Advances in Neural Information Processing Systems (NIPS)*, 2017.

Oriol Vinyals, Charles Blundell, Tim Lillicrap, Daan Wierstra, et al. Matching networks for one shot learning. In *Advances in Neural Information Processing Systems (NIPS)*, 2016.

Yuxiong Wang, Ross Girshick, Martial Hebert, and Bharath Hariharan. Low-shot learning from imaginary data. In *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 2018.

Alex Wong and Alan L Yuille. One shot learning via compositions of meaningful patches. In *International Conference on Computer Vision (ICCV)*, 2015.

Yuxin Wu and Kaiming He. Group normalization. *European Conference on Computer Vision (ECCV)*, 2018.

A TWO NEW BENCHMARKS FOR MCFS PROBLEM: *mcfs*IMAGENET & *mcfs*OMNIGLOT

ImageNet (Deng et al., 2009) may be the most widely used large-scale benchmark dataset for image classification. However, although it provides hierarchical information about class labels, it cannot be directly used to test the performance of MCFS learning methods. Because a fine class may belong to multiple coarse classes, and in MCFS problem, each sample has only one unique coarse-class label. In addition, ImageNet does not satisfy the criteria of "few-shot" per class. *mini*ImageNet (Vinyals et al., 2016) has been widely used as a benchmark dataset in meta-learning community to test the performance on few-shot learning task. *mini*ImageNet is a subset of data extracted from ImageNet; however, its data are sourced from only 80 fine classes, which is not "many-class" nor does this carry a class hierarchy.

Hence, to develop a benchmark dataset specifically for the purpose of testing the performance of MCFS learning methods, we extracted a subset of images from ImageNet and created a dataset called "*mcfs*ImageNet". Table 2 compares the statistics of *mcfs*ImageNet with several benchmark datasets, and more details of the class hierarchies in mcfsImageNet are given in the Appendix D. Comparing to the original ImageNet, we avoided selecting the samples that belong to more than one coarse classes into *mcfs*ImageNet to meet the class hierarchy requirements of MCFS problem, i.e., each fine class only belongs to one coarse class. Compared to *mini*ImageNet, *mcfs*ImageNet is about $5\times$ larger, and covers 754 fine classes - many more than the 80 fine classes in *mini*ImageNet. Moreover, on average, each fine class only has ~ 185 images for training and test, which is typical MCFS scenarios. Additionally, the number of coarse classes in *mcfs*ImageNet is 77, which is many less than 754 of the fine classes. This is consistent with the data properties found in many practical applications, where the coarse-class labels can only provide weak supervision, but each coarse class has sufficient training samples. Further, we avoided selecting coarse classes which were too broad or contained too many very different fine classes. For example, the "Misc" class in ImageNet has 20400 sub-classes, and includes both animal (3998 sub-classes) and plant (4486 sub-classes).

Omniglot (Lake et al., 2011) is a small hand-written character dataset with two levels. However, new coarse classes appear in the test set, which is inconsistent with our MCFS settings (all the coarse classes are exposed in training, but new fine classes can appear during test). As a result, we re-split Omniglot to fulfill the MCFS problem requirement and the class hierarchy information are listed in Appendix E.

B EXPERIMENTAL SETUP

Setup for the supervised learning. We use ResNet18 (He et al., 2016) for the backbone CNN. The transformation functions g and h in the attention module are two fully connected layers followed by group normalization (Wu & He, 2018) with a residual connection. We set the memory size to $m = 12$ and the number of clusters to $r = 3$, which can achieve a better trade-off between memory cost and performance. Batch normalization (Ioffe & Szegedy, 2015) is applied after each convolution and before activation. During pre-training, we apply the cross entropy loss on the probability predictions in Eq. (7). During fine-tuning, we fix the θ^{CNN}, θ_c^{MLP}, and θ_f^{MLP} to ensure the fine-tuning process is stable. We use SGD with a mini-batch size of 128 and a cosine learning rate scheduler with an initial learning rate 0.1. $\mu = 1.05$, $\eta = 0.95$, a weight decay of 0.0001, and a momentum of 0.9 are used. We train the model for 100 epochs during pre-training and 90 epochs for the fine-tuning.

Setup for the meta learning. We use the same backbone CNN, g, and h as in supervised learning. In each task, we sample the same number of classes for training and test, and follow the training procedure in Snell et al. (2017). We set an initial learning rate to 10^{-3} and reduce it by a factor $2\times$ every 10k iterations. Our model is trained by Adam (Kingma & Ba, 2015) with a mini-batch size of 128, a weight decay of 0.0001, and a momentum of 0.9. We train the model for 25k iterations in total. For class hierarchy, the objective function is the sum of the softmax with cross entropy losses on the coarse class and on the fine class, respectively.

C RELATED WORKS

Few-shot learning has a long history. Before deep learning, generative models (Fei-Fei et al., 2006) are trained to provide a global prior knowledge for solving the one-shot learning problem. However, with the advent of deep learning techniques, some recent approaches (Wong & Yuille, 2015; Lake et al., 2013) use generative models to encode specific prior knowledge, such as strokes and patches. More recently, Douze et al. (2018) and Wang et al. (2018) have applied hallucinations to training images and to generate more training samples, which converts a few-shot problem to a many-shot problem.

Meta-learning has been used in attempts to solve the few-shot learning problems. Meta learning was first proposed in the last century (Naik & Mammone, 1992; Schmidhuber, 1987), and) but has recently seen some significant improvements. For example, Lake et al. (2015) proposed a dataset of characters for meta-learningn while Koch et al. (2015) extended this idea into a Siamese network. A more challenging dataset (Ravi & Larochelle, 2017; Vinyals et al., 2016) was introduced later. Researchers have also studied RNN and attention based method to overcome the few-shot problem. More recently, Snell et al. (2017) is proposed based on a metric learning equipped KNN. In contrast, Finn et al. (2017) based their approach on the second order optimization. Mishra et al. (2018) uses temporal convolution to address the few-shot image recognition. However, unlike above methods, our model leverages the class hierarchy information, and can be easily applied to both the supervised learning and meta-learning scenarios.

D *mcfs*IMAGENET CLASS SPLITS

The hierarchy of coarse and fine classes is shown below. Every key (marked in **bold**) in the dictionary is a coarse class, the value is a list of the fine classes of this coarse classes.

n02470325: [n02482650, n02481500, n02483362, n02481103, n02482060, n02481235, n02482474, n02481366, n02482286, n02483708] **n01769347**: [n01782516, n01775370, n01772664, n01773797, n01773549, n01774384, n01777304, n01773157, n01778217, n01770081] **n12855042**: [n12856479, n12855710, n12855886, n12855494, n12855365, n12856287, n12856680, n12856091] **n13109733**: [n11705171, n12717224, n12734215, n12491017, n11710136, n11707827, n12634734, n12711984, n12709103, n12753245] **n07806221**: [n07807834, n07808904, n07806774, n07808268, n07808587, n07806879, n07807472, n07808022, n07807594, n07808479] **n01428580**: [n02583890, n01447331, n01449374, n02520147, n01439808, n02538562, n01442972, n02543565, n02527057, n01447658] **n01789386**: [n01793249, n01790812, n01790304, n01795735, n01815036, n01806297, n01793085, n01796729, n01794344, n01797020] **n12582231**: [n12590499, n12597466, n12587487, n12598027, n12595699, n12596148, n12583855, n12587803, n12597134, n12596345] **n01816887**: [n01819734, n01819313, n01818299, n01817263, n01819465, n01817346, n01822300, n01821869, n01818832, n01818515] **n12724942**: [n12728322, n12731029, n12727518, n12729521, n12726159, n12729729, n12728864, n12730544, n12725940, n12728508] **n07802417**: [n07804543, n07802863, n07889193, n07804900, n07804771, n07804657, n07802963, n07803310] **n07882497**: [n07628181, n07861247, n07861158, n07594066, n07628068, n07678586, n07594155, n07679034, n07839478, n07678953] **n01940736**: [n01945143, n01953594, n01944118, n01955084, n01947396, n01959029, n01965529, n01960177, n01963317, n01958346] **n07911677**: [n07914586, n07915800, n07916437, n07931452, n07918309, n07914995, n07917392, n07918193, n07917133, n07916183] **n12864545**: [n12865037, n12866002, n12866162, n12866459, n12865824, n12865708, n12865562, n12866635] **n07886572**: [n07887192, n07890226, n07889990, n07887304, n07887967, n07888816, n07890540, n07890068, n07887461, n07888229] **n01524359**: [n01561732, n01556182, n01537895, n01561452, n01593553, n01583828, n01539925, n01543632, n01535690, n01538630] **n12268246**: [n12278865, n12271933, n12278650, n12277150, n12276872, n12270278, n12276477, n12273344, n12271187, n12270741] **n01674216**: [n01682435, n01682714, n01680983, n01689811, n01687978, n01690466, n01678043, n01680655, n01693175, n01689081] **n02084071**: [n02088466, n02101006, n02113624, n02091467, n02111277, n02087394, n02102177, n02105412, n02094258, n02106662] **n02274024**: [n02305085, n02297819, n02304432, n02277742, n02302244, n02303284, n02281015, n02279972, n02276078, n02282257] **n02441326**: [n02443484, n02445171, n02442572, n02446206, n02445004, n02443346, n02450295, n02448060, n02447762, n02449183] **n02484322**: [n02488415, n02493793, n02494079, n02493509, n02492660, n02492948, n02487547, n02485536, n02485688, n02490811] **n07901587**: [n07906111, n07902799, n07905296, n07904865, n07907037, n07904293, n07905386, n07902443,

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**n07907943**: [n07910048, n07910152, n07908812, n07908411, n07910379, n07910970, n07911249, n07908567, n07908647, n07910538] **n02188699**: [n02197185, n02195526, n02203152, n02201626, n02198859, n02191979, n02196119, n02202124, n02204907, n02192513] **n07843775**: [n07848936, n07847917, n07848093, n07847827, n07848196, n07849733, n07616046, n07847453, n07849912, n07847585] **n02121808**: [n02122430, n02123478, n02123045, n02122510, n02123159, n02122298, n02123242, n02122878, n02123394, n02123917] **n11868814**: [n11876803, n11876204, n11870747, n11875523, n11879722, n11882074, n11882426, n11877646, n11877193, n11876432] **n02552171**: [n02656301, n02580679, n02555863, n02565324, n01451426, n02663211, n02578928, n02654112, n02572484, n02607470] **n12997654**: [n13013965, n13075684, n13053608, n13014265, n13013764, n13018088, n13020964, n13011595, n13032618, n13003522] **n03764276**: [n04006067, n04308273, n03466600, n04457474, n04308397, n03549199, n03811295, n04487894, n04363082, n03466493] **n09366317**: [n09362945, n09214916, n09230202, n09472597, n09411295, n09421951, n09193705, n09396465, n09269341, n09218641] **n07679356**: [n07682808, n07685218, n07685399, n07682477, n07683039, n07680761, n07690431, n07684938, n07681691, n07681450] **n07929519**: [n07919572, n07920872, n07920349, n07919441, n07920222, n07731284, n07919894, n07920663, n07920540, n07921239] **n02323449**: [n02324514, n02324431, n02327842,

n02324587, n02324850, n02327656, n02328150, n02325722, n02326862] **n13100156**: [n12766869, n11724109, n11734698, n12455950, n11723227, n11773987, n11767877, n12935609, n12767648, n12941220] **n12334293**: [n12336727, n12338454, n12336224, n12337617, n12316572, n12340581, n12338655, n12340755, n12338146, n12336973] **n01909422**: [n01914830, n01917882, n01917611, n01917289, n01915700, n01913166, n01916388, n01909906, n01916481] **n01838038**: [n01839949, n01842235, n01841679, n01840775, n01841441, n01839086, n01840412, n01843065, n01839330, n01840120] **n02206270**: [n02213663, n02209111, n02213788, n02211627, n02218371, n02221715, n02210427, n02216211, n02221414, n02214499] **n07712382**: [n07696625, n07696728, n07696839, n07697313, n07698672, n07865105, n07696977, n07697699, n07698401, n07697408] **n07811416**: [n07935043, n07820960, n07933154, n07816398, n07821758, n07812046, n07818825, n07826340, n07816164, n07820297] **n12685431**: [n12686077, n12686274, n12686496, n12686676, n12687957, n12686877, n12687044, n12687462, n12687698] **n12101870**: [n12139921, n12140903, n12140511, n12134486, n12123741, n12126084, n12121610, n12117326, n12130549, n12133462]

E *mcfs*OMNIGLOT CLASS SPLITS

The hierarchy of coarse and fine classes is shown below. Every key (marked in **bold**) in the dictionary is a coarse class, the value is a list of the fine classes of this coarse classes.

Training Hierarchy Classes:

Mkhedruli_(Georgian): [character10, character38, character25, character29, character21, character04, character13, character37, character34, character31, character17, character16, character03, character30, character02, character06, character24, character11, character39, character19, character07, character14, character32, character36] **Alphabet_of_the_Magi**: [character18, character05, character17, character03, character08, character01, character15, character07, character09, character10, character19, character11, character20] **Angelic**: [character12, character16, character20, character06, character13, character19, character04, character03, character07, character09, character05] **Early_Aramaic**: [character09, character02, character07, character11, character04, character19, character16, character05, character21, character18, character06, character12, character03, character13, character10] **Old_Church_Slavonic_(Cyrillic)**: [character21, character36, character38, character07, character15, character11, character29, character14, character43, character17, character34, character25, character41, character35, character23, character22, character20, character44, character19, character09, character10, character33, character45, character26, character32] **Gujarati**: [character05, character44, character06, character35, character40, character45, character07, character29, character12, character09, character24, character38, character46, character15, character32, character21, character18, character25, character04, character02, character23, character03, character31, character14, character34, character20, character37, character43, character30, character36, character26, character08, character28] **Japanese_(katakana)**: [character31, character44, character10, character21, character33, character14, character36, character06, character11, character28, character27, character04, character26, character43, character03, character08, character12, character24, character16, character15, character35, character05, character01, character41, character25, character29, character38, character39, character22, character02] **Syriac_(Serto)**: [character14, character23, character03, character04, character18, character06, character02, character22, character15, character09] **Tengwar**: [character21, character19, character15, character13, character03, character11, character16, character10, character18, character05, character14] **Korean**: [character03, character14, character35, character32, character04, character19, character15, character33, character01, character28, character09, character40, character16, character07, character39, character34, character37, character11, character36, character24, character10, character05] **Malayalam**: [character37, character34, character42, character01, character10, character40, character28, character06, character17, character35, character14, character19, character38, character13, character08, character46, character47, character21, character23, character18, character36, character24, character43, character33, character03] **Japanese_(hiragana)**: [character44, character05, character13, character19, character31, character40, character24, character50, character07, character11, character06, character01, character32, character10, character46, character04, character47, character45, character27, character42, character36, character09, character34, character49, character12, character28, character37, character26, character23, character52, character38, character17, character25, character30] **Atemayar_Qelisayer**: [character06, character08, character09, character16, character05, character14, character11, character01, character10, character13, character02, character20, character26] **Tibetan**: [character31, character30, character21, character18, character20, character34, character29, character10, character23, character16, character42, character17, character15, character03, character33, character01, character25, character13, character09, character05, character40, character26, character38, character06, character28] **Sylheti**: [character03, character28, character17, character13, character23, character27, character08,

character22, character05, character14, character12, character16, character04, character18, character20, character24] **Malay_(Jawi_-_Arabic)**: [character27, character11, character12, character13, character23, character36, character26, character33, character31, character39, character32, character40, character21, character09, character14, character17, character28, character38, character06] **Latin**: [character07, character08, character02, character24, character22, character06, character14, character09, character21, character10, character25, character04, character13, character19, character03, character26, character05, character18, character16, character15] **Syriac_(Estrangelo)**: [character20, character19, character04, character10, character09, character07, character21, character08, character22, character16, character15, character14, character03, character05, character01, character11, character17] **ULOG**: [character04, character02, character15, character05, character08, character12, character03, character16, character24, character13, character26, character23, character25, character19] **Blackfoot_(Canadian_Aboriginal_Syllabics)**: [character13, character03, character12, character11, character05, character07, character01, character10] **Futurama**: [character22, character20, character08, character11, character05, character06, character16, character02, character13, character03, character14, character15, character17, character12] **Gurmukhi**: [character34, character21, character08, character38, character04, character37, character09, character03, character26, character35, character20, character19, character41, character13, character16, character28, character10, character39, character32, character29, character33, character24, character12, character45, character22, character05] **Ojibwe_(Canadian_Aboriginal_Syllabics)**: [character08, character04, character01, character12, character13, character11, character03, character10, character05, character02] **Greek**: [character13, character14, character06, character22, character01, character19, character08, character02, character09, character07, character04, character18, character12, character03] **Armenian**: [character11, character13, character35, character36, character21, character26, character01, character30, character27, character32, character40, character05, character25, character16, character22, character19, character39, character15, character14, character33, character09] **Kannada**: [character01, character32, character20, character28, character40, character11, character10, character17, character25, character33, character02, character19, character27, character39, character37, character38, character36, character41, character29, character23, character16, character14, character04, character18, character21, character12, character24, character09] **Manipuri**: [character04, character20, character24, character32, character02, character09, character33, character30, character14, character29, character16, character05, character34, character03, character13, character12, character31, character10, character18, character15, character22, character23] **Oriya**: [character09, character31, character45, character27, character05, character07, character11, character23, character15, character20, character29, character44, character32, character06, character19, character46, character36, character03, character25, character01, character26, character04, character38, character22, character35] **Asomtavruli_(Georgian)**: [character10, character12, character17, character11, character03, character24, character25, character35, character32, character22, character21, character29, character14, character23, character34, character20, character33, character26, character16, character28, character04, character05, character08, character06] **Keble**: [character17, character03, character15, character18, character13, character19, character10, character07, character21, character26, character08, character12, character09, character11, character14, character16, character05, character22] **Arcadian**: [character09, character10, character03, character16, character26, character04, character08, character18, character23, character02, character14, character22, character05, character01] **Cyrillic**: [character33, character26, character01, character11, character08, character24, character22, character10, character04, character27, character07, character09, character06, character18, character20, character19, character21, character12, character25, character29, character32] **Hebrew**: [character16, character02, character10, character19, character13, character01, character11, character14, character22, character12, character07, character15, character21, character05] **Avesta**: [character23, character21, character17, character18, character03, character25, character19, character24, character22, character06, character09, character16, character05, character26, character15] **Glagolitic**: [character14, character01, character23, character42, character39, character06, character33, character03, character19, character10, character11, character37, character21, character04, character31, character41, character30, character07, character17, character35, character26, character28, character25, character29] **Ge_ez**: [character18, character11, character07, character22, character21, character04, character06, character13, character15, character25, character20, character12, character08, character05] **Bengali**: [character44, character06, character17, character45, character12, character09, character04, character32, character22, character46, character37, character14, character07, character26, character20, character41, character11, character33, character02, character40, character39, character10, character35, character28, character01, character19, character05, character27, character13] **Atlantean**: [character17, character26, character11, character15, character08, character19, character09, character12, character04, character18, character21, character03, character02, character06, character23] **Sanskrit**: [character20, character40, character24, character01, character37, character39, character28, character42, character13, character09, character02, character25, character23, character33, character19, character07, character35, character36, character17, character11, character38, character15, character16, character31, character03, character10, character26, character21, character29] **Braille**: [character12,

character14, character18, character15, character23, character05, character01, character10, character24, character02, character22, character11, character20, character21] **Burmese_(Myanmar)**: [character15, character23, character33, character26, character10, character08, character30, character25, character21, character07, character31, character19, character34, character05, character29, character27, character06, character20, character03, character09, character18, character24, character22, character12] **Tagalog**: [character05, character14, character04, character03, character12, character15, character10, character09, character01, character17, character11] **Mongolian**: [character25, character16, character11, character30, character14, character20, character18, character07, character17, character13, character19, character12, character29, character27, character08, character01, character28, character22, character26] **Inuktitut_(Canadian_Aboriginal_Syllabics)**: [character13, character05, character06, character15, character11, character16, character10, character14] **N_Ko**: [character23, character12, character16, character11, character32, character20, character19, character02, character10, character31, character13, character28, character18, character14, character24, character26, character21, character30, character15, character01] **Balinese**: [character19, character06, character17, character13, character11, character01, character24, character02, character04, character20, character23, character12, character14, character18, character09] **Aurek-Besh**: [character23, character20, character05, character17, character14, character06, character15, character09, character22, character13, character07, character03, character19, character16, character24, character08, character10, character02, character12, character21, character18, character11, character25] **Anglo-Saxon_Futhorc**: [character11, character14, character09, character01, character10, character16, character05, character27, character18, character02, character08, character21, character13, character29, character17, character20] **Tifinagh**: [character42, character38, character35, character36, character31, character08, character52, character26, character41, character50, character09, character45, character24, character11, character39, character19, character34, character05, character21, character16, character23, character37, character04, character28, character03, character32, character10, character43, character40, character48, character17, character44, character49, character06, character20] **Grantha**: [character39, character13, character12, character33, character35, character15, character16, character27, character20, character19, character30, character26, character42, character22, character23, character03, character02, character07, character38, character40, character25, character18, character08, character37, character32, character24]

Validation Hierarchy Classes:

Alphabet_of_the_Magi: [character16] **Angelic**: [character01, character10, character11] **Early_Aramaic**: [character17, character14] **Oriya**: [character14, character40, character10, character21, character33, character39, character12, character41, character16] **Gujarati**: [character13, character47, character33, character10, character22] **Japanese_(katakana)**: [character17, character46, character45, character30, character40, character07, character18] **Syriac_(Serto)**: [character13, character12, character17, character21, character08, character20, character19] **Tengwar**: [character09, character06, character22] **Korean**: [character25, character29, character26, character38, character06] **Malayalam**: [character12, character09, character30, character11, character31, character44, character39, character32, character04] **Arcadian**: [character13, character19, character07, character06] **Atemayar_Qelisayer**: [character18, character24, character25, character22] **Tibetan**: [character32, character11, character12, character41, character35] **Sylheti**: [character25, character01, character26, character06] **Old_Church_Slavonic_(Cyrillic)**: [character16, character28, character01, character12, character40, character42, character39] **ULOG**: [character07, character22, character06, character17, character14, character20, character18, character10] **Syriac_(Estrangelo)**: [character12, character06] **Tagalog**: [character08] **Blackfoot_(Canadian_Aboriginal_Syllabics)**: [character09, character08] **Futurama**: [character25, character10, character04, character26, character24, character19, character01] **Gurmukhi**: [character18, character17, character43, character25, character07, character42, character06, character02] **Ojibwe_(Canadian_Aboriginal_Syllabics)**: [character06, character09] **Mkhedruli_(Georgian)**: [character40, character33, character22, character26, character05, character27, character15, character12, character28] **Armenian**: [character37, character18, character08, character17] **Kannada**: [character15, character13, character08, character26, character05, character35, character07, character34, character30] **Manipuri**: [character06, character36, character11, character27, character38, character26] **Anglo-Saxon_Futhorc**: [character25, character24, character06] **Asomtavruli_(Georgian)**: [character02, character09, character15, character07, character39, character18, character30] **Keble**: [character24, character20, character04, character23, character01] **Japanese_(hiragana)**: [character22, character02, character33, character41, character14, character16, character51] **Braille**: [character13, character26, character04, character25, character17] **Hebrew**: [character20, character03, character18, character06, character09] **Avesta**: [character10, character01, character08, character11, character13, character20, character07] **Glagolitic**: [character44, character38, character08, character18, character36, character12, character13, character09] **Latin**: [character23] **Ge_ez**: [character01, character23, character09, character19] **Bengali**: [character29, character23, character21, character38] **Atlantean**: [character13, character20] **Greek**: [character05, character21, character24, character10] **Cyril-**

lic: [character02, character16] **Burmese_(Myanmar)**: [character14, character13, character32] **Grantha**: [character17, character14, character31, character21, character01, character11] **Mongolian**: [character23, character24, character15, character03] **Inuktitut_(Canadian_Aboriginal_Syllabics)**: [character02, character08, character12, character09] **N_Ko**: [character33, character03, character09, character06, character25] **Balinese**: [character15, character07, character03, character05] **Aurek-Besh**: [character26] **Tifinagh**: [character30, character15, character54, character33, character02, character18, character07, character13] **Sanskrit**: [character14, character18, character22, character27, character08] **Malay_(Jawi_-_Arabic)**: [character08, character05, character02, character16, character19, character18, character29]

Testing Hierarchy Classes:

Mkhedruli_(Georgian): [character01, character18, character20, character41, character08, character09, character23, character35] **Alphabet_of_the_Magi**: [character14, character04, character13, character06, character02, character12] **Angelic**: [character02, character08, character14, character17, character15, character18] **Early_Aramaic**: [character01, character08, character15, character22, character20] **Oriya**: [character30, character18, character43, character28, character17, character13, character24, character42, character02, character37, character08, character34] **Gujarati**: [character17, character39, character19, character11, character01, character16, character41, character27, character48, character42] **Japanese_(katakana)**: [character20, character32, character42, character09, character13, character37, character19, character34, character23, character47] **Syriac_(Serto)**: [character05, character07, character10, character11, character01, character16] **Ge_ez**: [character10, character16, character17, character14, character03, character24, character26, character02] **Korean**: [character31, character12, character22, character21, character18, character02, character23, character27, character30, character17, character20, character08, character13] **Malayalam**: [character07, character22, character15, character05, character25, character16, character02, character45, character41, character29, character26, character27, character20] **Atlantean**: [character16, character14, character25, character05, character01, character07, character10, character22, character24] **Atemayar_Qelisayer**: [character19, character21, character12, character04, character07, character17, character15, character23, character03] **Arcadian**: [character24, character20, character25, character12, character21, character17, character15, character11] **Tibetan**: [character04, character36, character19, character37, character07, character39, character22, character02, character24, character08, character27, character14] **Old_Church_Slavonic_(Cyrillic)**: [character02, character13, character08, character06, character30, character27, character03, character05, character24, character31, character37, character18, character04] **Malay_(Jawi_-_Arabic)**: [character04, character03, character15, character37, character20, character34, character24, character35, character25, character30, character07, character10, character01, character22] **Cyrillic**: [character13, character15, character05, character14, character23, character31, character28, character17, character03, character30] **Syriac_(Estrangelo)**: [character23, character18, character13, character02] **Tagalog**: [character07, character06, character13, character02, character16] **Bengali**: [character25, character18, character36, character16, character30, character15, character03, character42, character43, character31, character34, character08, character24] **ULOG**: [character09, character01, character11, character21] **Gurmukhi**: [character30, character14, character11, character44, character31, character27, character23, character36, character15, character40, character01] **Ojibwe_(Canadian_Aboriginal_Syllabics)**: [character07, character14] **Sanskrit**: [character34, character06, character30, character41, character12, character04, character05, character32] **Armenian**: [character24, character34, character41, character07, character31, character12, character28, character29, character20, character38, character23, character02, character03, character10, character06, character04] **Kannada**: [character06, character22, character03, character31] **Manipuri**: [character35, character37, character17, character39, character25, character28, character19, character01, character07, character40, character21, character08] **Anglo-Saxon_Futhorc**: [character22, character19, character28, character03, character23, character07, character15, character26, character12, character04] **Asomtavruli_(Georgian)**: [character36, character27, character37, character31, character01, character40, character19, character38, character13] **Keble**: [character25, character06, character02] **Japanese_(hiragana)**: [character03, character35, character15, character08, character43, character20, character18, character21, character29, character39, character48] **Latin**: [character12, character01, character11, character20, character17] **Hebrew**: [character08, character17, character04] **Avesta**: [character14, character12, character02, character04] **Glagolitic**: [character40, character24, character45, character20, character32, character43, character05, character02, character15, character27, character22, character34, character16] **Tengwar**: [character25, character01, character08, character20, character24, character23, character04, character17, character02, character07, character12] **Greek**: [character20, character15, character17, character16, character23, character11] **Sylheti**: [character02, character10, character07, character19, character15, character21, character11, character09] **Braille**: [character09, character16, character07, character08, character19, character06, character03] **Burmese_(Myanmar)**: [character01, character16, character11, character28, character17, character04, character02] **Futurama**: [character21, character23, character09, character18, character07] **Mon-**

golian: [character02, character09, character06, character05, character21, character04, character10] **Inuktitut_(Canadian_Aboriginal_Syllabics)**: [character01, character03, character04, character07] **N_Ko**: [character27, character07, character04, character22, character17, character08, character05, character29] **Blackfoot_(Canadian_Aboriginal_Syllabics)**: [character06, character02, character04, character14] **Balinese**: [character08, character10, character22, character16, character21] **Aurek-Besh**: [character04, character01] **Tifinagh**: [character12, character53, character51, character46, character55, character25, character22, character14, character47, character01, character27, character29] **Grantha**: [character10, character34, character29, character04, character05, character06, character43, character36, character28, character09, character41]