BNS: Building Network Structures Dynamically for Continual Learning

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Abstract

Continual learning (CL) of a sequence of tasks is often accompanied with the *catastrophic forgetting* (CF) problem. Existing research has achieved remarkable results in overcoming CF, especially for *task continual learning*. However, limited work has been done to achieve another important goal of CL, *knowledge transfer*. In this paper, we propose a technique (called BNS) to do both. The novelty of BNS is that it dynamically builds a network to learn each new task to overcome CF and to transfer knowledge across tasks at the same time. Experimental results show that when the tasks are different (with little shared knowledge), BNS can already outperform the state-of-the-art baselines. When the tasks are similar and have common knowledge, BNS outperforms the baselines substantially by a large margin due to its transfer knowledge capability.

1 Introduction

Continual learning (CL) incrementally learns a sequence of tasks in a neural network. Each task consists of a set of classes to be learned together. CL is often accompanied by the *catastrophic forgetting* (CF) problem [38]. Two main settings for CL have been extensively studied, namely, *task continual learning* (Task-CL) and *class continual learning* (Class-CL). Task-CL learns a classifier for each task. In testing, the task id is provided for the test data so that the specific task model can be applied to assign a class to the test sample. Although Class-CL also learns a sequence of tasks, in testing the task id is not provided for each sample. This paper focuses on Task-CL.

A large amount of research has been done on overcoming CF. The main existing techniques include the regularization-based methods [63, 12, 24], replay-based methods [43, 19, 56] and the structure-based methods [51, 61, 39]. Regularization-based methods are primarily designed to evaluate the importance of the parameters learned from old tasks, and then use some mechanisms to protect those parameters so that the performance of old tasks will not be affected much in the process of learning new tasks. Replay-based methods use part of the data cached in the past or train a generator to generate some similar past data to help maintain the performance of the old tasks in learning new tasks. Structure-based methods allow the neural network to adaptively adjust the network structure during the learning process or to add a learning module that does not share in the continual learning process. In the Task-CL setting, several techniques have overcome CF, e.g, HAT [51] (see Section 4.3).

However, another major objective of CL, *knowledge transfer across tasks* [41, 9], has received relatively little attention. An ideal Task-CL algorithm must do well on both (preventing CF and transferring knowledge). Being able to prevent CF alone is far from satisfactory. We will see in Section 4.3 that the knowledge transfer ability of the current Task-CL algorithms is very weak. This paper proposes a technique based on reinforcement learning (RL) called BNS (Building Network Structures dynamically for CL) to explicitly perform both CF prevention and knowledge transfer at the same time and automatically. When the tasks are different with little shared knowledge, BNS should

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prevent CF. When the tasks are similar with shared knowledge, BNS should transfer knowledge across tasks to achieve higher accuracy than without knowledge transfer.

BNS has three components: *a neural structure search agent*, *a set of actions*, and *the environment*. The environment includes *the current task data*, *a continual learner*, *a knowledge repository* and *a replay buffer*. We propose to use the similarity of the new task and the old tasks as the state representation in the environment. This enables knowledge transfer as more similar tasks tend to have more shared knowledge to be transferred across tasks. For each new task, the agent uses the state to sample a sequence of actions to construct a new continual learner for the task, which includes building a new network structure and selecting the past knowledge (*i.e.,* parameters) from the knowledge repository to initialize the parameters. The continual learner then learns the current task. After learning, a specially designed reward is computed based on the current task validation data and the saved data of old tasks in the replay buffer (to avoid CF and to transfer knowledge to the current task). The reward is used to guide the training of the agent through RL. Thus, BNS achieves both CF avoidance and knowledge transfer at the same time. The final model learned by the continual learner not only can perform the current new task well but also maintain the performance of the old tasks.

Experimental results on five datasets MNIST, CIFAR10, CIFAR-100, F-EMNIST and F-Celeba show that BNS markedly outperforms the existing state-of-the-art Task-CL baselines. For datasets (F-EMNIST and F-Celeba) with high task similarities, BNS can leverage knowledge transfer to improve the accuracy substantially compared to the baselines. Even for datasets (MNIST, CIFAR10, and CIFAR-100) with very different/dissimilar tasks, apart from overcoming CF, it can also improve the accuracy in most cases, which existing Task-CL baselines are hard to do.

2 Related work

The existing CL approaches mainly focus on overcoming CF. Limited work has been done to explicitly leverage the knowledge gained in the continual learning process. In general, these methods can be divided into three categories: regularization-based, memory-based, and structure-based methods.

Regularization-based methods deal with CF by keeping the important parameters for old tasks minimally modified in new task learning. For example, EWC [24] uses fisher information to quantify the importance of parameters to old tasks, and selectively alters the learning rates of parameters to protect the parameters. Many papers dealing with CF employ similar ideas [63, 14, 3, 44, 60, 22, 40, 12, 1, 49]. In the extreme, [62] finds orthogonal projections of weight updates that do not disturb the weights of old tasks. Many techniques also use knowledge distillation [32, 59, 7, 4, 34, 28, 54], which is another group of methods that rely on regularization, knowledge distillation loss.

Memory-based methods save a small number of training examples of each old task or generate some pseudo-examples of the old tasks to be used to jointly train with the current task data [56]) This approach is also called *experience replay*. In the data memorization paradigm, the representative work includes GEM [36], A-GEM [8], and many others [46, 43, 59, 45, 11, 18]. In the generation paradigm, there is also extensive research [52, 50, 20, 58, 19, 30, 39, 16], which typically learns a generator to generate pseudo old data. Our work also saves some training examples, but they are used in reward calculation in our setting rather than in training as in the existing methods.

Structure-based methods dynamically expand the network in learning each new task [32, 61, 60, 31, 39] or use masks over parameters to activate a subset of the network [37, 51], which BNS also does. However, these existing approaches do not deal with knowledge transfer, which BNS does. Thus, BNS is able to deal with both CF and knowledge transfer automatically at the same time.

Earlier works in lifelong learning did knowledge transfer [55, 48, 6]. However, since they mainly use the traditional learning methods such as regression [48] and naive Bayes [10, 57] to build an independent model for each task, there is no CF. CAT [21] learns a sequence of mixed tasks, but it does knowledge transfer only among detected similar tasks, but not dissimilar tasks. BNS can transfer knowledge regardless of task similarity. Progressive Network [47] tries to perform forward transfer. It builds a model for each task and then connects all the models. However, it cannot do backward transfer and its network size grows quadratically in the number of tasks. It is not scalable.

Our method is also related to neural architecture search (NAS) as we search for an optimal network structure. The goal of traditional NAS is to replace the manually designed models to find an advanced network structure for a specific task. A NAS method usually employs a reinforcement learning (RL)

method [64, 53] to select actions to construct the final neural architecture. However, this method usually requires considerable computing power. To solve the problem of high computational cost, a weight sharing strategy has been proposed [42, 33, 5, 15]. ENAS [42] is a weight sharing algorithm using RL. After training, the parameters of the previously sampled network structure are retained. When the newly sampled network contains some substructure of the previous network, the new network will reuse some parameters of the previous network substructure. Our method borrows the idea of ENAS, which has not been used in CL before. The major difference between our work and ENAS is that our policy exploits task similarities to enable our method to transfer knowledge across tasks as similar tasks tend to have shared knowledge that can be transferred to enable new tasks to learn better. Further, our actions and reward computation are specifically designed to enable BNS to achieve both knowledge transfer and CF avoidance at the same time, which ENAS does not do.

3 Method

Our Task-CL setting is as follows. We incrementally learn a sequence of N tasks. Each task t has a training dataset $D^t_{train} = \{x^t_j, y^t_j\}^{n_t}_{j=1}$, where x^t_j is an input instance and y^t_j is its class label, and n_t is the number of training examples of the t-th task. Similarly, the test dataset and validation dataset of task t are denoted by D^t_{test} and D^t_{valid} (the use of the validation data will become clear shortly). We denote the total datasets of task t by $D^t = \{D^t_{train}, D^t_{test}, D^t_{valid}\}$. Our goal is to design a Task-CL algorithm that can adaptively determine the network structure for each new task t to selectively transfer the previously learned knowledge to overcome CF and to learn the new task t better. We use reinforcement learning to help achieve our goal.

Overview of BNS: As mentioned in the introduction, the proposed reinforcement learning based task continual learning (Task-CL) algorithm BNS consists of three components: *a neural structure search agent*, *a set of actions*, and *an environment*. When learning the new task t, the environment consists of the *current task dataset* D^t, *a continual learner* $f(\cdot;\theta_t)$, *a knowledge repository* $\mathcal{K}$ and *a replay buffer* $\mathcal{T}$. At a high level, BNS works as follows. **First**, the current task dataset D^t and the cached data of each old task in the replay buffer $\mathcal{T}$ are used to compute their similarity. The set of similarities of the new task with all old tasks forms the current environment state representation S_t. **Second**, the agent takes S_t as input to sample an action sequence a_t to build a new continual learner $f(\cdot;\theta_t)$. The actions determine the network structure and parameter initialization of the continual learner. **Third**, the new continual learner is trained using the training set D^t_{train} in D^t, and then calculates the reward r^t for the model using the validation set D^t_{valid} of D^t and the saved old task data in the replay buffer $\mathcal{T}$. **Fourth**, it uses the reward to update the agent via reinforcement learning.

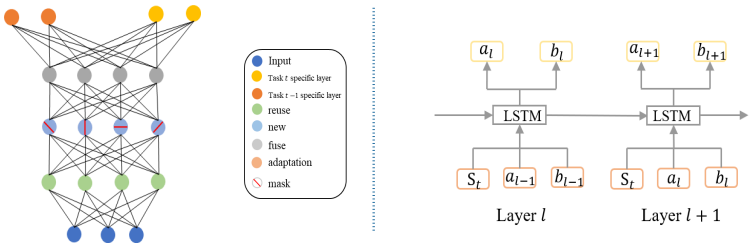
The above four steps are repeated to train the agent N **iterations** or times on task t until it converges. After the agent is well trained, we select the continual learner with the highest reward as the final model for task t. This model not only performs well on the current task but also maintains the performance of the old tasks. After learning task t, the validation dataset D^t_{valid} and the parameters of $f(\cdot;\theta_t)$ are saved in the replay buffer $\mathcal{T}$ and the knowledge repository $\mathcal{K}$ respectively. Note that at any time, we only keep the trained model of the current continual learner for the last task.

3.1 Environment, Agent, Action, State and Reward

Environment: It contains the current task dataset D^t, the current continual learner $f(\cdot;\theta_t)$, the replay buffer $\mathcal{T}$ and the knowledge repository $\mathcal{K}$. BNS uses a simple network topology, $f(\cdot;\theta_t)$, i.e., a network with L shared layers (shared among all the learned tasks) and a task specific layer (*i.e.*, the last classification layer) for each task. In learning the current task t, we calculate the similarity $s_{t,i}$ between task t and each old task i to obtain $S_t = [s_{t,0}, ..., s_{t,t-1}]$. We regard S_t as the current state representation of the environment. Specifically, we use a pre-trained feature extractor[1] $F(\cdot)$ to encode each instance of the current task's validation set D^t_{valid} and the saved data of previous tasks in the replay buffer $\mathcal{T}$. We then compute the current data representation X_t using the validation set D^t_{valid} of task t and the data representation X_k of the saved validation set $D^k_{valid} \in \mathcal{T}$ of the old task k in the replay buffer $\mathcal{T}$. After that, we compute the similarity $s_{t,k}$ of X_t and X_k.

$$X_t = \frac{1}{m_t}\sum_{j=1}^{m_t} F(x_{t,j}), \quad X_k = \frac{1}{m_k}\sum_{j=1}^{m_k} F(x_{k,j}), \quad s_{t,k} = \text{Similarity}(X_t, X_k). \tag{1}$$

[1] In this paper, we use ResNet18 pre-trained on ImageNet in Pytorch to calculate the task similarity.



(A) **(B)**

Figure 1: **(A)**: The schematic diagram of the continual learner after the agent learned task t. **(B)**: Agent of BNS, where S_t is the environment state of the learning task t ; a_l is the layer-wise action of layer l of the continual learner; b_l is the element-wise action of layer l of the continual learner.

where m_k, m_t are the number of validation examples and Similarity can be any similarity function such as cosine, KL divergence or L_p norm. When using KL divergence, we use the softmax function to convert X_t and X_k into probability distributions. This paper uses the three functions together through concatenation as the measure of similarity.

Agent: The agent aims to produce a sequence of actions to build an optimal network for the continual learner $f(\cdot;\theta_t)$ for the current task t. In each training iteration of the agent for task t, it samples an action sequence to construct each layer of the network of $f(\cdot;\theta_t)$ using the current environment state S_t. Since there is correlation between the adjacent layers in the neural network, the actions for building the neural network should have a front-to-back dependency. Thus, BNS uses a LSTM [17] based network as the agent to decide the action for each layer of the current continual learner $f(\cdot;\theta_t)$. The agent is trained with policy gradient by maximizing the expected reward computed using the current task performance and the CF avoidance on the old task data in the replay buffer $\mathcal{T}$.

Action: BNS has two types of actions: *layer-wise actions* (*i.e.,* “reuse”, “adaptation”, “new”, "fuse") and *element-wise action* (*i.e.,* "mask"). They decide how each layer of the continual learner should be constructed by leveraging the shared layers’ weights of each old task learned by its continual learner stored in $\mathcal{K}$. For the layer-wise actions: “**reuse**” makes the new task use the same parameters as a previous task (sampled over the corresponding layers of all the old tasks according to the “reuse” probability). Since it can reuse any previous task’s corresponding layer, the number of reuse increases as the task increases. “**adaptation**” expands the network by adding a small number of parameters. Specifically, we add some new additional neural units to the original layer to increase the capacity of the current continual learner. “**new**” spawns new parameters of exactly the same size as that of the current layer’s parameters, and all the new parameters are randomly initialized. "**fuse**" makes the new task use the average parameter values of all previous tasks’ corresponding layers. For each layer, the agent also needs to decide whether to use "**mask**" to protect some units so that its previous parameters (knowledge) will not be updated and forgotten (see Eq. (2) for details). Figure 1(A) shows the schematic diagram of a continual learner composed of these actions.

We use the convolution neural network as an example to introduce how each action works. For the l-th layer of the convolutional neural network, the default kernel size is 5×5. The action “reuse” (or ”fuse") is to use a previous task’s l_{th} layer’s existing weights (or the average of all previous tasks l-th layers’ existing weights) for the l_{th} layer of the current continual learner. For “adaptation”, we use a 1×1 convolution layer added to the original 5×5 convolution layer in parallel. For the “new” action, we introduce a replicated 5×5 layer that is initialized randomly. Given the output y_l^t of the units of the l-th layer, our element-wise "mask" m_l^t and the layer final output y_l^t are

$$\begin{aligned} m_l^t &= \sigma(\gamma e_l^t), \\ y_l^t &= m_l^t \odot y_l^t. \end{aligned} \tag{2}$$

where σ, γ and e_l^t are the sigmoid function, a hyper-parameter and the l_{th} layer embedding of task t, respectively. It can also be seen from Eq.(2) that the "mask" can generate task specific features. From another perspective, the five actions defined for each layer of the continual learner can be divided into two categories: changing the network structure (*i.e.,* "adaptation", "mask") and initializing the parameters (*i.e.,* "reuse", "new" and "fuse").

Reward: Once a continual learner is built in an iteration, it is trained with the current task training data D^t_{train} and then a reward is computed for the model of the continual learner for the iteration. We design the reward by considering both the current task t's performance improvement over the previous iteration computed using a Up-ratio function on its validation data and the forgetting rate of all previous tasks using a Drop-ratio function. The Up-ratio of the continual learner constructed by the agent in the current iteration i of action sampling is as follows,

$$u^t_i = \frac{acc^t_{i,t}}{acc^t_{i-1,t}} \tag{3}$$

where i, $acc^t_{i,t}$ ($acc^t_{i-1,t}$) are the sample step or iteration of the agent and the accuracy of the current (previous) iteration continual learner $f(\cdot, \theta_t)$ on the current task t's validation set D^t_{valid}. The Drop-ratio, which measures $f(\cdot, \theta_t)$'s remembering (CF avoidance) ability, is as follows

$$d^t_i = \frac{1}{t-1} \sum_{k=1}^{t-1} \frac{acc^t_{i,k}}{acc^*_k} \tag{4}$$

where acc^*_k (or $acc^t_{i,k}$) is the accuracy of the final continual learner $f(\cdot, \theta_k)$ (or the current $f(\cdot, \theta_t)$) on the previous task k's validation set $D^k_{valid} \in \mathcal{T}$. Our reward for the current iteration i is

$$r^t_i = d^t_i + \beta u^t_i \tag{5}$$

where β is a hyper-parameter. For simplicity, we omit the subscript i from now on.

3.2 Training BNS

Figure 1(B) gives our LSTM based agent network. The LSTM samples actions via softmax classifiers in an auto-regressive fashion: the action from the previous step and environment state S_t are fed into the next step. In the first step, the agent network receives an empty action embedding with state S_t as input. BNS has two sets of learnable parameters: the parameters of the agent LSTM $\pi_w(S_t, a_t)$, denoted by w, and the parameters of the current continual learner $f(\cdot, \theta_t)$, denoted by θ_t. The training procedure of BNS consists of two interleaving phases. The first phase trains θ_t, the parameters of the current learner, using a whole pass over the training dataset D^t_{train}. The second phase trains w, the parameters of the agent LSTM. These two phases are alternated during the training of BNS and trained for a fixed number of steps, 200 for each task in our experiments. More details are as follows.

Training the continual learner $f(\cdot, \theta_t)$: In this step, the agent first samples an action sequence which is used to reconstruct a continual learner $f(\cdot, \theta_t)$ for learning the current task. Then, we fix the agent's policy $\pi_w(S_t, a_t)$ and minimize the expected loss

$$\mathcal{L}(\theta_t) = \frac{1}{n_t} \sum_{j=1}^{n_t} \ell_t(f(x^t_j, \theta_t), y^t_j) \tag{6}$$

where, ℓ_t is the standard cross-entropy loss, computed on a minibatch of the training data, with a model $f(\cdot, \theta_t)$ sampled from $\pi_w(S_t, a_t)$. Our policy is to output an action for each layer of the current continual learner. When the action is "reuse" or "fuse", in order to ensure that these parameters will not change too much and thus alleviate forgetting when training the current task, we introduce L2 transfer regularization [13, 23] to constrain the training of the corresponding layer's parameters. In particular, we mark μ^* as the parameters obtained from the knowledge repository $\mathcal{K}$ when using the action "reuse" or "fuse". Finally, we perform stochastic gradient descent (SGD) on θ_t to optimize the following loss function to train each task

$$\mathcal{L}(\theta_t) = \frac{1}{n_t} \sum_{j=1}^{n_t} \ell_t(f(x^t_j, \theta_t), y^t_j) + \eta \cdot ||\theta_t - \mu^*||^2_2 \tag{7}$$

where η is a hyper-parameter.

Training the agent: When the continual learner $f(\cdot, \theta_t)$ converges, we use Eq. (5) to calculate the reward r^t (r^t_i with iteration i omitted), and then use the standard policy gradient algorithm to update the agent's parameters. In this step, we fix θ_t and only update the policy parameters w, aiming to maximize the expected reward. Formally, we update the parameters w using the following function,

$$w \leftarrow w + \alpha \cdot \bigtriangledown_w log \pi_w(S_t, a_t) \cdot r^t \tag{8}$$

Table 1: Datasets details. For each of the first three datasets, the number of classes is the total number of classes in the dataset. For each of the last two datasets, the number of classes represents the number of classes per task and each dataset has 10 tasks, not shown in the table.

Dataset	Classes	Training	Testing
MNIST	10	60,000	10,000
CIFAR10	10	50,000	10,000
CIFAR100	100	50,000	10,000
F-EMNIST	62 (per task)	7,673	858
F-Celeba	2 (per task)	960	110

where α is the learning rate of the agent.

Deriving the continual learner for the current task: We first sample several models from the trained policy $\pi_w(S_t, a_t)$. For each sampled model, we first train them on the current task and then compute its reward using the current task's validation set and replay buffer $\mathcal{T}$. We then take only the model with the highest reward as the final learned model.

4 Experiments

We evaluate the proposed BNS on five image classification datasets, three standard benchmarks MNIST [27], CIFAR10 and CIFAR-100 [25] and two additional datasets F-EMNIST and F-Celeba [21] originally used for federated learning, which have similar tasks and thus allow us to evaluate the knowledge transfer ability of BNS. F-EMNIST has 10 tasks and each task contains the written digits and characters (62 classes of one individual writer. F-Celeba also has 10 tasks and each of them contains images of a celebrity labeled by whether he/she is smiling or not. The datasets statistics are given in Table 1. Our goal is two-fold: **(1)** to verify whether searching a specific network for each task through reinforcement learning can deal with CF, and **(2)** to verify whether similarities between tasks can help build a good network for knowledge transfer to achieve improved accuracy.

4.1 Baselines

We consider the following 9 baselines for comparison with BNS, which is a task continual learning (Task-CL) system. **SGD** uses a feature extractor and a classifier as the continual learner to incrementally learn all tasks. There is no mechanism for dealing with CF or knowledge transfer. **LWF** [32] uses knowledge distillation to deal with CF. **EWC** [63] is a commonly used baseline in most continual learning papers. **IMM** [29] combines the sequentially trained independent models for different tasks to perform all the tasks in the sequence. **HAT** [51] uses masks to protect task parameters to deal with CF. **GEM** [35] is a replay method for Task-CL. **UCL** [2] is a Task-CL method that tries to improve HAT. **HNET+R** [56] is a latest replay Task-CL method (HENT+R performs better than HENT). **GPM** [49] is a recent Task-CL method that learns new tasks by taking gradient steps in orthogonal direction to the gradient subspaces deemed important for the past tasks. Note, LWF, EWC and IMM were originally designed for class continual learning (Class-CL). They were adapted for Task-CL in HAT [51]. We use these versions and run their code in the HAT repository.

4.2 Implementation Details and Evaluation Metrics

For experiments using MNIST and F-EMNIST, our BNS and all baselines except HNET+R[2] use the same three fully connected layers as the shared feature extractor, and a classifier on top with one fully connected layer for each task. In these two datasets, BNS does not use the action "adaptation" in agent to sample actions for the continual learner. For experiments with F-Celeba, CIFAR10 and CIFAR100, BNS and all baselines except HNET+R use AlexNet [26] as the basic network, which is borrowed from HAT [51]. Its shared feature extractor consists of three convolutional layers followed by two fully connected layers. The task specific classifier is one fully connected layer. In these three datasets, BNS uses all actions to search for a suitable architecture for the continual learner. For all experiments, we use a single Nvidia RTX 2080Ti GPU.

[2]Experiments with HNER+R use its own network as it is highly complex and is very difficult to change.

Table 2: Average results of ACC, BWT and Trans for BNS and baselines on MNIST, CIFAR10 and CIFAR100 with dissimilar tasks over 5 runs, where A_5, A_2 and A_{50} represent the number of tasks that are continually learned on the corresponding dataset.

Model	MNIST A_5			MNIST A_2			CIFAR10 A_5			CIFAR10 A_2			CIFAR100 A_{50}		
	ACC	BWT	Trans	ACC	BWT	Trans	ACC	BWT	Trans	ACC	BWT	Trans	ACC	BWT	Trans
SGD	85.77	−17.45	−14.06	90.47	−17.26	−8.83	73.57	−23.46	−18.83	76.03	−23.28	−10.58	61.14	− − 30.24	−29.22
LWF	99.53	−0.36	−0.28	98.82	−0.46	−0.48	76.86	−18.63	−14.95	83.22	−6.62	−3.40	52.91	−37.90	−37.44
EWC	85.99	−17.23	−13.82	91.58	−15.34	−7.71	79.44	−13.63	−12.37	84.18	−3.58	−2.43	68.78	−21.88	−21.57
IMM	87.25	−15.61	−12.56	94.46	−9.17	−4.83	72.81	−22.09	−19.00	78.39	−16.58	−8.23	67.86	−22.53	−22.48
UCL	98.74	−1.22	−1.07	97.40	−0.67	−1.90	85.29	−5.93	−6.52	83.66	−3.04	−2.95	64.28	−25.54	−26.21
GPM	98.56	−0.65	−1.25	98.27	−0.57	−1.03	88.62	−2.68	−3.19	83.70	−4.72	−2.92	78.43	−3.76	−11.92
GEM	99.28	−0.36	−0.54	96.45	−0.78	−2.84	77.64	−4.03	−14.17	62.87	−2.09	−23.74	78.05	−0.78	−12.30
HNET+R	99.61	−0.21	−0.20	98.58	−0.58	−0.72	**92.17**	−1.26	**0.31**	85.76	−0.18	−0.42	76.73	−15.17	−13.72
HAT	99.74	0.00	−0.08	99.03	0.00	−0.26	90.89	0.00	−0.92	86.25	0.00	−0.36	80.46	**0.00**	−9.89
BNS	**99.87**	**0.01**	**0.04**	**99.26**	**0.00**	**−0.04**	91.40	**0.67**	−0.42	**87.64**	**0.01**	**1.02**	**82.39**	−4.35	**−7.96**

Table 3: Average results of ACC, BWT and Trans for BNS and the baselines on F-EMNIST and F-Celeba with similar tasks over 5 runs.

Model	F-EMNIST			F-Celeba		
	ACC	BWT	Trans	ACC	BWT	Trans
SGD	13.49	−26.66	−25.87	54.93	−1.62	−6.88
LWF	8.11	−2.20	−31.25	57.18	−1.61	−4.63
EWC	43.47	−8.67	4.10	55.27	−1.22	−6.53
IMM	17.52	−25.74	−21.84	57.81	−0.80	−4.00
UCL	49.75	−1.63	10.38	55.26	−5.65	−6.55
GPM	57.84	6.40	19.07	58.08	**1.03**	−3.69
GEM	53.82	**21.75**	15.02	54.51	−3.62	−7.27
HNET+R	24.95	−43.69	−13.85	55.84	−3.23	−5.92
HAT	56.02	0.00	16.65	59.82	0.00	−1.99
BNS	**60.38**	0.53	**21.01**	**65.44**	−2.59	**3.62**

Parameter settings: For BNS, we use SGD as the optimizer with learning rate 0.1 to train the continual learner $f(\cdot, \theta_t)$ except F-EMNIST and F-Celeba (learning rate 0.01). The parameters of the agent (LSTM) is updated by the Adam optimizer using the learning rate 0.0001. The hyper-parameters η and β are set to 0.001 and 0.003 respectively. To be consistent with the baseline settings, our continual learner trains 100 epochs for all datasets except MNIST (10 epochs). We use ten percent of the training data of each task as the validation set for reward computation. After a task is learned, its validation set is saved in the replay buffer.

Evaluation metrics: We adopt the final classification accuracy (ACC) as the basic evaluation metric. For each dataset, we report the average accuracy of all tasks tested using their respective test data after all tasks have been learned, thus the final accuracy. In order to compare the ability in overcoming CF and knowledge transfer, we introduce two other indicators. The first one is backward transfer (**BWT**) [35] to measure forgetting, which indicates how much the learning of new tasks has influenced the accuracy of the models for the previous tasks. BWT < 0 means that the learning of new tasks leads to some forgetting, BWT > 0 indicates that the learning of new tasks helps the previous tasks. The second one is a new metric (**Trans**), which measures forward transfer ability, showing how helpful the knowledge learned from previous tasks is to each new task in learning process. In particular, Trans compares the accuracy of the final continual learner on each task with the accuracy of training an independent model for each task separately (no continual learning).

$$\text{ACC} = \frac{1}{N}\sum_{t=1}^{N} \text{acc}_{N,t}; \quad \text{BWT} = \frac{1}{N-1}\sum_{t=1}^{N-1} \text{acc}_{N,t} - \text{acc}_{t,t}; \quad \text{Trans} = \frac{1}{N}\sum_{t=1}^{N} \text{acc}_{N,t} - \text{acc}_t^{'}. \quad (9)$$

where N is the total number of tasks learned; $\text{acc}_{t,t}$ is the accuracy on the test set of task t right after task t is learned; $\text{acc}_t^{'}$ is the accuracy on the test set of task t of the independent model trained on task t. Accordingly $\text{acc}_{N,t}$ is the accuracy of task t after all N tasks have been learned. Note that since our BNS is built on HAT's architecture and may also sample the action "mask", the key mechanism in HAT for protecting the sub-network of each task to prevent forgetting. So comparing with HAT, we will see the knowledge transfer effect of BNS compared to a Task-CL system.

4.3 Experimental Results

To evaluate the effectiveness of forgetting avoidance and knowledge transfer of the continual learner of BNS, we use the 3 metrics in Eq. 9. Each row in the table gives the average results over 5 runs of all compared systems. The mean of results are summarized in Table 2 and Table 3. The standard

deviations are summarized in Table Appendix A.1 For MNIST, CIFAR10 and CIFAR100, we evaluate the effectiveness under three settings, 5 tasks (A_5), 2 tasks (A_2) and 50 tasks (A_{50}). For example, CIFAR10 A_5 means that the original dataset is divided into 5 tasks and each task contains two classes. For F-MNIST and F-Celeba, the 10 tasks are fixed in the original datasets. We analyze the results in the two tables from the following perspectives.

Final accuracy (ACC): BNS performs very well. Only HNET+R performs slightly better than BNS on CIFAR10 A_5. However, HNET+R performs poorly in the other experiments in Table 2, especially on CIFAR100 A_{50}. On the two similar task datasets F-EMNIST and F-Celeba (Table 3), the current state-of-the-art models, HNET+R and GPM, are very weak compared to BNS and they are even poorer than HAT. BNS outperforms all baselines by a large margin, which shows that its ability to handle multiple tasks using the final continual learner is powerful.

With and without continual learning (CL): Here we compare the results of learning each task separately (without CL) and CL and study the impact of CL. The *Trans* metric is for this purpose. Recall Trans is the difference between the final accuracy ACC of the continual learner after all tasks are learned and the accuracy of learning a model for each task separately and independently (which is ACC - Trans). The Trans column in Table 2 shows that BNS produces similar or better results than learning separately when the tasks are different. The baselines are clearly poorer. For CIFAR100 A_{50}, there are some loss of accuracy, but the baselines lose even more. The Trans column in Table 3 shows a very different story when we have similar tasks. We see that five CL baselines can improve the accuracy (positive Trans values) of learning separately without CL (ACC - Trans) for F-EMNIST, which show some knowledge transfer. But the knowledge transfer ability of BNS is significantly better than all baselines. For example, the Trans values of GPM on F-EMNIST is 19.07% and on F-Celeba is -3.69% (negative transfer), but these of BNS are 21.01% and 3.62% respectively. Note that the final accuracy ACC of all other baselines are weaker than HAT, which is markedly poorer than BNS. This again demonstrates the knowledge transfer ability of BNS.

Overcoming catastrophic forgetting (CF): BWT measures the ability of preventing CF. SGD performs extremely poorly with very negative values (negative backward transfer or CF) for BWT for all datasets. This is because SGD has no mechanism to deal with CF. Comparing the BWT values of BNS and the baselines, we can see that BNS performs very well except a few cases with GPM and HAT (no CF), but their final accuracy ACC values are substantially lower.

Backward knowledge transfer: As indicated in Section 4.2, BWT not only measures CF avoidance (*i.e.*, BWT < 0), but also measures backward knowledge transfer from new tasks to old tasks (*i.e.*, BWT > 0). For all datasets, HAT has no backward transfer (BWT $= 0.00$) and no forgetting. Our BNS achieves none negative backward transfer in 5 out of the 7 experiments. The baseline GPM achieves only in 3, out of which 2 (F-EMNIST and F-CEleba) still result in much lower final accuracy (ACC) than BNS, indicating that the forward transfer capability of GPM is poor (see below).

Forward knowledge transfer: This is defined as the difference between the accuracy of a task when it is first learned (ACC $- \frac{N-1}{N}$BWT) and the accuracy of learning the task separately (ACC $-$ Trans), *i.e.*, Trans $- \frac{N-1}{N}$BWT, which shows whether the knowledge learned from previous tasks can help learn the new task. We summarize the experimental results of this metric in Appendix A.2. We can again see that BNS is substantially better over all. As discussed above, for the two similar tasks datasets in Table 3, GPM's backward transfer is more effective, but GPM's *forward transfer* (Trans $- \frac{N-1}{N}$BWT) results are only 13.31% and -4.61% but those of BNS are 20.53% and 5.95% respectively, which explains why GPM's final accuracy ACC results are much lower than BNS. For the best baseline HAT, they are respectively 16.65% and -1.99%, which are also substantially lower than those of BNS.

In summary, we can conclude that for dissimilar tasks with little shared knowledge, BNS can deal with CF as well as state-of-the-art baselines and in many cases, it can even achieve some positive knowledge transfer. For similar tasks with shared knowledge, the knowledge transfer capability of BNS is considerably better than the baselines. This indicates that BNS is a much better model for achieving the two objectives of Task-CL, CF avoidance and knowledge transfer.

4.4 Actions Used by the Agent

In Figure 2, we plot the percentage of each action used in the action sequences generated by the agent for all tasks in our experiments. It can be seen that in the datasets with similar tasks (F-EMNIST

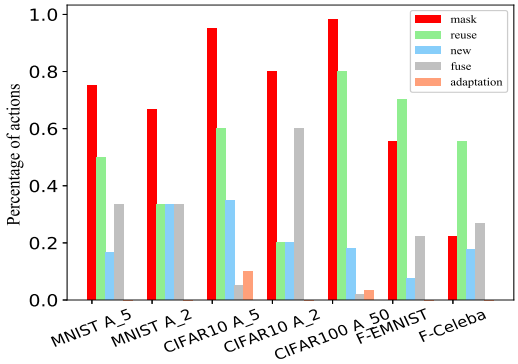


Figure 2: The percentage of each action used in the continual learner. Note that "mask" co-exists with other actions. At the same time, "adaptation" is accompanied by "reuse".

Table 4: Ablation study. BNS (zero-smi) means that no task similarity is used as an input to the agent. BNS (one-smi) (or BNS) means that only the cosine similarity (or cos, KL and L_p-norm together) is (are) used to calculate task correlation and is used as an input to the agent.

Components	MNIST	CIFAR10	CIFAR100	F-EMNIST	F-Celeba
SGD	85.77	73.57	61.14	13.49	54.93
BNS (zero-sim)	99.24	88.99	78.50	57.75	62.28
BNS (one-sim)	99.85	90.73	80.21	58.41	66.62
BNS	99.87	91.40	82.39	60.38	65.44

and F-Celeba), the percentage of action "masks" used is much lower. This is so because for similar tasks sharing and knowledge transfer are needed but masks are for protecting previous knowledge. In Appendix A.1, we will present a case study to show the action selection of the agent.

4.5 Ablation Experiments and Analysis

As discussed earlier, BNS produces a task-related network structure and gives a specific initialization method for each task according to the similarity of the task to previous tasks. In order to verify the effectiveness of including the task similarity, we compare the results of three settings on five datasets MNIST A_5, CIFAR10 A_5, CIFAR100 A_{50}, F-EMNIST and F-Celeba. The first setting is without task similarity as the agent input, which degenerates into a traditional neural architecture search algorithm, referred to as BNS (zero-sim). The second setting uses one similarity, cosine similarity, as the agent input, referred to as BNS (one-sim). The third setting uses all similarity measures as an input to the agent, which is our final BNS model. Table 4 gives the results of the ablation experiments.

By comparing the results of BNS (zero-sim) and SGD, it can be seen that after storing the parameters learned in the past, using NAS (neural architecture search) to search for each task has a significant positive effect on overcoming catastrophic forgetting (CF). That is, designing a new initialization method for each task using the parameters of previous tasks and appropriately changing the network capacity can already help overcome CF significantly. Additionally, introducing one or more similarities as the input to the agent further improves the model's ability to overcome CF (see the results of BNS (one-sim) and BNS). This demonstrates that it is highly effective to generate the network structure and initialization method based on task similarity.

5 Conclusion

This paper proposed a novel reinforcement learning based method, BNS, for task continual learning (Task-CL). The proposed model can dynamically adjust the network structure and parameter initialization method of each task by exploiting the similarities and differences of the tasks to achieve both objectives of Task-CL, overcoming catastrophic forgetting and transferring knowledge across tasks to improve accuracy. Experimental results showed that the performance of BNS is superior to the state-of-the-art baselines in both forgetting prevention and knowledge transfer. The knowledge transfer ability of the baselines are especially weak compared to BNS.

References

[1] Tameem Adel, Han Zhao, and Richard E Turner. Continual learning with adaptive weights (claw). *ICLR*, 2020.

[2] Hongjoon Ahn, Sungmin Cha, Donggyu Lee, and Taesup Moon. Uncertainty-based continual learning with adaptive regularization. In *Advances in Neural Information Processing Systems*, pages 4394–4404, 2019.

[3] Rahaf Aljundi, Francesca Babiloni, Mohamed Elhoseiny, Marcus Rohrbach, and Tinne Tuytelaars. Memory Aware Synapses: Learning what (not) to forget. *arXiv preprint arXiv:1711.09601*, 2017.

[4] Eden Belouadah and Adrian Popescu. Il2m: Class incremental learning with dual memory. In *ICCV*, October 2019.

[5] Gabriel Bender, Pieter-Jan Kindermans, Barret Zoph, Vijay Vasudevan, and Quoc Le. Understanding and simplifying one-shot architecture search. volume 2, pages 883–893, 2018.

[6] Haitham Bou Ammar, Eric Eaton, Jose Marcio Luna, and Paul Ruvolo. Autonomous Cross-Domain Knowledge Transfer in Lifelong Policy Gradient Reinforcement Learning. In *AAAI*, 2015.

[7] Francisco M Castro, Manuel J Marín-Jiménez, Nicolás Guil, Cordelia Schmid, and Karteek Alahari. End-to-end incremental learning. In *ECCV*, pages 233–248, 2018.

[8] Arslan Chaudhry, Marc'Aurelio Ranzato, Marcus Rohrbach, and Mohamed Elhoseiny. Efficient lifelong learning with a-gem. In *ICLR*, 2019.

[9] Zhiyuan Chen and Bing Liu. *Lifelong Machine Learning*. Morgan & Claypool Publishers, 2018.

[10] Zhiyuan Chen, Nianzu Ma, and Bing Liu. Lifelong learning for sentiment classification. In *ACL*, pages 750–756, 2015.

[11] Cyprien de Masson d'Autume, Sebastian Ruder, Lingpeng Kong, and Dani Yogatama. Episodic memory in lifelong language learning. In *NeurIPS*, 2019.

[12] Prithviraj Dhar, Rajat Vikram Singh, Kuan-Chuan Peng, Ziyan Wu, and Rama Chellappa. Learning without memorizing. In *CVPR*, 2019.

[13] Theodoros Evgeniou and Massimiliano Pontil. Regularized multi–task learning. In *KDD*, pages 109–117, 2004.

[14] Chrisantha Fernando, Dylan Banarse, Charles Blundell, Yori Zwols, David Ha, Andrei A Rusu, Alexander Pritzel, and Daan Wierstra. Pathnet: Evolution channels gradient descent in super neural networks. *arXiv preprint arXiv:1701.08734*, 2017.

[15] Zichao Guo, Xiangyu Zhang, Haoyuan Mu, Wen Heng, Zechun Liu, Yichen Wei, and Jian Sun. Single path one-shot neural architecture search with uniform sampling, 2020.

[16] Tyler L Hayes, Kushal Kafle, Robik Shrestha, Manoj Acharya, and Christopher Kanan. Remind your neural network to prevent catastrophic forgetting. *arXiv preprint arXiv:1910.02509*, 2019.

[17] Sepp Hochreiter and Jürgen Schmidhuber. Long short-term memory. *Neural computation*, 9(8):1735–1780, 1997.

[18] Saihui Hou, Xinyu Pan, Chen Change Loy, Zilei Wang, and Dahua Lin. Learning a unified classifier incrementally via rebalancing. In *CVPR*, pages 831–839, 2019.

[19] Wenpeng Hu, Zhou Lin, Bing Liu, Chongyang Tao, Zhengwei Tao, Jinwen Ma, Dongyan Zhao, and Rui Yan. Overcoming catastrophic forgetting for continual learning via model adaptation. In *ICLR*, 2019.

[20] Nitin Kamra, Umang Gupta, and Yan Liu. Deep Generative Dual Memory Network for Continual Learning. *arXiv preprint arXiv:1710.10368*, 2017.

[21] Zixuan Ke, Bing Liu, and Xingchang Huang. Continual learning of a mixed sequence of similar and dissimilar tasks. In *NeurIPS*, 2020.

[22] Ronald Kemker and Christopher Kanan. FearNet: Brain-Inspired Model for Incremental Learning. In *ICLR*, 2018.

[23] Wolf Kienzle and Kumar Chellapilla. Personalized handwriting recognition via biased regularization. In *ICML*, pages 457–464, 2006.

[24] James Kirkpatrick, Razvan Pascanu, Neil Rabinowitz, Joel Veness, Guillaume Desjardins, Andrei A Rusu, and Others. Overcoming catastrophic forgetting in neural networks. volume 114, pages 3521–3526. National Acad Sciences, 2017.

[25] Alex Krizhevsky and Geoffrey Hinton. Learning multiple layers of features from tiny images. *Technical Report TR-2009, University of Toronto, Toronto.*, 2009.

[26] Alex Krizhevsky, I. Sutskever, and G. Hinton. Imagenet classification with deep convolutional neural networks. In *NIPS*, 2012.

[27] Yann LeCun, Corinna Cortes, and Christopher JC Burges. The mnist database of handwritten digits. *http://yann.lecun.com/exdb/mnist/*, 1998.

[28] Kibok Lee, Kimin Lee, Jinwoo Shin, and Honglak Lee. Overcoming catastrophic forgetting with unlabeled data in the wild. In *ICCV*, 2019.

[29] Sang-Woo Lee, Jin-Hwa Kim, Jaehyun Jun, Jung-Woo Ha, and Byoung-Tak Zhang. Overcoming catastrophic forgetting by incremental moment matching. In *NIPS*, pages 4655–4665, 2017.

[30] Timothée Lesort, Hugo Caselles-Dupré, Michael Garcia-Ortiz, Andrei Stoian, and David Filliat. Generative models from the perspective of continual learning. *https://arxiv.org/abs/1812.09111*, 2018.

[31] Xilai Li, Yingbo Zhou, Tianfu Wu, Richard Socher, and Caiming Xiong. Learn to grow: A continual structure learning framework for overcoming catastrophic forgetting. In *ICML*, 2019.

[32] Zhizhong Li and Derek Hoiem. Learning without forgetting. *PAMI*, 40(12):2935–2947, 2017.

[33] Hanxiao Liu, Karen Simonyan, and Yiming Yang. Darts: Differentiable architecture search. 2018.

[34] Yaoyao Liu, An-An Liu, Yuting Su, Bernt Schiele, and Qianru Sun. Mnemonics training: Multi-class incremental learning without forgetting. *arXiv preprint arXiv:2002.10211*, 2020.

[35] David Lopez-Paz and Marc'Aurelio Ranzato. Gradient episodic memory for continual learning, 2017.

[36] David Lopez-Paz and Marc'Aurelio Ranzato. Gradient Episodic Memory for Continual Learning. In *NIPS*, pages 6470–6479, 2017.

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

[38] Michael McCloskey and Neal J Cohen. Catastrophic interference in connectionist networks: The sequential learning problem. In *Psychology of learning & motiv.*, volume 24. 1989.

[39] Oleksiy Ostapenko, Mihai Puscas, Tassilo Klein, Patrick Jahnichen, and Moin Nabi. Learning to remember: A synaptic plasticity driven framework for continual learning. In *CVPR*, pages 11321–11329, 2019.

[40] German I Parisi, Jun Tani, Cornelius Weber, and Stefan Wermter. Lifelong Learning of Spatiotemporal Representations with Dual-Memory Recurrent Self-Organization. *arXiv preprint*, 2018.

[41] German Ignacio Parisi, Ronald Kemker, Jose L. Part, Christopher Kanan, and Stefan Wermter. Continual lifelong learning with neural networks: A review. *Neural Networks*, 2019.

[42] Hieu Pham, Melody Y. Guan, Barret Zoph, Quoc V. Le, and Jeff Dean. Efficient neural architecture search via parameter sharing, 2018.

[43] Sylvestre-Alvise Rebuffi, Alexander Kolesnikov, and Christoph H Lampert. iCaRL: Incremental classifier and representation learning. In *CVPR*, pages 5533–5542, 2017.

[44] Hippolyt Ritter, Aleksandar Botev, and David Barber. Online structured laplace approximations for overcoming catastrophic forgetting. In *NIPS*, pages 3738–3748, 2018.

[45] David Rolnick, Arun Ahuja, Jonathan Schwarz, Timothy P. Lillicrap, and Greg Wayne. Experience replay for continual learning. In *NeurIPS*, 2019.

[46] Andrei A Rusu, Neil C Rabinowitz, Guillaume Desjardins, Hubert Soyer, James Kirkpatrick, Koray Kavukcuoglu, Razvan Pascanu, and Raia Hadsell. Progressive neural networks. *arXiv preprint arXiv:1606.04671*, 2016.

[47] Andrei A. Rusu, Neil C. Rabinowitz, Guillaume Desjardins, Hubert Soyer, James Kirkpatrick, Koray Kavukcuoglu, Razvan Pascanu, and Raia Hadsell. Progressive neural networks. *CoRR*, 2016.

[48] Paul Ruvolo and Eric Eaton. ELLA: An efficient lifelong learning algorithm. In *ICML*, 2013.

[49] G. Saha, I. Garg, and K. Roy. Gradient projection memory for continual learning. 2021.

[50] Ari Seff, Alex Beatson, Daniel Suo, and Han Liu. Continual learning in generative adversarial nets. *arXiv preprint arXiv:1705.08395*, 2017.

[51] Joan Serrà, Dídac Surís, Marius Miron, and Alexandros Karatzoglou. Overcoming catastrophic forgetting with hard attention to the task. In *ICML*, 2018.

[52] Hanul Shin, Jung Kwon Lee, Jaehong Kim, and Jiwon Kim. Continual learning with deep generative replay. In *NIPS*, pages 2994–3003, 2017.

[53] Mingxing Tan, Bo Chen, Ruoming Pang, Vijay Vasudevan, Mark Sandler, Andrew Howard, and Quoc V. Le. Mnasnet: Platform-aware neural architecture search for mobile, 2019.

[54] Xiaoyu Tao, Xiaopeng Hong, Xinyuan Chang, and Yihong Gong. Bi-objective continual learning: Learning'new'while consolidating'known'. In *AAAI*, pages 5989–5996, 2020.

[55] Sebastian Thrun. Lifelong learning algorithms. In *Learning to Learn*, pages 181–209. Springer, 1998.

[56] Johannes von Oswald, Christian Henning, João Sacramento, and Benjamin F Grewe. Continual learning with hypernetworks. *ICLR*, 2020.

[57] Hao Wang, Bing Liu, Shuai Wang, Nianzu Ma, and Yan Yang. Forward and backward knowledge transfer for sentiment classification. In *ACML*, 2019.

[58] Chenshen Wu, Luis Herranz, Xialei Liu, Joost van de Weijer, Bogdan Raducanu, et al. Memory replay gans: Learning to generate new categories without forgetting. In *NIPS*, pages 5962–5972, 2018.

[59] Yue Wu, Yinpeng Chen, Lijuan Wang, Yuancheng Ye, Zicheng Liu, Yandong Guo, and Yun Fu. Large scale incremental learning. In *CVPR*, 2019.

[60] Ju Xu and Zhanxing Zhu. Reinforced continual learning. In *NIPS*, pages 899–908, 2018.

[61] Jaehong Yoon, Eunho Yang, Jeongtae Lee, and Sung Ju Hwang. Lifelong Learning with Dynamically Expandable Networks. In *ICLR*, 2018.

[62] Guanxiong Zeng, Yang Chen, Bo Cui, and Shan Yu. Continuous learning of context-dependent processing in neural networks. *Nature Machine Intelligence*, 2019.

[63] Friedemann Zenke, Ben Poole, and Surya Ganguli. Continual learning through synaptic intelligence. In *ICML*, pages 3987–3995, 2017.

[64] Barret Zoph, Vijay Vasudevan, Jonathon Shlens, and Quoc V. Le. Learning transferable architectures for scalable image recognition, 2018.

Checklist

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] See Appendix A.3
   (c) Did you discuss any potential negative societal impacts of your work? [No] Because our work does not have any negative societal impacts.
   (d) Have you read the ethics review guidelines and ensured that your paper conforms to them? [Yes]
2. If you are including theoretical results...
   (a) Did you state the full set of assumptions of all theoretical results? [N/A]
   (b) Did you include complete proofs 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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