Hub-Pathway: Transfer Learning from A Hub of Pre-trained Models

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Abstract

Transfer learning aims to leverage knowledge from pre-trained models to benefit the target task. Prior transfer learning work mainly transfers from a single model. However, with the emergence of deep models pre-trained from different resources, model hubs consisting of diverse models with various architectures, pre-trained datasets and learning paradigms are available. Directly applying single-model transfer learning methods to each model wastes the abundant knowledge of the model hub and suffers from high computational cost. In this paper, we propose a *Hub-Pathway* framework to enable knowledge transfer from a model hub. The framework generates data-dependent pathway weights, based on which we assign the pathway routes at the input level to decide which pre-trained models are activated and passed through, and then set the pathway aggregation at the output level to aggregate the knowledge from different models to make predictions. The proposed framework can be trained end-to-end with the target task-specific loss, where it learns to explore better pathway configurations and exploit the knowledge in pre-trained models for each target datum. We utilize a noisy pathway generator and design an exploration loss to further *explore* different pathways throughout the model hub. To fully *exploit* the knowledge in pre-trained models, each model is further trained by specific data that activate it, which ensures its performance and enhances knowledge transfer. Experiment results on computer vision and reinforcement learning tasks demonstrate that the proposed Hub-Pathway framework achieves the state-of-the-art performance for model hub transfer learning.

1 Introduction

With the emergence of large-scale datasets, various large-scale deep models are developed in wide range of areas such as computer vision [15, 56, 62] and natural language processing [13, 4]. These models not only show state-of-the-art performance in the tasks that they are designed for, but also achieve high performance when fine-tuned on various downstream tasks with different distributions. On the other hand, due to the requirement of large-scale annotated data, deep learning is still difficult to apply in specific domains without sufficient data [28]. Therefore, transfer learning, which aims to transfer knowledge from existing models and datasets to the target task, has attracted more and more attention recently [65, 4].

Current deep learning paradigm tends to increase the scale of the pre-trained model to embed more knowledge into the model, which can be transferred to more diverse tasks [20, 4]. However, infinitely increasing the model scale requires machines with larger storage and stronger GPUs, which are expensive and cost much energy. Instead, many pre-trained models from different resources are already available, including pre-trained on diverse datasets or tasks, e.g. ImageNet for classification [47], or BERT for language modelling [13], pre-trained with diverse learning paradigms, e.g. supervised learning [24], self-supervised learning [16] or unsupervised learning [7] and with various

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architectures, e.g. single-stage [35] or two-stage models [23] for object detection. These diverse models contain abundant knowledge and introduce low cost in both training and inference. Thus, there is a high motivation to enable knowledge transfer from all of these models. We define the problem as *model hub transfer learning*, where a model hub consists of pre-trained models from different resources.

Human beings also face the same problem of transfer learning from a model hub, where the different pre-trained models are similar to different regions of our brain specializing for different tasks. When solving a new task, human beings only call on the most relevant region of the brain to address the task. Recently, Dean et al. [12] also propose the outlook that the next-generation AI architecture should activate different parts of the model to solve different tasks. Motivated by these, we design pathways to activate different pre-trained models for prediction depending on the input data. However, there exist two challenges to design such pathways. Firstly, how to explore and find the optimal pathway configuration to activate the most relevant models for each target datum? Secondly, even knowing which pre-trained models to use, how to aggregate and exploit the knowledge in these pre-trained models?

We propose a new *Hub-Pathway* framework to address the above challenges, which enables effective knowledge transfer from a model hub. We design an architecture with the pathway route at the input level to select which pre-trained models to activate and the pathway aggregation at the output level to aggregate the prediction from different pre-trained models, where both the pathway route and the pathway aggregation are based on pathway weights generated data-dependently by a network. We only activate the pathways with top k weights to avoid negative transfer of irrelevant models and improve the efficiency of the framework. The framework is optimized by a task-specific loss to ensure that the pathways introduce high transfer performance. To promote the exploration the pathways, we employ a noisy pathway generator and design an exploration loss to encourage the framework to explore and compare different pathways and find better pathway configurations. To promote the exploitation of the knowledge in the activated models, we further fine-tune the models with the specific data activating them. In all, our contribution can be summarized as:

- We investigate the important problem of transfer learning from a model hub and propose a general Hub-Pathway framework which can address different situations where models may be trained from different datasets and learning paradigms and with diverse architectures. We design data-dependent pathways to route different data to different models at the input level and aggregate the transferred knowledge at the output level to make predictions.
- We promote the exploration and exploitation of the framework to enhance more effective transfer learning from a model hub. We design a noisy pathway generator and an exploration loss to encourage exploring more models and pathway configurations. We further propose to fine-tune the activated models with specific data to fully utilize the transferred knowledge.

2 Related Work

Transfer Learning. Transfer learning is a learning paradigm to improve the performance of the target task by transferring knowledge from source domains [42]. Early works transfer knowledge by directly reusing features extracted by the pre-trained model [41, 14] and later works find that fine-tuning the pre-trained model introduces higher transfer performance [1, 19]. As an easy and effective transfer learning method, many empirical studies investigate the effectiveness fine-tuning on various downstream tasks and scenarios, such as classification [30, 63], few-shot learning [46], medical imaging [45], object detection and instance segmentation [22]. Recently, several works explore the limitations of the vanilla fine-tuning method and develop new techniques to improve the performance, including regularizing the parameters [58] or features [33, 8] and exploring category relationships [60] or category intrinsic structures [64] by auxiliary tasks. Also, there are works studying the transferability of each layer in a pre-trained model [59]. However, these studies focus on fine-tuning from a single model and it remains unclear how to extend single model transfer learning techniques to multiple pre-trained models, where simply assembling every single model is inefficient.

Transfer Learning with Multiple Models. In the presence of multiple pre-trained models, recent works estimate the transferability of each pre-trained model and select the best one [54, 2, 40, 61], but subject to the inaccurate measurement of model transferability which is a hard problem itself, such model-level selection may degrade the performance and lose the rich knowledge in all the

models since only a single best model is utilized. To address this problem, several works propose to aggregate the features [48, 34] or parameters [51] of all the pre-trained models. However, all of these methods assume that the pre-trained models form a model zoo where all models have layer-to-layer correspondence or even share the same architecture, which is unrealistic for the most general case of transfer learning with arbitrary models. We instead propose model hub transfer learning to remove all the constraint on the pre-trained models and realize the most general case of transfer learning.

Conditional Computation. Our method is also related to conditional computation, where parts of the network are active on a per-example basis. A series of works [11, 17, 10] introduce the idea of multiple mixture-of-experts (MoE) [39] activated by data-adaptive gating networks. [50] introduces sparsely-gated mixture-of-experts layers to form outrageously large neural networks. Different from these methods which create mixture-of-experts from homogeneous networks with random initializations, our hub-pathway method simultaneously explores the pathways through different pre-trained models with diverse knowledge and exploits the relevant part of knowledge to enhance transfer learning performance on the downstream tasks.

3 Hub-Pathway

We first define the problem of model hub transfer learning. Then we introduce the Hub-Pathway framework with smart designs to boost its exploration and exploitation of the model hub, simultaneously improving positive transfer of relevant knowledge and avoiding negative transfer of harmful knowledge.

The most common transfer learning scenario considers only one single pre-trained model Θ at hand to serve the target task $\mathcal{D} = \{(\mathbf{x}, \mathbf{y})\}$. In *model hub transfer learning*, we consider a situation where we have a hub of pre-trained models $\{\Theta_1, \Theta_2, \cdots, \Theta_m\}$, where all models can differ in all the aspects including the pre-training datasets, pretext tasks, learning paradigms and the network architectures. This problem setting can be generally applied in various realistic problems even if the pre-trained models are obtained from quite different resources.

Motivated by the cognitive science and the pathway idea in deep networks, we propose a Hub-Pathway framework to address the problem. We illustrate the architecture of our framework in Figure 1. We modify pre-trained models by replacing their output head layers with target-task-specific output layers, which form the models we will transfer from. As our motivation stated above, different data have different relations with the pre-trained models and should activate and transfer knowledge from different models. To realize this idea, we employ a pathway generator network G which outputs data-dependent pathway weights $G(\mathbf{x})$ based on the input data $\mathbf{x}$, with each dimension indicating the weight of one specific model in the hub. The dense pathway weights in $G(\mathbf{x})$ still activate all the pathways to all the pre-trained models. To utilize the most suitable pre-trained models for the target data, we only keep the top k pathway weight and set the rest pathway weights as 0:

$$\bar{G}(\mathbf{x}) = f_{\text{topk}}\left(G(\mathbf{x}), k\right), \text{where } f_{\text{topk}}\left(G(\mathbf{x}), k\right)_i = \begin{cases} G(\mathbf{x})_i & G(\mathbf{x})_i \text{ in the top } k \text{ entries of } G(\mathbf{x}) \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

Such a design has two benefits: (1) the models with useful knowledge to each target datum are transferred but those of negative influence will be eliminated; (2) there are only data forwarding and back-propagation through the activated models, which makes both training and testing more efficient.

Based on the pathway weight $G(\mathbf{x})$, we assign the pathway route at the *input level* as $\mathbb{I}\big[\bar{G}(\mathbf{x}) > 0\big]$, which only passes the input data through the pre-trained models with a pathway weight large than 0. The pathways with a 0 pathway weight are blocked and the corresponding models are not used for the current data. Then at the *output level*, an aggregator network A composes the outputs from different models with the pathway weights and outputs the final prediction of the model hub as $A\big(\big[\bar{G}(\mathbf{x})_i \cdot \Theta_i(\mathbf{x})\big]_{i=1}^{m}\big)$, where the function $[\cdot]$ concatenates all the m vectors. To train the framework, we then adopt a target-task-specific loss on the final prediction:

$$\mathcal{L}_{\text{task}} = \mathbb{E}_{(\mathbf{x},\mathbf{y})\sim\mathcal{D}}\ell\left(A\left(\left[\bar{G}(\mathbf{x})_i \cdot \Theta_i(\mathbf{x})\right]_{i=1}^{m}\right), \mathbf{y}\right), \tag{2}$$

where ℓ is the target-task loss, e.g. cross-entropy loss for the classification task. $\mathcal{L}_{\text{task}}$ ensures that the derived pathway configuration and model parameters contribute to the high performance on the target task, leading the framework to explore better pathways and exploit deeper the activated knowledge.

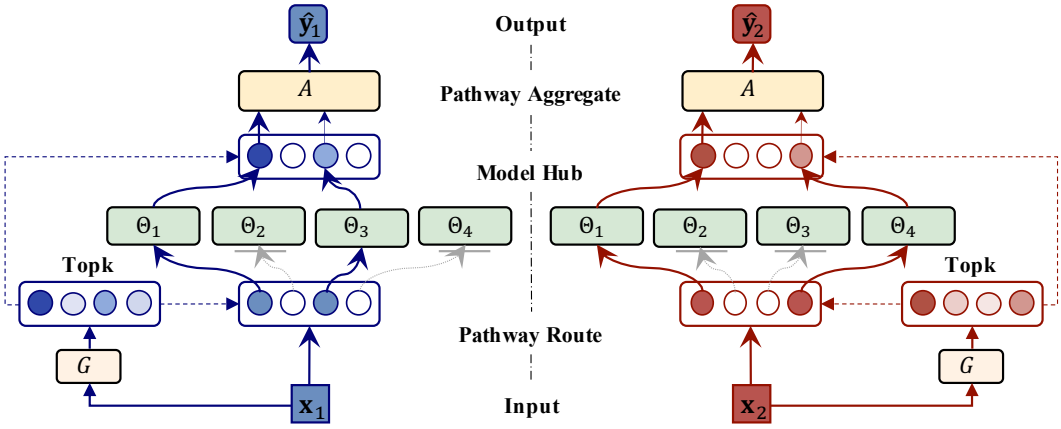


Figure 1: The architecture of our Hub-Pathway framework. We showcase using four pre-trained models Θ_1, Θ_2, Θ_3 and Θ_4, which are not changed in architecture but only fine-tuned in parameters. We generate the pathway weights by a generator network G and only keep the top k pathway weights while setting others as 0. We set a pathway route at the *input level* and a pathway aggregation at the *output level* based on the pathway weights. The pathway route only makes the data pass the pathway with pathway weight large than 0 while the pathway aggregation aggregates the predictions from different pre-trained models. A final aggregation network A generates the final prediction based on the transferred knowledge. The different colors are to highlight that *for different input data, our framework introduces different pathways to make the best use of pre-trained knowledge*.

3.1 Enhancing Exploration on Hub Pathways

When optimized with only the task-specific loss, the pathway framework has the risk of over-fitting and falling to a local optimum by trivially activating and repeatedly updating with a few specific models, which ignores other potentially more useful models and wastes the rich knowledge in the hub. Such a phenomenon is called *hub collapse* in this paper. With the aim of encouraging the exploration of models with high transferability throughout the model hub, we design from the architecture level and the loss level by employing a noisy pathway generator and introducing an exploration loss.

In order to implement a noisy pathway generator, $G(\mathbf{x})$ is designed to embody a standard subnetwork G_p and a randomized subnetwork G_n with ϵ drawn from a standard Gaussian distribution:

$$G(\mathbf{x}) = \text{Softmax}\big(G_p(\mathbf{x}) + \epsilon \cdot \text{Softplus}(G_n(\mathbf{x}))\big), \epsilon \sim \mathcal{N}(0, 1), \tag{3}$$

where $\text{Softmax}(\mathbf{z}) = \frac{\exp(\mathbf{z})}{\sum_{z \in \mathbf{z}} \exp(z)}$ and $\text{Softplus}(\mathbf{z}) = \log(1 + \exp(\mathbf{z}))$. The standard part $G_p(\mathbf{x})$ reflects which models are preferred and the noise term $G_n(\mathbf{x})$ adds some randomness to the pathway weights, which encourages the framework to explore other models or configurations during training.

Taking the key idea of maximum-entropy reinforcement learning that maximizes the exploration ability of the agent through the maximum entropy of the policy, we define the exploration loss $\mathcal{L}_{\text{explore}}$ by directly imposing a maximum-entropy regularization on the output of the pathway generator:

$$\mathcal{L}_{\text{explore}} = -\mathcal{H}\left(\mathbb{E}_{(\mathbf{x},\mathbf{y})\sim\mathcal{D}} G(\mathbf{x})\right), \tag{4}$$

where $\mathcal{H}(\mathbf{z}) = -\sum_i z_i \cdot \log(z_i)$ is the entropy function. The loss $\mathcal{L}_{\text{explore}}$ maximizes the entropy of the average pathway weights of all the target data. It enforces that from the viewpoint of the whole dataset, all models have the chance to be activated and different pathways over the pre-trained models are fully explored if they truly promote the target performance, thereby avoiding the hub collapse.

3.2 Enhancing Exploitation in Activated Models

With the above pathway designs and losses, we can learn better data-dependent pathways for each piece of target data. With the derived pathways, we know which pre-trained models to transfer knowledge from, and there remains the question of how to fully exploit such knowledge. The task-specific loss $\mathcal{L}_{\text{task}}$ utilizes and updates the knowledge in activated models, but each model contributes

only a fraction to such prediction and optimization process. To further enhance the transfer of knowledge and ensure the performance of the activated models, we further tune the pre-trained models $\Theta_i|_{i=1}^m$ with the task-specific loss on the specific data that activate them:

$$\mathcal{L}_{\text{exploit}} = \sum_{i=1}^{m} \mathbb{E}_{(\mathbf{x},\mathbf{y})\sim\mathcal{D}} \mathbb{I}\left(\bar{G}(\mathbf{x})_i > 0\right) \ell\left(\Theta_i(\mathbf{x}), \mathbf{y}\right). \tag{5}$$

The above mechanism of further exploiting more useful models in the hub for each datum shares similar spirit with reinforcement learning in exploiting the more rewarded states in the environments.

Empowering Hub-Pathway with exploration and exploitation, the final optimization problem becomes:

$$\begin{aligned} &\arg\min_{G,A} \mathcal{L}_{\text{task}} + \lambda \cdot \mathcal{L}_{\text{explore}} \\ &\arg\min_{\Theta_i|_{i=1}^m} \mathcal{L}_{\text{task}} + \mathcal{L}_{\text{exploit}}, \end{aligned} \tag{6}$$

where we use a trade-off λ between the target-task-specific loss and the exploration-encouraging loss since they have different scale. $\mathcal{L}_{\text{task}}$ and $\mathcal{L}_{\text{exploit}}$ are both derived from the target-task-specific loss with the same scale and thus no trade-off is needed. Our Hub-Pathway framework simultaneously explores data-dependent pathway configurations throughout the model hub and exploits the activated models by aggregating their useful knowledge and enhancing knowledge transfer to downstream tasks. The framework can be trained in an end-to-end way. The computation cost at both the training and testing time is at most k times of the single model fine-tuning, which is much more efficient than a naive ensemble of multiple models with the computation cost linearly increasing with the hub size.

4 Experiments

To verify that Hub-Pathway framework can address the general model hub transfer learning problem, we conduct experiments on tasks including image classification, facial landmark detection and reinforcement learning, which are proposed in [51]. In addition to the model hub with the homogeneous architecture evaluated by prior work [51], we also conduct experiments on different downstream tasks with the model hub consisting of pre-trained models with heterogeneous architectures, which is a more general situation that cannot be solved effectively by existing works. The implementation code and additional experimental results can be found in the supplementary materials.

4.1 Transfer Learning in Image Classification

We then conduct experiments for image classification, which is a widely investigated problem with many competitive prior work on transfer learning.

Homogeneous Model Hub. Previous work of Zoo-Tuning [51] explores a hub of models with the *homogeneous* architecture. We follow this setting and use 5 ResNet-50 models pre-trained on 5 widely-used computer vision datasets: (1) Supervised pre-trained model and (2) Unsupervised pre-trained model with MOCO [21] on ImageNet [47], (3) Mask R-CNN [23] model for detection and instance segmentation, (4) DeepLabV3 [6] model for semantic segmentation, and (5) Keypoint R-CNN model for keypoint detection, pre-trained on COCO-2017 challenge datasets of each task. All pre-trained models are drawn from torchvision model hub [43] or from the original implementation.

Heterogeneous Model Hub. To verify that Hub-Pathway could address more general model hub transfer learning settings, we further conduct experiments on a model hub consisting of models with *heterogeneous* architectures. We consider a model hub consisting of some other famous architectures including MobileNetV3 [27], EfficientNet [53], Swin Transformer [36] and ConvNeXt [37]. For the MobileNetV3 architecture, we use the MobileNetV3-Large-1.0 pre-trained model, which achieves the best performance in this model family. For the last three architectures, we use EfficientNet-B3 (EffNet-B3), Swin-Transformer-Tiny (Swin-T) and ConvNeXt-Tiny (ConvNeXt-T), which achieve comparable performance when pre-trained on ImageNet. We also utilize the Mask R-CNN model mentioned above to further increase the diversity of the training data and tasks in the hub.

Benchmarks. We verify the efficacy of Hub-Pathway on 7 various classification tasks evaluated in [51], including: **(1)** *General* classification benchmarks with **CIFAR-100** [32] and **COCO-70** [60]; **(2)** *Fine-grained* benchmarks for aircraft (**FGVC Aircraft** [38]), car (**Stanford Cars** [31]) and indoor scene (**MIT-Indoors** [44]) classification; **(3)** *Specialized* benchmarks collected from the DeepMind Lab environment (**DMLab** [3]) and Sentinel-2 satellite (**EuroSAT** [25]). We follow the common fine-tuning principle and replace the last layer with a randomly initialized fully connected layer [59].

Table 1: Results on the classification benchmarks with the homogeneous model hub.

Model	General		Fine-Grained			Specialized		Avg.
	CIFAR	COCO	Aircraft	Cars	Indoors	DMLab	EuroSAT	
ImageNet	81.18	81.97	84.63	89.38	73.69	74.57	98.43	83.41
MoCo	75.31	75.66	83.44	85.38	70.98	75.06	98.82	80.66
MaskRCNN	79.12	81.64	84.76	87.12	73.01	74.73	98.65	82.72
DeepLab	78.76	80.70	84.97	88.03	73.09	74.34	98.54	82.63
Keypoint	76.38	76.53	84.43	86.52	71.35	74.58	98.34	81.16
Ensemble	82.26	82.81	87.02	91.06	73.46	76.01	98.88	84.50
Distill	82.32	82.44	85.00	89.47	73.97	74.57	98.95	83.82
K-Flow	81.56	81.91	85.27	89.22	73.37	75.55	97.99	83.55
Zoo-Tuning-L	83.39	83.50	85.51	89.73	75.12	75.22	**99.12**	84.51
Zoo-Tuning	**83.77**	**84.91**	86.54	90.76	75.39	75.64	**99.12**	85.16
Hub-Pathway	83.31	84.36	**87.52**	**91.72**	**76.91**	**76.47**	**99.12**	**85.63**

We conduct each experiment 3 times with different seeds and report the average top-1 accuracy. More details on the datasets and implementation can be found in supplementary materials.

Results on Homogeneous Model Hub. We show the results on all the benchmarks in Table 1. We compare with fine-tuning from each single pre-trained model, the ensemble by a voting of the predictions of different pre-trained models after fine-tuning (Ensemble), knowledge distillation from the Ensemble model (Distill) and model zoo transfer learning methods including: Knowledge Flow [34] (K-Flow), Zoo-Tuning-L and Zoo-Tuning [51]. For our method, we activate top-2 models for each datum in all our experiments. Hub-Pathway outperforms all the compared methods. In particular, different pre-trained models also show different transfer performance on different benchmarks, which demonstrates that different pre-trained models have different transferability to different target tasks. We observe that the methods using all the pre-trained models outperform single-model fine-tuning, which demonstrates that the model hub contains much more abundant knowledge than a single pre-trained model and proves the practical use of the model hub transfer learning setting. Hub-Pathway and Zoo-Tuning both outperform Ensemble and Distill, which demonstrates that a simple ensemble of pre-trained models may not fully utilize the knowledge in the model hub and also may cause different pre-trained models to influence each other. Finally, our Hub-Pathway outperforms Zoo-Tuning and Zoo-Tuning-L even though Zoo-Tuning is specially designed to address the situation that all the pre-trained models have the same architecture. The observation demonstrates that Hub-Pathway finds more transferable models and better transfer knowledge from them.

Results on Heterogeneous Model Hub. Previous work of Knowledge Flow requires manually designing the connections of different layers across different models and applying feature transformation between them. It cannot work in such a model hub with heterogeneous architectures since correspondence between layers of different pre-trained models is unknown and their features have different shapes and structures. Zoo-Tuning has an even stricter constraint of the same architecture of the models in the hub, which limits its application in such a more general situation. Therefore, we only compare our method with single-model transfer learning, Ensemble and Distill. From Table 2, we observe that Hub-Pathway outperforms all these methods in most of the tasks. Note that, with the activation of 2 models for each input, the *training and inference cost* of Hub-Pathway is much less than the strong Ensemble method. The observation demonstrates that compared with existing methods, Hub-Pathway is an effective and efficient solution to the more general situations.

4.2 Transfer Learning in Facial Landmark Detection

We conduct experiments on the Facial Landmark Detection datasets to further demonstrate that Hub-Pathway can be applied to wide range of applications. We use the same model hub as the image classification setting in Section 4.1 and transfer to three facial landmark detection tasks: **300W** [49], **WFLW** [57], and **COFW** [5], which creates a large domain gap between pre-trained models and the target task. We generally follow the protocol in [52] and the standard training scheme in [57]. In testing, each keypoint location is predicted by transforming the highest heat value location to the

Table 2: Results on the classification benchmarks with the heterogeneous model hub.

Model	General		Fine-Grained			Specialized		Avg.
	CIFAR	COCO	Aircraft	Cars	Indoors	DMLab	EuroSAT	
MaskRCNN	79.12	81.64	84.76	87.12	73.01	74.73	98.65	82.72
MobileNetV3	83.14	83.28	80.26	86.37	75.09	70.09	98.95	82.45
EffNet-B3	87.28	86.97	83.99	89.34	78.16	72.69	99.13	85.37
Swin-T	84.37	84.12	80.82	89.10	73.39	72.22	98.69	83.24
ConvNeXt-T	86.96	87.15	84.23	90.67	81.66	73.80	98.65	86.16
Ensemble	87.72	88.04	87.11	92.68	82.79	**74.86**	99.23	87.49
Distill	87.33	88.09	85.26	91.39	81.51	74.75	99.24	86.80
Hub-Pathway	**89.01**	**89.14**	**88.12**	**92.93**	**84.40**	74.80	**99.26**	**88.24**

original image space and adjusting it with a quarter offset in the direction from the highest response to the second highest response [9]. More experimental details can be found in supplementary materials.

Results. We use the inter-ocular distance as normalization and report the normalized mean error (NME) for evaluation in Table 3, where smaller values mean better performance. We observe that fine-tuning from a single pre-trained model outperforms training from scratch, which demonstrates that knowledge transfer generally improves the target performance even though the pre-trained models are trained from different tasks. K-Flow and Zoo-Tuning perform worse than Ensemble with a non-trivial margin (≥ 0.05) in most of the tasks, which demonstrates that these two methods fail to extract and transfer generalizable knowledge and thus do not perform well under a large domain gap between the pre-trained models and the target task. Hub-Pathway instead outperforms Ensemble with 0.1 on the WFLW task and achieves a comparable performance to Ensemble on the 300W and COFW. It is worth noting that Hub-Pathway is much more efficient in computation and memory than Ensemble. The results demonstrate that Hub-Pathway could generalize across tasks even with domain gaps.

Table 3: NME results on facial landmark detection tasks. Smaller values mean better performance.

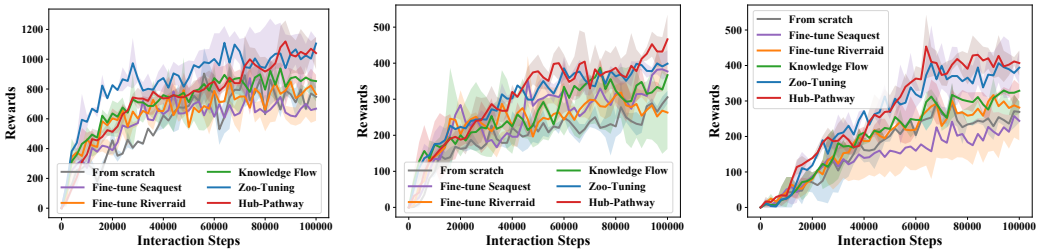
Model	300W	WFLW	COFW
From Scratch	3.66	5.33	4.20
ImageNet	3.52	4.90	3.66
MoCo	3.45	4.75	3.63
MaskRCNN	3.53	4.87	3.67
DeepLab	3.53	4.89	3.73
Keypoint	3.50	4.90	3.66
Ensemble	**3.33**	4.64	**3.46**
Distill	3.45	4.74	3.53
K-Flow	3.71	5.28	4.58
Zoo-Tuning	3.41	4.58	3.51
Hub-Pathway	**3.33**	**4.54**	3.51

4.3 Transfer Learning in Reinforcement Learning

To demonstrate the generalizability of the proposed Hub-Pathway framework to various domains and tasks, we further conduct experiments on reinforcement learning models.

Benchmarks. Current reinforcement learning algorithms have already achieved human-level performance on Atari games, but suffer from the low data efficiency with the requirement of a large amount of interaction steps. So we measure our method at 100k interaction steps (400k environment steps with action repeat of 4) on Atari, which is similar to the time to train a human learner. We use the Seaquest and Riverraid tasks as source tasks and construct the model hub consisting of optimal policies for the source tasks learned by reinforcement learning. We transfer the model hub to 3 downstream tasks: Alien, Gopher, and JamesBond.

Implementation Details. For the learning algorithm, we follow the implementation of Data-Efficient Rainbow [55], which modifies hyper-parameters of Rainbow [26] for data efficiency. The model of Data-Efficient Rainbow consists of 2 convolutional layers: 32 filters of size 5×5 with the stride of 5 and 64 filters of size 5×5 with the stride of 5, followed by a flatten layer and 2 noisy linear layers [18] with the hidden size of 256. We use Adam optimizer [29] with a learning rate of 1×10^{-4}.



(a) Alien (b) Gopher (c) JamesBond

Figure 2: Results of model hub transfer learning to three reinforcement learning tasks in Atari games.

Other hyper-parameters are kept the same as those in [55]. We repeat each experiment 5 times with different seeds and report the mean and variance of the results.

Results. We show the transfer learning performance to the three downstream tasks in Figure 2. We compare with several methods including training from scratch, fine-tuning each single model, and two multi-model transfer learning methods: Knowledge Flow [34] and Zoo-Tuning [51]. We observe that the proposed Hub-Pathway outperforms these state-of-the-art methods. Compared with Zoo-Tuning, which is a method tailored for this setup, Hub-Pathway also outperforms it on Gopher and JamesBond and achieves comparable performance on Alien. In particular, fine-tuning from a single-model converges to the same or even worse reward than training from scratch, which demonstrates that brutely fine-tuning does not improve the policy performance in reinforcement learning. Our Hub-Pathway framework fully utilizes the transferred knowledge from the pre-trained policies and thus improves the target task performance substantially.

4.4 Analysis

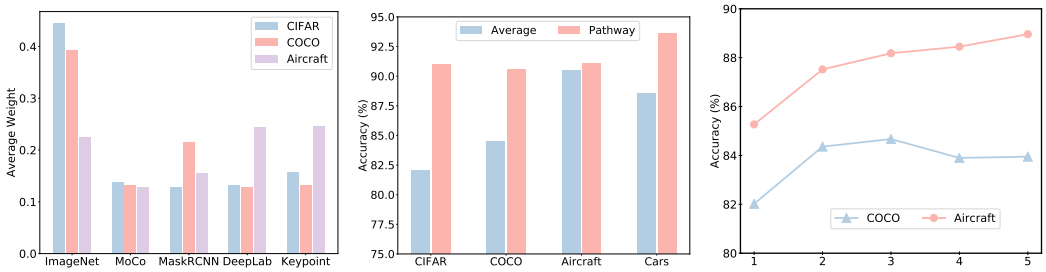
Variants of Hub-Pathway. We conduct experiments on the variants of Hub-Pathway to verify the efficacy of each component in our framework: (1) Hub-Pathway w/ random path replaces the learned data-dependent pathway with a random pathway, which aims to demonstrate the learned pathway actually finds the more transferable pre-trained models; (2) Hub-Pathway w/o explore removes the loss $\mathcal{L}_{\text{explore}}$, which may learn pathways discarding some pre-trained models forever; (3) Hub-Pathway w/o exploit removes the loss $\mathcal{L}_{\text{exploit}}$, which does not fine-tune the activated pre-trained models with the exploit loss. Hub-Pathway is the proposed framework with all the components. We conduct experiments under the classification setting and transfer to the task of COCO and Cars. The results are shown in Table 4. We observe that Hub-Pathway outperforms Hub-Pathway w/o explore, which demonstrates that it is important to explore more pathway configurations. Hub-Pathway outperforms Hub-Pathway w/o exploit, which demonstrates that fine-tuning the activated pre-trained models encourages knowledge transfer to the target task. Hub-Pathway outperforms Hub-Pathway w/ random path, which demonstrates that the proposed framework learns a non-trivial pathway to select the most transferable pre-trained models for the target data prediction.

Table 4: Ablation study on Hub-Pathway.

Method	COCO	Cars
Pathway w/ random path	80.97	90.61
Pathway w/o explore	81.34	89.75
Pathway w/o exploit	80.10	90.59
Hub-Pathway	84.36	91.72

Analysis on Pathway Weights. We visualize the average pathway weight of each pre-trained model on all the target data in different datasets in Figure 3(a). We observe that for different datasets, the distribution of average pathway weight across all the pre-trained models are different. The observation demonstrates the challenge that different pre-trained models have different transferability to the target task and the proposed Hub-Pathway could assign different pathway weights to different models.

The above results only demonstrate that Hub-Pathway assigns diverse weights to different pre-trained models, but the quality of the pathway weights is still unknown. To verify the quality, we fine-tune all the pre-trained models on the target dataset and select the samples that can be classified correctly



(a) Average Weights (b) Quality of Weights (c) Choice of k

Figure 3: (a) The average pathway weights of different pre-trained models for different datasets; (b) The quality measurement of the learned pathway weights; (c) The target prediction performance with respect to different choices of k.

by at least one of the models in the model hub from each dataset. Then an accurate pathway weight should assign the highest pathway weight to at least one of the models with the correct prediction. For each sample, we make the prediction in two ways: one is to use the pre-trained model with the highest pathway weight and the other is to use a randomly selected pre-trained model from the model hub. We report the prediction accuracy of these two ways on the selected samples in different datasets in Figure 3(b). The results show that the selected pre-trained model with the highest pathway weight performs much better than a uniformly sampled model, which indicates that the learned pathway can find which pre-trained models are more transferable.

Choice of k in f_{topk}. Our framework only activates the models within the highest top k pathway weights. We investigate the influence of the value k on the final target performance in Fig 3(c). We observe that the performance does not change rapidly with respect to k except for $k = 1$, which means that aggregating the knowledge from different pre-trained models is important. It indicates that we can use the Hub-Pathway framework for efficient transfer learning from the model hub.

Table 5: Computational cost and parameter size of Hub-Pathway, Ensemble and the ImageNet model.

Model	Acc (%)	Params (M)	FLOPs (G)	Train (iters/s)	Inference (samples/s)
ImageNet	83.41	23.71	4.11	10.87	484.92
Ensemble	84.50	118.55	20.55	2.30	98.64
Hub-Pathway	85.63	128.43	9.11	4.68	240.48

Complexity Analysis. Model hub transfer learning usually includes many pre-trained models and thus the computational and the memory cost should be controlled to an acceptable extent. We compare the time complexity and the parameter size of our framework, a single model and the ensemble of all models in Table 5. We observe that Hub-Pathway only has a little more parameters than Ensemble, but can be trained much more efficiently than it. Even compared with ImageNet, which is a single model, Hub-Pathway only has about twice of the cost. The high efficiency attributes to our design of keeping top k pathways, which only activates a few models for forwarding and back-propagation.

5 Conclusion

In this paper, we propose a Hub-Pathway framework to enable knowledge transfer from a hub of diverse pre-trained models. We design an architecture with data-dependent pathways to control which pre-trained models are used for the current data at the input level and aggregate the outputs from activated pre-trained models at the output level. The framework is optimized by a task-specific loss to ensure that the pathways introduce high transfer performance. We employ a noisy pathway generator and design an exploration loss to encourage the framework to explore and compare different pathways. To promote the exploitation of the knowledge in the activated models, we further fine-tune the models with the specific data activating them. Experimental results on model hubs with homogeneous and heterogeneous architectures demonstrate that the proposed framework achieves the state-of-the-art performance for model hub transfer learning.

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1. For all authors...
   (a) Do the main claims made in the abstract and introduction accurately reflect the paper's contributions and scope? [Yes]
   (b) Did you describe the limitations of your work? [Yes]
   (c) Did you discuss any potential negative societal impacts of your work? [N/A]
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   (a) Did you state the full set of assumptions of all theoretical results? [N/A]
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   (a) Did you include the code, data, and instructions needed to reproduce the main experimental results (either in the supplemental material or as a URL)? [Yes]
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