Roadblocks for Temporarily Disabling Shortcuts and Learning New Knowledge

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Abstract

Deep learning models have been found with a tendency of relying on shortcuts, i.e., decision rules that perform well on standard benchmarks but fail when transferred to more challenging testing conditions. Such reliance may hinder deep learning models from learning other task-related features and seriously affect their performance and robustness. Although recent studies have shown some characteristics of shortcuts, there are few investigations on how to help the deep learning models to solve shortcut problems. This paper proposes a framework to address this issue by setting up roadblocks on shortcuts. Specifically, it can automatically make modifications based on the original task. Roadblocks are placed during the modification process to ensure that the learned knowledge, including shortcuts, is insufficient to complete the modified task. Therefore, the model trained on the modified task will no longer over-rely on shortcuts. Extensive experiments demonstrate that the proposed framework significantly improves the training of networks on both synthetic and real-world datasets in terms of classification accuracy and feature diversity. Moreover, visualization results show that the mechanism behind the proposed our method is consistent with our expectations. In summary, our approach can effectively disable the shortcuts and thus learn more robust features.

1 Introduction

Deep learning has triggered the current rise of artificial intelligence and is the workhorse of today's machine intelligence [13]. One of the great advantages of deep learning is the ability to automatically extract the required features according to the task. And the massive amount of data that drives the model is the key to the success of deep learning. Regrettably, deep learning methods can hardly take full advantage of the training data, and an important reason is over-reliance on simple features. Deep learning methods have recently been found to have a tendency to learn simple features only [4]. The learned simple features may be sufficient for the accessible data (training data), and the model will have difficulty learning other complex but effective features.

Insufficient learning of effective features may hurt accuracy and generalization performance. Worse yet, when the sample distribution changes and the learned simple features are no longer valid, deep learning models may collapse since they did not learn other features. Therefore, suppressing the reliance on simple features is indispensable for designing models.

Shortcuts in deep learning are described as the decision rules that perform well on standard benchmarks but fail to be transferred to more challenging testing scenarios according to [4]. We make a more specific explanation for easier evaluation. For a task, there are a number of features that should be considered. Since the training set is limited, perhaps only a subset of features is sufficient to make a decision. Decision rules that rely on an easy-to-learn subset of features are called shortcuts. The

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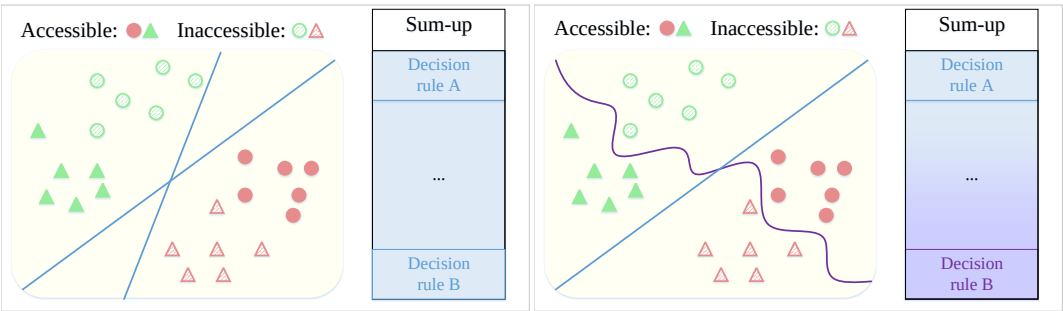
36th Conference on Neural Information Processing Systems (NeurIPS 2022).

concept of *shortcut* has two key points, (1) only use a subset of effective features but perform well on training set; (2) easy to learn and affect the learning of other complex but also effective features.

Figure 1 provides an intuitive illustration of what shortcuts are and why shortcuts affect the generalization of deep learning models. Each sample in Figure 1 has two features (color, shape). The training set only has red circles and green triangles, while the testing set contains the other two combinations. For the training set, decision rules are valid whether they are based on color or shape, but both of them may fail on the testing set because the training set does not articulate the intent. A task may require the selection of a particular decision rule or a sum-up. But either way, the diversity of decision rules is a foundation.



(a) Functionally similar decision rules.

(b) Functionally diverse decision rules.

Figure 1: Shortcuts and exhaustive decision rules.

Some studies expand the difference between decision rules at the feature level [10]. However, differentiated decision rules may still be functionally similar, see Figure 1a. To obtain the functionally diverse decision rules shown in Figure 1b, we propose to temporarily disable shortcuts.

It is important to note that shortcuts are disabled temporarily, not forever. We believe that simplicity does not mean bad, but more decision rules might help. Our approach is simply providing more options. The integration of decision rules should depend on the task scenarios, and we also provide some suggestions.

To address the issue of deep learning methods not learning anything other than shortcuts, we propose Roadblocks to temporarily disable shortcuts and force the model to learn new knowledge. The ability of Roadblocks that disables the shortcuts is achieved by reconstructing datasets under the guidance of trained models. A reconstructed sample should retain most of the attributes of the original sample while disabling the learned attributes. Thus, the model trained with reconstructed samples will naturally reduce the reliance on shortcuts and learn new knowledge.

Enlarging the distance directly [10] at the feature level often only learns the decision rules shown in Figure 1a, but it is difficult to learn functional differences. We believe the reason is the redundancy and weak interpretability of deep learning models. There is currently no metric that can measure the functional differences of the models well. Most previous researches on shortcuts focus on what features are more likely to be shortcuts, and the corresponding solutions mostly rely on the prior knowledge of shortcuts [5, 8, 18]. Priori-based methods require accurate prior knowledge and targeted design, which is difficult to accomplish in most scenarios. Unlike them, Roadblocks do not use any prior knowledge about shortcuts and can deal with different forms of shortcuts.

In summary, the contributions of this work are mainly three-fold:

- We propose a new framework to help models learn more diverse knowledge. Compared with methods based on distance at the feature level, our method can learn brand new knowledge and obtain functionally diverse decision rules.
- We propose a new strategy for disabling shortcuts, which requires no priors and is suitable for a wider range of application scenarios.
- Our method can effectively improve the generalization ability of the model and can reach state-of-the-arts in the debiasing task.

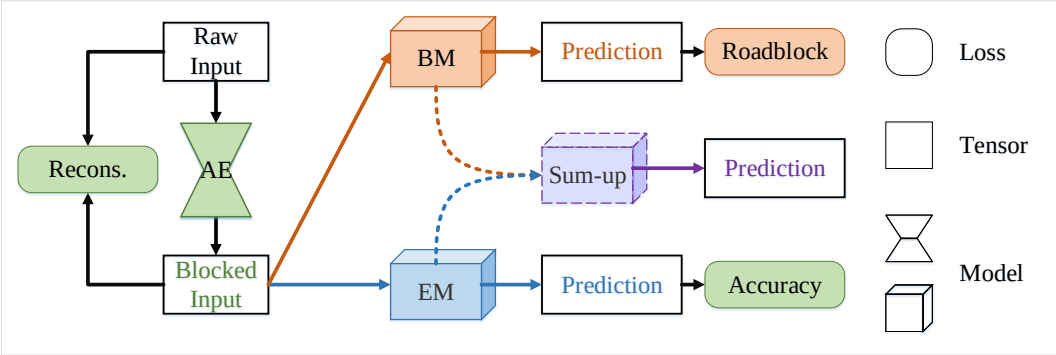


Figure 2: Framework of Roadblocks. The basic framework of Roadblocks consists of three sub-models, autoencoder (AE) in green, blocked model (BM) in red and explorer model (EM) in blue. The purple model represents the sum-up of BM and EM.

2 Method

This section will introduce our strategy to address the shortcut problem, which is temporarily disabling shortcuts and learning more diverse knowledge. First, we specify some definitions and the evaluation system. Then, we introduce our Roadblocks framework. Finally, the working process of the framework will be introduced.

2.1 Shortcut Suppression Task

Shortcuts are described as decision rules that perform well on independently-identical-distribution (i.i.d.) testing sets but fail to generalize to out-of-distribution (o.o.d.) testing sets [4]. We refer to this idea and describe the shortcut more precisely, **shortcuts are decision rules that rely on an easy-to-learn subset of features.**

For classification tasks, suppose a distribution $\mathcal{D}$ whose feature space can be represented by $\mathcal{F}$. Supposing that a training set D_{train} is sampled from $\mathcal{D}$, and there exist a decision rule that based on $\mathcal{F}_{train}$ that can perform well on D_{train}. $\mathcal{F}_{train}$ is a subspace of $\mathcal{F}$. Such a decision rule has the potential risk of failing in other datasets sampled from $\mathcal{D}$ because it ignores other features in $\mathcal{F}$.

For ease of measurement, we refer to the setting of the debiasing task. The feature space contains two main features, $\mathcal{F} = [F_T, F_B]$. In the training data, the target feature F_T corresponds to the ground truth perfectly; while biased feature F_B corresponds to the ground truth with a large probability. Nonetheless, there is still a possibility that $\mathcal{F}_{train}$ is closer to F_B because F_B is simpler, which means that the model may not have learned F_T as we expected. To verify the learning of F_T in the testing data, F_T still corresponds to the ground truth perfectly, and F_B is no longer helpful.

2.2 Framework of Roadblocks

Assuming that existing models use shortcuts, a strategy to find more reasonable decision rules is to use the idea of Roadblocks that forces the new model not to use the same decision rule as any previous model.

Figure 2 illustrates the framework of our approach. The overall model is composed of three parts. Blocked models are trained models that perform well on the i.i.d. test dataset. The autoencoder is used to modify the original input, thereby limiting the performance of blocked models. Once the blocked models perform poorly on the modified input, the explorer models trained with the modified input will find new ways to achieve competitive performance. None of the three sub-models need a specific structure, as long as they have sufficient representation capabilities.

Let AE, BM, EM denote autoencoder, blocked model, explorer model, respectively. BM is a pre-trained model with good performance, which is fixed during the training process. AE receives the raw input I_{raw} and modifies it into blocked input I_{rec}. The mean square error (MSE) is used to measure

the similarity between them,

$$Loss_{rec} = MSE(I_{raw}, I_{rec}). \tag{1}$$

The reconstructed input needs to meet two requirements, (1) it is difficult to distinguish with the existing decision rules, and (2) it can be correctly distinguished.

I_{rec} will first be used as the input of BM. The MSE of the prediction $BM(I_{rec})$ and the pseudo label $label_{ep}$ will be used as the roadblock loss,

$$Loss_{rb} = MSE(BM(I_{rec}), label_{ep}). \tag{2}$$

The pseudo label $label_{ep}$ is set to consider all possible categories with equal probability, which is $label_{ep} = [\frac{1}{n}, \frac{1}{n}, ..., \frac{1}{n}])$, where n is the number of categories. In this way, the purpose of AE is to generate I_{rec} to confuse BM.

I_{rec} will also be used as the input of EM. In order for the EM to achieve better classification performance, the accuracy loss between the prediction $EM(I_{rec})$ and the ground-truth label is calculated for training,

$$Loss_{ac} = MSE(EM(I_{rec}), label_{gt}). \tag{3}$$

2.3 Working Process

Core training process BM is a pre-trained model, and it does not participate in the training process of the proposed framework. Both AE and EM need to be trained. We alternately train them for a more stable training process. A typical training cycle consists of two parts, (1) AE is trained with roadblock loss and reconstruction loss; (2) EM is trained under the guidance of accuracy loss,

$$\theta_{AE} = \arg\min_{\theta_{AE}}(\lambda_{rb} Loss_{rb} + \lambda_{rec} Loss_{rec}), \tag{4}$$

$$\theta_{EM} = \arg\min_{\theta_{EM}}(\lambda_{ac} Loss_{ac}). \tag{5}$$

Here, θ_{AE} and θ_{EM} denote the parameters of AE and EM respectively, and $\boldsymbol{\lambda} = [\lambda_{rb}, \lambda_{rec}, \lambda_{ac}]$ are the corresponding loss weights.

Multi-model BM can be any model that performs well on training set. In addition to vanilla models, a EM generated by Roadblocks method can also be used as BM to train a new EM. BM can also be a set of models $BM = [BM_1, BM_2, ..., BM_n]$. Correspondingly, the roadblock loss needs to be adjusted to

$$Loss_{rb} = \frac{1}{n} \sum_i MSE(BM_i(I_{rec}), label_{ep}). \tag{6}$$

We suggest adding the well-trained EM to the set of BM and then training the new EM. When the new EM fails to perform well on the training set, it means that it is difficult to learn more effective features, at which point the loop terminates. The experiments suggest that in most cases, two models are sufficient. Therefore, to reduce the computational cost, we usually use two models.

Sum-up The proposed framework contains multiple sub-models that learn different effective features respectively. We do not recommend discarding any features directly, as the ease of learning and the effectiveness of features are not necessarily related. We recommend designing according to specific scenarios. Without priors on the test scene, we recommend using the feature fusion strategy because it is more likely to have good generalization. Another idea is to vote, and o.o.d. samples can be detected if there is a significant difference in the votes of the submodels. For some tasks with priors, the appropriate model can be directly selected. For example, for debiasing tasks, a reasonable idea is to choose the model that performs better on the training set because the biased features are less matched with the ground truth.

3 Experiments

To verify whether functionally different decision rules are learned, we choose datasets with multiple attribute labels for experiments. The experimental setup refers to the design of the debiasing task [15]. Each individual attribute in the training set corresponds well to the ground truth, while only one attribute matches the ground truth one-to-one in the testing set. Taking Figure 1 as an example,

Table 1: Image classification accuracy evaluated on CMNIST datasets. The ratio represents the proportion of minority samples, and the smaller the ratio, the more difficult it is to debias. The best results are highlighted in bold, while the second-best results are denoted with underlines. A check mark (✓) indicates that no priors about the feature are used, while a cross mark (×) is the opposite. The results of previous methods are from [15].

Dataset	Ratio (%)	Vanilla [7]	EnD [29]	ReBias [1]	LFF [23]	LDD [15]	Ours
		✓	×	×	✓	✓	✓
CMNIST	0.5	$35.19_{\pm 3.49}$	$34.28_{\pm 1.20}$	$\mathbf{70.47}_{\pm 1.84}$	$52.50_{\pm 2.43}$	$65.22_{\pm 4.41}$	$\underline{66.64}_{\pm 2.15}$
	1.0	$52.09_{\pm 2.88}$	$49.50_{\pm 2.51}$	$\mathbf{87.40}_{\pm 0.78}$	$61.89_{\pm 4.97}$	$81.73_{\pm 2.34}$	$\underline{82.04}_{\pm 1.61}$
	2.0	$65.86_{\pm 3.59}$	$68.45_{\pm 2.16}$	$\mathbf{92.91}_{\pm 0.15}$	$71.03_{\pm 2.44}$	$84.79_{\pm 0.95}$	$\underline{84.93}_{\pm 1.34}$
	5.0	$82.17_{\pm 0.74}$	$81.15_{\pm 1.43}$	$\mathbf{96.96}_{\pm 0.04}$	$80.57_{\pm 3.84}$	$\underline{89.66}_{\pm 1.09}$	$88.65_{\pm 0.93}$

Table 2: Debiasing performance on CelebA. 'Unbiased' means that all combinations appear at the same frequency, and 'Bias-conflicting' means that only the minority of combinations appear. The † results are from [15] and ‡ results are from [29].

Dataset	Testing set	Vanilla [7]	EnD [29]	ReBias [1]	LFF [23]	LDD [15]	Ours
		✓	×	×	✓	✓	✓
CelebA	Unbiased	$62.00^{\ddagger}_{\pm 0.02}$	$\underline{75.93}^{\ddagger}_{\pm 1.31}$	$69.33_{\pm 1.72}$	$66.20^{\ddagger}_{\pm 1.21}$	$64.82_{\pm 1.36}$	$\mathbf{79.73}_{\pm 1.15}$
	Bias-conflicting	$33.75^{\ddagger}_{\pm 0.28}$	$\underline{53.70}^{\ddagger}_{\pm 5.24}$	$44.20_{\pm 7.09}$	$45.48^{\ddagger}_{\pm 4.33}$	$47.63_{\pm 4.58}$	$\mathbf{64.06}_{\pm 0.78}$
BAR	Bias-conflicting	$49.91^{\dagger}_{\pm 0.53}$	$52.16^{\dagger}_{\pm 0.18}$	$53.25^{\dagger}_{\pm 0.63}$	$58.81^{\dagger}_{\pm 2.64}$	$\underline{63.50}^{\dagger}_{\pm 1.47}$	$\mathbf{69.51}_{\pm 2.43}$

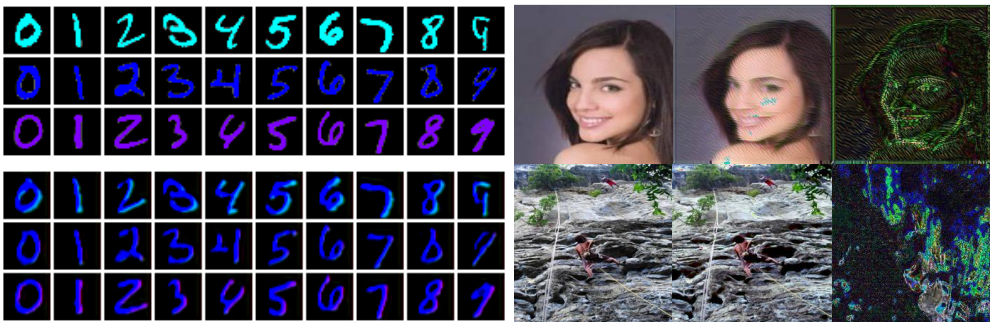
the training set is mainly red circles and green triangles, and the four combinations have the same proportion in the testing set. We use the synthetic dataset CMNIST [15], which adds a second attribute by coloring MNIST [14]. We also use real-world datasets CelebA [20], and BAR [23] that were validated to have shortcuts to test the practicality of our method. Details of datasets and implementation are described in the appendix. Extensive experiments have been conducted to demonstrate the following effects of Roadblocks: 1) greatly enhance the ability to explore new knowledge, 2) significantly improve the generalization of deep learning models.

3.1 Exploration of Knowledge

To verify whether Roadblocks can reduce models' reliance on shortcuts, we compared the performance of the conventionally trained CNNs (Vanilla) and some representative debiasing methods and our Roadblocks method. We first test on a controlled datasets CMNIST to facilitate analysis. The experimental results are shown in Table 1.

For CMNIST, each sample has two key features, color, and digit. Although the colors are slightly less matched with ground truth, deep learning models tend to learn colors. Our method can help deep learning models learn more decision rules that utilize digit features.

Models also often rely on shortcuts to complete their tasks in real-world scenarios. We conducted experiments on the face attribute dataset CelebA [20] and the action recognition dataset BAR [23]. For real-world datasets, we keep its native ratio to maintain the authenticity during the training process. And then we test whether the model learned more knowledge through testing sets of different distributions. For CelebA, following the experimental setup of LFF [23], we trained models to classify 'HeavyMakeup'. Then we select the same number of samples from all possible combinations of [Gender, HeavyMakeup] to form the unbiased testing set and minority combinations to form the bias-conflicting testing set. BAR contains six actions, and the backgrounds of the training and testing sets are significantly different. The testing set has only bias-conflict samples. The results are shown in Table 2. It can be seen that our method has obvious performance improvement compared to the state-of-the-art methods. In particular, for the bias-conflict dataset which is more difficult, our method achieves more than 10% improvement.



(a) CMNIST (b) CelebA and BAR

Figure 3: Visualization of reconstructed images. For CMNIST (a), the top 3 rows shows some of the original samples, and bottom 3 rows show the modified samples generated during the training process. For CelebA and BAR (b), left, middle and right are original images, reconstructed images, and their differences. Results were picked at random, more results can be seen in the appendix.

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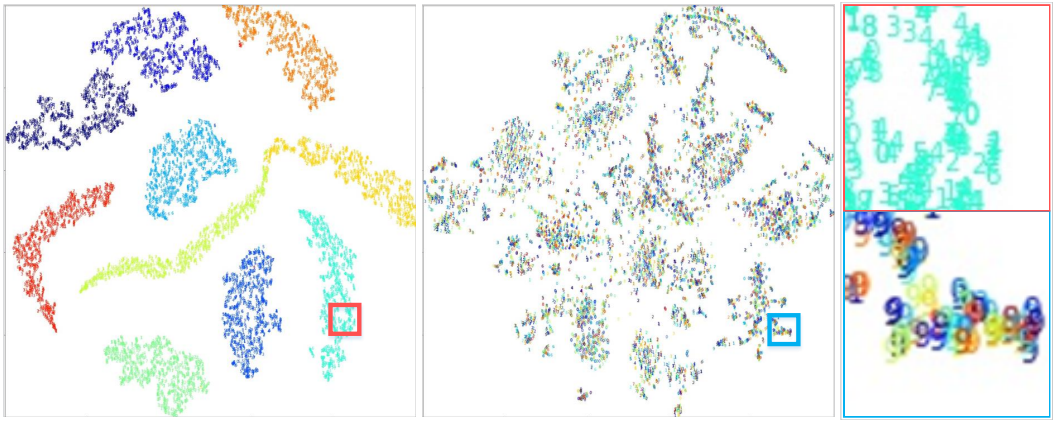
3.2 Disabling Shortcuts

The above experiments verified the effectiveness of our Roadblocks framework in learning functionally diverse decision rules. Next, it is necessary to confirm whether the effective mechanism of the proposed method is consistent with the original intention of the design. Specifically, it is necessary to verify that some information in the reconstructed image is indeed corrupted so that the existing decision rules cannot make correct predictions. Thus, we visualized reconstructed images, and the result is shown in Figure 3. It can be observed that for CMNIST, our method can implement the disabling of the shortcut (color) by repainting digits. For different digits, the strategy of repainting is consistent, which shows that only the color attribute is disabled in the painting stage, while the number attribute is retained. Therefore, it is still feasible to use these samples to learn numbers, which is also well illustrated in Table 1.

For real-world datasets, similar modification methods are challenging to achieve, and our approach mainly implements the destruction by adding noise. For CelebA, AE tries to blur the gender attribute by some blurring (mainly focused on the face contour). For BAR, the blurring of AE mainly revolves around the environment. For the convenience of observation, we show the difference map of the original image and the reconstructed image, which is five times the absolute value of the difference of each pixel value between the two.

We also used t-SNE [30] to visualize the features extracted by the vanilla model and our approach, and the result is shown in Figure 4. Each colored number represents a sample. It is evident that the vanilla model does an excellent job of partitioning the dataset according to color. However, a closer look reveals that samples of the same color, regardless of the digit, are in the same cluster. In contrast, the model trained by our approach can distinguish digits and have certain invariance to color. Distinguishing digits is more complex than color, so getting sharp boundaries is more complicated.

To visually demonstrate the model's ability to explore new knowledge, we use Grad-CAM [26] to visualize the focus of models on the BAR dataset, and saliency maps are shown in Figure 5. In this experiment, we use ResNet-18 as the backbone, and the last fully connected layer is modified to a linear layer (512, 10) to match the number of categories. And the last convolutional layer is used as the target layer of Grad-CAM. For CMNIST, it is difficult to tell the difference from the saliency map because the colors and shapes correspond to the same regions. This is also the reason why we do not disable shortcuts using saliency map based methods. For CelebA and BAR, it can be seen that the attention regions of our approach are significantly different from that of the vanilla model. For correctly classified samples, our approach can find more effective information. Grad-CAM also provides some explanation for samples that vanilla misclassifies, but our method classifies correctly. For example, for samples of mountain climbing, the EM of our approach focuses on the climber, and the vanilla model focuses on the mountain. Both of these features are important, and our approach has better generalization ability because it utilizes more effective features. The samples of CMNIST and CelebA were randomly selected, and we selected more representative samples for BAR. There



(a) Vanilla (b) Ours (EM) (c) Zoom-in

Figure 4: The t-SNE results on CMNIST. It reflects the distance between the features extracted by the model to some extent. Each colored number represents a sample. (a) corresponds to the vanilla model, (b) corresponds to our model, and (c) provides a zoom-in view of the boxed areas.

Figure 5: Saliency maps. The top and bottom rows show the Grad-CAM results of vanilla model and EM of our approach respectively. Warm colors indicate a high level of attention. Green borders indicate correct classification and red borders indicate incorrect classification.

are more examples of samples in the appendix to facilitate more analysis and discussion, while also ensuring generality.

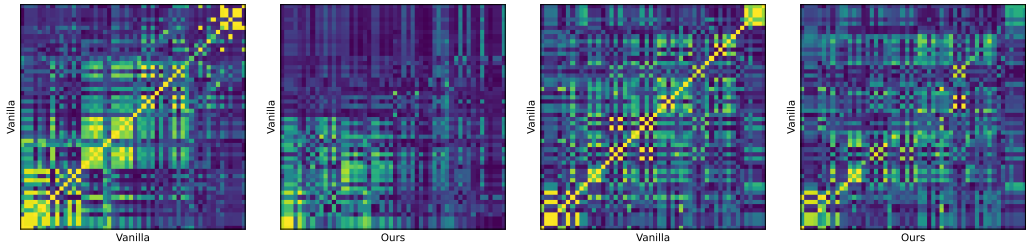
Grad-CAM is an excellent interpretability method, but it can only show differences in models at a spatial scale. Therefore, for datasets such as CMNIST, where different features overlap a lot in spatial scales, saliency maps cannot well reflect the differences between models.

The reconstruction results and saliency maps visually demonstrate that our approach does learn more effective features following our design intent. These methods still have some limitations. To verify the ability of our method to improve model diversity as fully as possible, we further quantify the model diversity.

3.3 Model Diversity

Our core purpose is to learn more knowledge (i.e., effective features). Therefore, it is necessary to choose appropriate metrics to measure the similarity between models. We applied SVCCA [24] to measure the similarity of the models. SVCCA is a tool for comparing two representations in a way that is invariant to affine transform. It receives the feature maps of middle layers and calculates the similarity between each pair of feature maps. Figure 6 shows some SVCCA results between the models. Figure 6a and Figure 6b are calculated on CMNIST (5pct), Figure 6c and Figure 6d

are calculated on BAR. CelebA is too large to be calculated, so we did not perform corresponding experiments.



(a) CMNIST, V-V (b) CMNIST, V-O (c) BAR, V-V (d) BAR, V-O

Figure 6: The SVCCA similarities. Bright tones indicate higher similarity. 'V' and 'O' denote vanilla and ours respectively. For example, (a) represents the similarities between layers of two vanilla models on the CMNIST dataset.

For the CMNIST dataset, the diagonal of the SVCCA matrix of the vanilla model is bright, indicating a high similarity between the same layers. While the similarity between our model and the vanilla model is slight, there are only a few brighter regions between several lower layers. The comparison of the two shows that the model trained by our method is significantly different from the vanilla model at the feature level. Therefore, our method helps to improve the diversity of models. It can also be observed that some adjacent layers also have high similarities. The BAR dataset is more complex than the CMNIST dataset. Therefore, the similarity between adjacent layers in the vanilla model is lower. Some layers of our model and the corresponding layers vanilla model are similar, which we think may correspond to some complex semantic features.

4 Related Work and Discussion

4.1 Related Work

Shortcut learning. Geirhos et al. [4] provided a comprehensive summary of shortcuts and defined them as decision rules that perform poorly on the o.o.d. testing set. A considerable amount of research has been devoted to analysing the formation of shortcuts, providing many valuable conclusions [27, 22]. Deep learning models is found to have the tendency to use textures rather than shapes to make predictions [5], which has inspired a new round of thinking among researchers on the mechanism of deep learning. Katherine and Andrew [9] explored the conditions under which features are more likely to be shortcuts, which is very helpful to deepen our understanding of shortcuts. In addition, various data augmentation methods are used to drive models to learn features beyond known shortcuts. Some researches [5, 8, 18] assumed that the texture feature is the only shortcut, and the designed data augmentation techniques effectively reduce the model's reliance on texture. There are also ways to exclude shortcuts by introducing a prior on the difficulty of the target task [3]. However, research on suppressing shortcut without relying on prior knowledge is still basically an unknown area to explore.

Fairness and debiasing. The debiasing task can be understood as solving the problem that the model has learned a certain bias attribute in the data set, but failed to learn the relatively difficult target attribute. Some researchers have explored the preferences of deep learning methods themselves and dealt with them accordingly, such as the tendency to use textures rather than shapes [5] and the tendency to learn low-frequency features in images [2]. Besides, several existing approaches aimed at mitigating the bias also assume certain bias types [12, 31, 17, 29, 25]. Instead of defining specific types of bias, some approaches [23, 15, 19, 16] rely on the straightforward assumption that simple features are biased features. A typical example is *Learn from Failure*. The main idea is twofold; (a) intentionally train the first network to be biased by repeatedly amplifying its "prejudice", and (b) debias the training of the second network by focusing on samples that go against the prejudice of the biased network in (a). Unlike them, our approach does not use biased priors, but solves the debiasing problem by learning more knowledge. Compared with other debiasing methods, it has a wider range of application scenarios.

Adversarial training The proposed roadblocks share some similarities with adversarial training. Adversarial examples obtained by adding small designed perturbations can make the model go wrong [28]. Adversarial training [11] can effectively improve the adversarial robustness of the model. Our approach and adversarial training clearly differ in purpose, which also introduces design differences. Adversarial examples only require the model to predict incorrectly, whereas our method requires the model to be completely confused. Therefore, by design, the false labels we use are all categories, including the true category, with equal probability. We also conduct experiments using adversarial training, and the results are shown in the appendix.

4.2 Discussion

Functionally identical features may have different representations. Increasing the diversity of features, in other words, learning more knowledge, is a natural idea, but its implementation is not as simple. An intuitive way to learn different features is to expand the distance between the two models at the feature level. We refer to the framework of negative correlation learning and expand the distance between models at the feature level as much as possible on the premise of ensuring consistent prediction results. Experimental results (see the appendix) show that it is difficult to learn decision rules other than shortcuts through such a learning paradigm. We believe that the reason is that the excellent representational ability of the deep learning model allows it to represent functionally identical features in different ways. Therefore, a simpler and more effective approach is our Roadblocks, which forces the model to learn new features by temporarily disabling the already learned features by modifying the input. Rather than some distance between features, we remind that functional differences between features may be more important.

From comprehensiveness to exactness. Our method is designed for general image classification tasks. The priors about the features and the distribution difference between training and testing sets are unknown. On the one hand, comprehensiveness (i.e., maximizing the use of effective features in the accessible data) is a reasonable goal since such models are the most robust against complex test scenarios. For comprehensiveness, our approach allows the model to temporarily disable shortcuts and learn new effective features as much as possible. Its effectiveness and benefits have been described above. On the other hand, exactness (i.e., only using some specific features) is a more realistic goal for many tasks. Our approach also provides a new implementation for feature screening. By first training a model to learn features that are not required for the task and then restricting the use of such features, it will be easier for the model to follow the designer's intent. Achieving the requirement for exactness at the lowest cost will be a key point for the designer.

5 Conclusion

In this work, we develop a novel framework to prevent deep learning models from merely using shortcuts (simple decision rules) while ignoring other effective features. Experimental results on multi-attribute datasets in complex testing scenarios demonstrate that our Roadblocks have a strong capacity of reducing reliance on shortcuts and learning new knowledge, which is very difficult for conventional deep learning methods and debiasing models. Extensive experiments also show that Roadblocks achieve excellent performance in terms of extracting new knowledge and improving model diversity. We expect our Roadblocks may help shed light on the nature of shortcut learning in neural networks, and provide a feasible paradigm for training models without depending on shortcuts.

6 Acknowledgments

This work was supported by the Anhui Provincial Natural Science Foundation under Grant 2108085UD12, and in part by the National Natural Science Foundation of China under Grants U19B2044 and 61836011. We acknowledge the support of GPU cluster built by MCC Lab of Information Science and Technology Institution, USTC.

References

[1] Hyojin Bahng, Sanghyuk Chun, Sangdoo Yun, Jaegul Choo, and Seong Joon Oh. Learning de-biased representations with biased representations. In Hal Daumé III and Aarti Singh, editors, *Proceedings of the 37th International Conference on Machine Learning*, volume 119 of *Proceedings of Machine Learning Research*, pages 528–539. PMLR, 13–18 Jul 2020.

[2] Guangyao Chen, Peixi Peng, Li Ma, Jia Li, Lin Du, and Yonghong Tian. Amplitude-phase recombination: Rethinking robustness of convolutional neural networks in frequency domain. In *IEEE/CVF International Conference on Computer Vision*, pages 448–457, 2021.

[3] Nikolay Dagaev, Brett D Roads, Xiaoliang Luo, Daniel N Barry, Kaustubh R Patil, and Bradley C Love. A too-good-to-be-true prior to reduce shortcut reliance. *arXiv preprint arXiv:2102.06406*, 2021.

[4] Robert Geirhos, Jörn-Henrik Jacobsen, Claudio Michaelis, Richard Zemel, Wieland Brendel, Matthias Bethge, and Felix A. Wichmann. Shortcut learning in deep neural networks. *Nature Machine Intelligence*, 2(11):665–673, 2020.

[5] Robert Geirhos, Patricia Rubisch, Claudio Michaelis, Matthias Bethge, Felix A. Wichmann, and Wieland Brendel. Imagenet-trained CNNs are biased towards texture; increasing shape bias improves accuracy and robustness. In *International Conference on Learning Representations*, 2019.

[6] Ian J Goodfellow, Jonathon Shlens, and Christian Szegedy. Explaining and harnessing adversarial examples. *arXiv preprint arXiv:1412.6572*, 2014.

[7] Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. In *IEEE Conference on Computer Vision and Pattern Recognition*, pages 770–778, 2016.

[8] Katherine Hermann, Ting Chen, and Simon Kornblith. The origins and prevalence of texture bias in convolutional neural networks. In H. Larochelle, M. Ranzato, R. Hadsell, M. F. Balcan, and H. Lin, editors, *Advances in Neural Information Processing Systems*, volume 33, pages 19000–19015. Curran Associates, Inc., 2020.

[9] Katherine Hermann and Andrew Lampinen. What shapes feature representations? exploring datasets, architectures, and training. In H. Larochelle, M. Ranzato, R. Hadsell, M. F. Balcan, and H. Lin, editors, *Advances in Neural Information Processing Systems*, volume 33, pages 9995–10006. Curran Associates, Inc., 2020.

[10] Zhen Huang, Xu Shen, Jun Xing, Tongliang Liu, Xinmei Tian, Houqiang Li, Bing Deng, Jianqiang Huang, and Xian-Sheng Hua. Revisiting knowledge distillation: An inheritance and exploration framework. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 3579–3588, June 2021.

[11] Andrew Ilyas, Shibani Santurkar, Dimitris Tsipras, Logan Engstrom, Brandon Tran, and Aleksander Madry. Adversarial examples are not bugs, they are features. *Advances in neural information processing systems*, 32, 2019.

[12] Byungju Kim, Hyunwoo Kim, Kyungsu Kim, Sungjin Kim, and Junmo Kim. Learning not to learn: Training deep neural networks with biased data. In *IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 9004–9012, 2019.

[13] Yann LeCun, Yoshua Bengio, and Geoffrey Hinton. Deep learning. *Nature*, 521(7553):436–444, May 2015.

[14] Y. Lecun, L. Bottou, Y. Bengio, and P. Haffner. Gradient-based learning applied to document recognition. *Proceedings of the IEEE*, 86(11):2278–2324, 1998.

[15] Jungsoo Lee, Eungyeup Kim, Juyoung Lee, Jihyeon Lee, and Jaegul Choo. Learning debiased representation via disentangled feature augmentation. In A. Beygelzimer, Y. Dauphin, P. Liang, and J. Wortman Vaughan, editors, *Advances in Neural Information Processing Systems*, 2021.

[16] Yoonho Lee, Huaxiu Yao, and Chelsea Finn. Diversify and disambiguate: Learning from underspecified data. *arXiv preprint arXiv:2202.03418*, 2022.

[17] Yi Li and Nuno Vasconcelos. Repair: Removing representation bias by dataset resampling. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, June 2019.

[18] Yingwei Li, Qihang Yu, Mingxing Tan, Jieru Mei, Peng Tang, Wei Shen, Alan Yuille, and cihang xie. Shape-texture debiased neural network training. In *International Conference on Learning Representations*, 2021.

[19] Evan Z Liu, Behzad Haghgoo, Annie S Chen, Aditi Raghunathan, Pang Wei Koh, Shiori Sagawa, Percy Liang, and Chelsea Finn. Just train twice: Improving group robustness without training group information. In Marina Meila and Tong Zhang, editors, *Proceedings of the 38th International Conference on Machine Learning*, volume 139 of *Proceedings of Machine Learning Research*, pages 6781–6792. PMLR, 18–24 Jul 2021.

[20] Ziwei Liu, Ping Luo, Xiaogang Wang, and Xiaoou Tang. Deep learning face attributes in the wild. In *Proceedings of International Conference on Computer Vision*, December 2015.

[21] Aleksander Madry, Aleksandar Makelov, Ludwig Schmidt, Dimitris Tsipras, and Adrian Vladu. Towards deep learning models resistant to adversarial attacks. In *International Conference on Learning Representations*, 2018.

[22] Vaishnavh Nagarajan, Anders Andreassen, and Behnam Neyshabur. Understanding the failure modes of out-of-distribution generalization. In *International Conference on Learning Representations*, 2020.

[23] Junhyun Nam, Hyuntak Cha, Sungsoo Ahn, Jaeho Lee, and Jinwoo Shin. Learning from failure: De-biasing classifier from biased classifier. In H. Larochelle, M. Ranzato, R. Hadsell, M. F. Balcan, and H. Lin, editors, *Advances in Neural Information Processing Systems*, volume 33, pages 20673–20684. Curran Associates, Inc., 2020.

[24] Maithra Raghu, Justin Gilmer, Jason Yosinski, and Jascha Sohl-Dickstein. Svcca: Singular vector canonical correlation analysis for deep learning dynamics and interpretability. In *Advances in Neural Information Processing Systems*, volume 30. Curran Associates, Inc., 2017.

[25] Shiori Sagawa*, Pang Wei Koh*, Tatsunori B. Hashimoto, and Percy Liang. Distributionally robust neural networks. In *International Conference on Learning Representations*, 2020.

[26] Ramprasaath R. Selvaraju, Michael Cogswell, Abhishek Das, Ramakrishna Vedantam, Devi Parikh, and Dhruv Batra. Grad-cam: Visual explanations from deep networks via gradient-based localization. In *Proceedings of the IEEE International Conference on Computer Vision*, Oct 2017.

[27] Harshay Shah, Kaustav Tamuly, Aditi Raghunathan, Prateek Jain, and Praneeth Netrapalli. The pitfalls of simplicity bias in neural networks. In *Proceedings of the 34th International Conference on Neural Information Processing Systems*, NIPS'20, Red Hook, NY, USA, 2020. Curran Associates Inc.

[28] Christian Szegedy, Wojciech Zaremba, Ilya Sutskever, Joan Bruna, Dumitru Erhan, Ian Goodfellow, and Rob Fergus. Intriguing properties of neural networks. In *2nd International Conference on Learning Representations, ICLR 2014*, 2014.

[29] Enzo Tartaglione, Carlo Alberto Barbano, and Marco Grangetto. End: Entangling and disentangling deep representations for bias correction. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 13508–13517, June 2021.

[30] Laurens van der Maaten and Geoffrey Hinton. Visualizing data using t-sne. *Journal of Machine Learning Research*, 9(86):2579–2605, 2008.

[31] Haohan Wang, Zexue He, and Eric P. Xing. Learning robust representations by projecting superficial statistics out. In *International Conference on Learning Representations*, 2019.

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 Section 4.2
   (c) Did you discuss any potential negative societal impacts of your work? [No] Our work has no negative social impact in our opinion.
   (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]
3. If you ran experiments...
   (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] See appendix
   (b) Did you specify all the training details (e.g., data splits, hyperparameters, how they were chosen)? [Yes] See appendix
   (c) Did you report error bars (e.g., with respect to the random seed after running experiments multiple times)? [Yes] Our experimental results are presented in tabular form with mean and standard deviation.
   (d) Did you include the total amount of compute and the type of resources used (e.g., type of GPUs, internal cluster, or cloud provider)? [No]
4. If you are using existing assets (e.g., code, data, models) or curating/releasing new assets...
   (a) If your work uses existing assets, did you cite the creators? [Yes]
   (b) Did you mention the license of the assets? [No]
   (c) Did you include any new assets either in the supplemental material or as a URL? [No]
   (d) Did you discuss whether and how consent was obtained from people whose data you're using/curating? [Yes] All the datasetS we use is public
   (e) Did you discuss whether the data you are using/curating contains personally identifiable information or offensive content? [No]
5. If you used crowdsourcing or conducted research with human subjects...
   (a) Did you include the full text of instructions given to participants and screenshots, if applicable? [N/A]
   (b) Did you describe any potential participant risks, with links to Institutional Review Board (IRB) approvals, if applicable? [N/A]
   (c) Did you include the estimated hourly wage paid to participants and the total amount spent on participant compensation? [N/A]

A Appendix

A.1 Implementation Details

Our code is mainly based on pytorch and will be available at `https://github.com/badcode-iip/Roadblocks`. The datasets used in the paper are all public datasets. There are many versions of CMNIST, the one we use is the version as LFF [23]. It contains identically distributed training and validation sets, and an unbiased testing set. We did not use any preprocessing for CMNIST. The details and download methods of CelebA [20] and BAR [23] can be found in the corresponding papers. We preprocessed CelebA and BAR (resize, normalize) for easier training, we also applied horizontal flipping for augmentation. The implementation of t-SNE is from scikit-learn, and the implementations of Grad-CAM and SVCCA are all from open source code. For Table 1, we use 3-layer MLPs, the number of neurons are (3*28*28, 100, 100, 32, 10). For the rest of the experiments, we use ResNet-18 as the classifier, and the pre-training parameters provided by pytorch only in experiments on CelebA and BAR. The autoencoder is consist of a encoder (3 Conv2d layer) and a correspond decoder. We use Adam as the optimizer, learning rate is 1e-3 and alpha is 1e-6. The max epoch is 100. The batch size is 64 for CMNIST and 16 for CelebA and BAR. $[\lambda_{ac}, \lambda_{rb}, \lambda_{rec}]$ are set to [1, 1, 10] for CelebA and [1, 0.01, 10] for CMNIST and BAR.

A.2 Functionally identical features may have different representations.

We use negative correlation learning to train models with feature-level differences, hoping to learn different decision rules. In order to show the results more intuitively, we divide the testing set into independently-identical-distribution (i.i.d.) part and out-of-distribution (o.o.d.) part. The results are shown in Table 3. It can be seen that none of them can classify o.o.d. samples correctly, which means that none of them can learn features other than color.

Table 3: Performance of different knowledge exploring methods.

Method	Metric	i.i.d. set	o.o.d. set
NCL	L1	1.00 ± 0.00	0.00 ± 0.00
NCL	L2	1.00 ± 0.00	0.00 ± 0.00
NCL	JS	1.00 ± 0.00	0.00 ± 0.00
NCL	Wasserstein	1.00 ± 0.00	0.00 ± 0.00

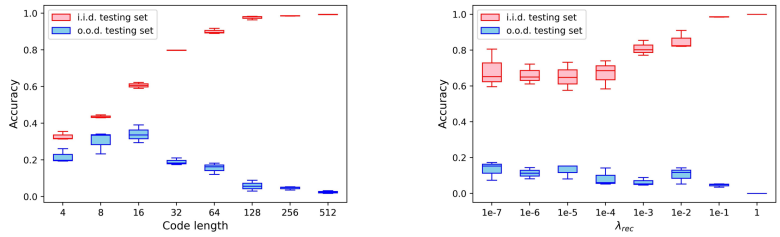
A.3 What if autoencoder is not strong enough?

The reconstruction capability of AE has a direct impact on the setting of Roadblocks. In this section we use 3-layer MLPs to build AE. By adjusting the reconstruction ability and the weight of reconstruction, we conduct further analysis on the behavior of the model. While keeping other hyperparameters unchanged, we modified the number of neurons in the code layer of AE to limit its reconstruction capability, then we repeated the previous experiment, the fluctuation of performance is shown in Figure 7a.

When the reconstruction capability of AE is low, the model cannot complete the basic i.i.d. task, and when it is high, the model may again prefer shortcuts. Only the results in the middle section just meet our expectations. Fortunately, we can avoid the first case by requiring reasonable training accuracy. And for the second case, we propose two simple strategies, on the one hand, we can consider the setting that just avoided the first case; on the other hand, adjusting the weights of reconstruction loss can also guide models with high reconstruction capabilities to make reasonable trade-offs.

Let us change a perspective and discuss the behavior of AE. It can be seen that with the expansion of the code layer, the accuracy on the i.i.d. testing set continues to improve, and the accuracy on the o.o.d. testing set increases first and then decreases. When the reconstruction capability is insufficient, AE tends to use attributes other than shortcuts, which is understandable because the roadblock loss is preventing AE from using shortcuts. As the reconstruction capability improves, AE gradually learns shortcuts and weighs the shortcuts and other attributes under the guidance of losses.

When the ability to rebuild is greatly compromised, the weight of reconstruction loss also has impact on the training process. We use hold the structure of BM and EM as ResNet-18, the weights of



(a) (b)

Figure 7: The impact of changes in code length and λ_{rec}.

other losses λ_{rb} and λ_{ac} are both set to 1. The structure of AE is MLP, (512, 256, 512). When other hyperparameters remain unchanged, the experimental results of different λ_{rec} are shown in Figure 7b. The settings of λ_{rec} can be roughly divided into three types according to i.i.d. set accuracy and o.o.d. set accuracy. (1) too high, $Acc._{i.i.d.}$ is close to 1, and $Acc._{o.o.d.}$ is close to 0, which means that AE tends to completely reconstruct original images, and EM can still learn shortcuts since roadblocks are invalid; (2) too low, $Acc._{i.i.d.}$ is low, and $Acc._{o.o.d.}$ is close to a random result, although roadblocks can work at this time, it is difficult for EM to learn with reconstructed images; (3) appropriately, $Acc._{i.i.d.}$ is good enough, and $Acc._{o.o.d.}$ is close to a random result, which indicates that EM has learned attributes other than shortcuts, and no longer relies too much on shortcuts while maintaining accuracy. It can be seen that when λ_{rec} is not too high, $Acc._{o.o.d.}$ is stable, so even if we may not be able to obtain o.o.d. testing sets in real scenarios, it is not difficult to find suitable λ_{rec} under the guidance of $Acc._{i.i.d.}$.

A.4 Can adversarial training handle shortcuts?

We discuss the relationship of our method to adversarial training in the main text. Table 4 is the performance of simple adversarial training with fast gradient sign untargeted adversarial attack [6] under the l2 constraint on CMNIST. The maximum norm of the adversarial perturbation ϵ is 0.3, we use Adam as the optimizer, learning rate is 1e-2. It can be seen that adversarial training does not have a significant effect on biased datasets.

Table 4: Adversarial training on CMNIST.

Ratio (%)	Vanilla	Adversarial
0.5	74.90 ± 2.10	72.78 ± 4.48
1	65.77 ± 1.11	64.14 ± 1.41
2	50.13 ± 2.18	45.31 ± 4.23
5	33.07 ± 0.87	30.47 ± 0.90

We further conducted experiments under different adversarial training parameter settings, and the results are shown in Table 5. It can be seen that the accuracy of the adversarial trained models on the adversarial samples and the clean samples are basically the same. This is a demonstration that adversarial training has helped the model achieve a certain degree of adversarial robustness. As epsilon increases, the accuracy of l2 improves, while the accuracy of linf increases first, but it is difficult to converge when epsilon is too large.

Some visualizations of adversarial examples shown in Figure 8 can help us understand why adversarial training has limited effect on the shortcut problem. It can be seen that the difference between the adversarial sample and the real sample is almost invisible to the naked eye, and it is difficult to observe clear digital information in the adversarial noise magnified by 100 times.

We also conduct experiments on PGD [21], but it seems difficult to obtain effective adversarial examples using MLPs. So we use ResNet-18 as the backbone. epsilon=0.03, k=4, alpha=0.03/4. The accuracy is 92.91 on CMNIST (5pct) and 88.54 on adversarial examples. (vanilla can achieve 93.34).

Table 5: The performance of adversarial training on CMNIST under different experimental settings.

ϵ	0.001	0.005	0.01	0.05	0.1	0.5
l2-clean	68.45	66.13	71.03	73.37	71.59	76.69
l2-adv	68.44	66.06	70.97	73.61	70.97	73.19
linf-clean	69.47	73.66	77.26	67.70	51.58	11.35
linf-adv	69.44	73.14	74.00	52.08	35.85	11.35

(a) clean (b) adv. (c) 100*δ

Figure 8: FGSM samples. Results are taken from the testing set of CMNIST, $ratio = 5\%, \epsilon = 0.3$, l2.

Figure 9 shows some samples of PGD. It can be seen that the noise of PGD seems to be more uniform compared to that of FGSM. Neither can distinguish colors or numbers with the naked eye.

Based on these experimental results, we believe that simple adversarial training cannot solve the shortcut problem that this paper attempts to solve.

(a) clean (b) adv. (c) 100*δ

Figure 9: PGD samples. Results are taken from the testing set of CMNIST, $ratio = 5\%, \epsilon = 0.3$, l2.

A.5 How to choose hyperparameters?

We tested different combinations of lambdas and selected the one that performed better, the result is shown in Figure 10. For other hyperparameters, we did not tune too much, but adopted empirical settings.

A.6 More visualization results

We show more visualization experiments to demonstrate the generality of our conclusions. Figure **??** is the result of CelebA and Figure 12 is the result of BAR. For both of them, from top to bottom, is the original image, the reconstructed image, the difference, the saliency map of the original model, and the saliency map of EM.

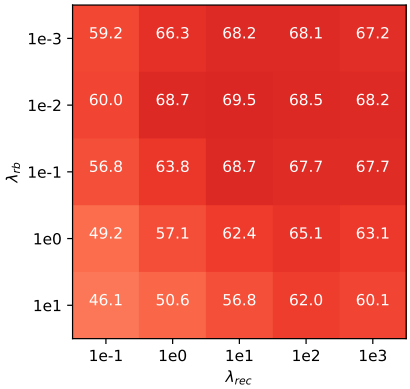


Figure 10: The sensitivity to weights of losses.

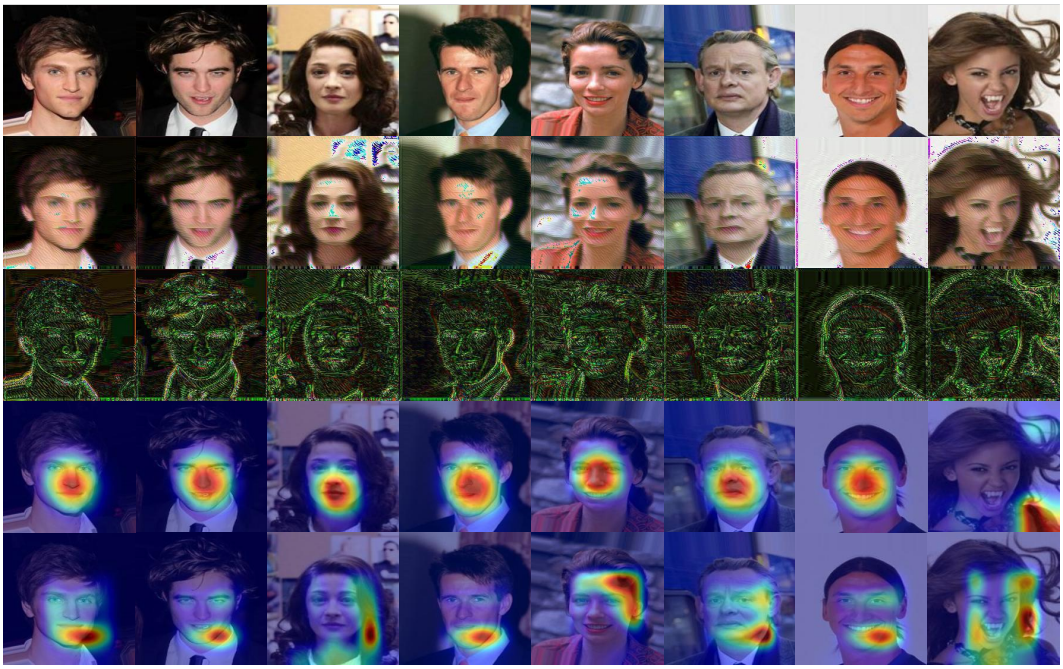


Figure 11: Visualizations on CelebA

We also show some selected results to try to analyze why our method can improve the generalization ability of the model. Figure 13 is selected based on the predictions of BM and EM. Green boxes indicate that the samples are classified correctly, and red boxes indicate the wrong predictions. For action classification, what should really be concerned with is the action of the person itself rather than other things in the scene. Our method is able to better focus on the person, which results in better performance on the testing set where the environment changes. For example, for the vanilla model, mountain climbing is misclassified as fishing based on climbing ropes, and diving is misclassified as throwing based on spectator background, while EM can give the correct predictions.

In the proposed approach, AE and EM are alternately trained. As the training continues, AE may modify the samples in different ways, as shown in Figure 14 image below. The upper left corner is the original image, followed by the reconstruction results of AE at 10, 20, and 30 epochs.

A.7 More datasets results

We selected 10 categories of ImageNet to test the proposed approach in general scenarios. The 10 categories are n01608432, n01641577, n02106166, n02127052, n02389026, n02422106, n02690373,

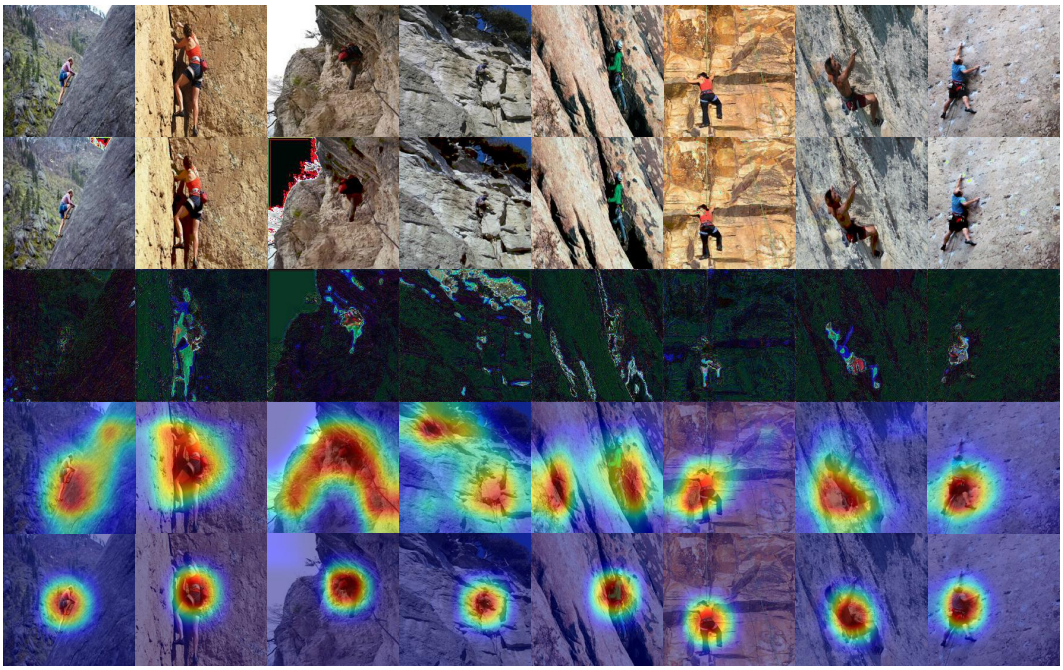


Figure 12: Visualizations on BAR

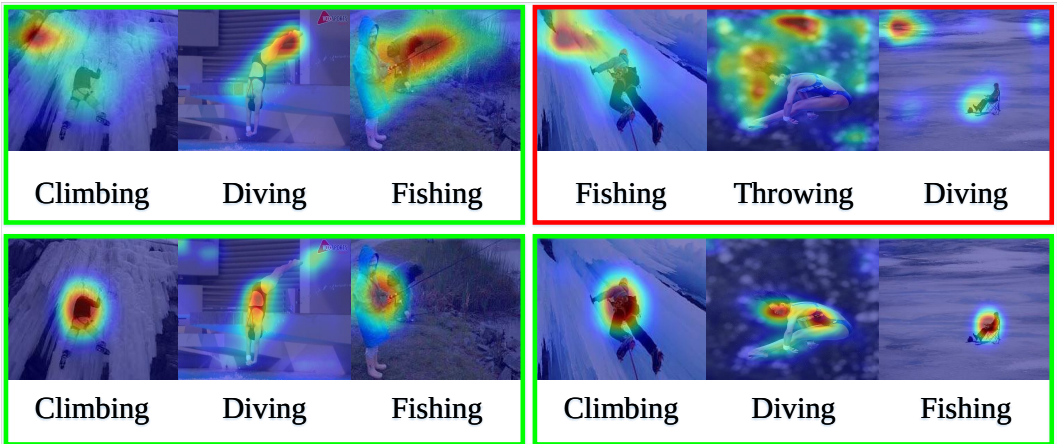


Figure 13: Some selected saliency maps. The upper row corresponds to vanilla and the lower row corresponds to EM. These saliency maps explain the difference when both are paired, and why EM has better generalization performance.

n03095699, n03100240, n03417042. Figure 15 presents the corresponding reconstruction results and saliency maps.

Table 6: Performance on ImageNet.

Method	0	1	2	3	4	5	6	7	8	9	Avg.
Vanilla	92.0	88.0	92.0	84.0	96.0	100.0	98.0	90.0	92.0	94.0	92.6
Ours	92.0	92.0	100.0	94.0	98.0	98.0	94.0	96.0	96.0	100.0	96.0

In the ImageNet-9 dataset, we chose to modify the background to generate a challenging testing set (mixed-rand, mixed-next), and the results are shown in Table 7 and Figure 16.

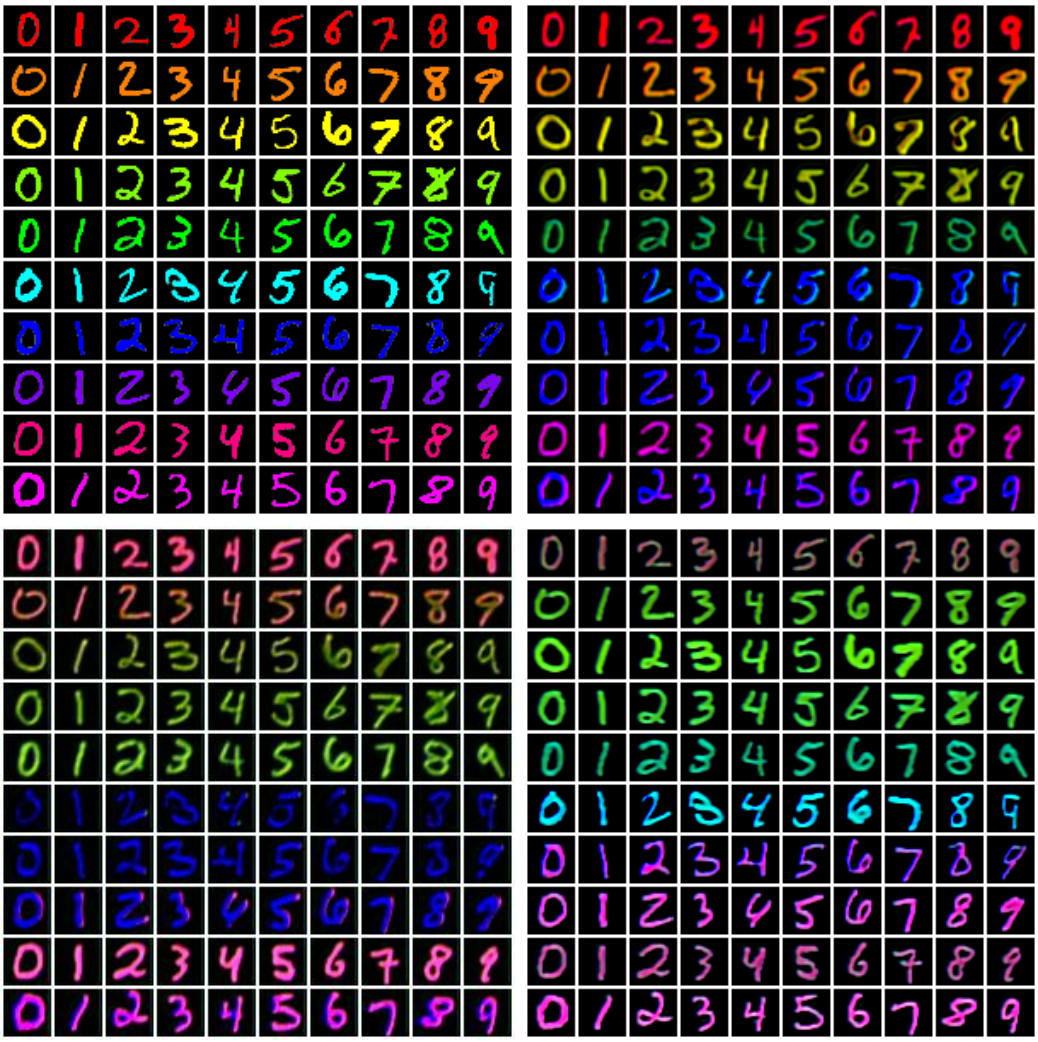


Figure 14: Reconstruction results on CMNIST.

Table 7: Performance on ImageNet-9.

Method	Origin	Mixed-rand	Mixed-next
Vanilla	90.08	66.32	62.59
Ours	90.50	70.21	67.73

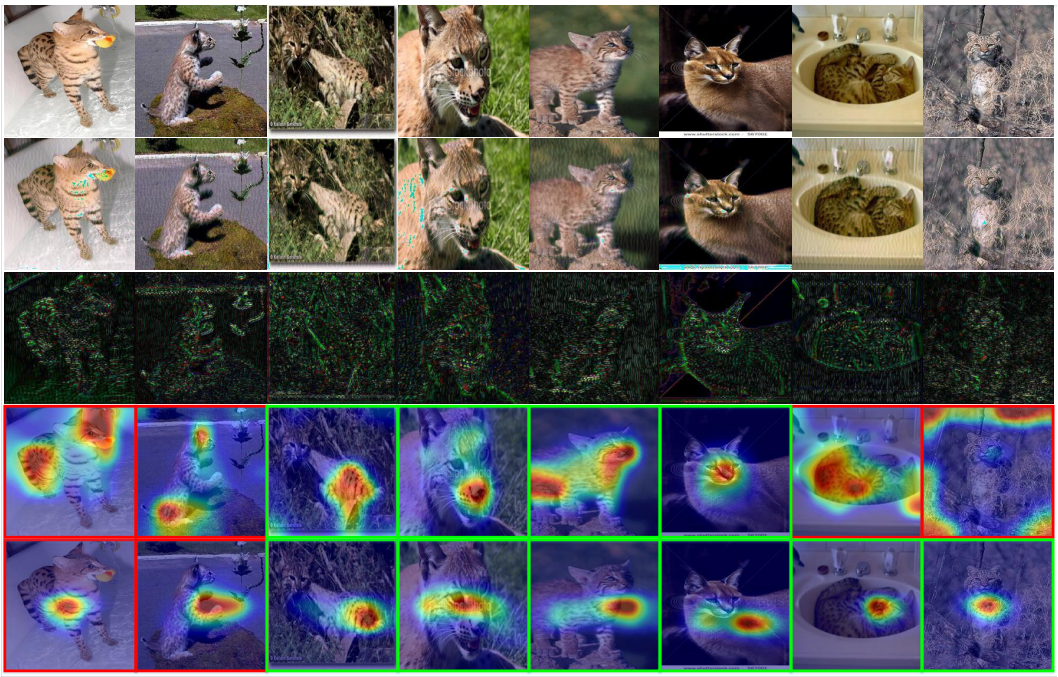


Figure 15: Visualizations on ImageNet.

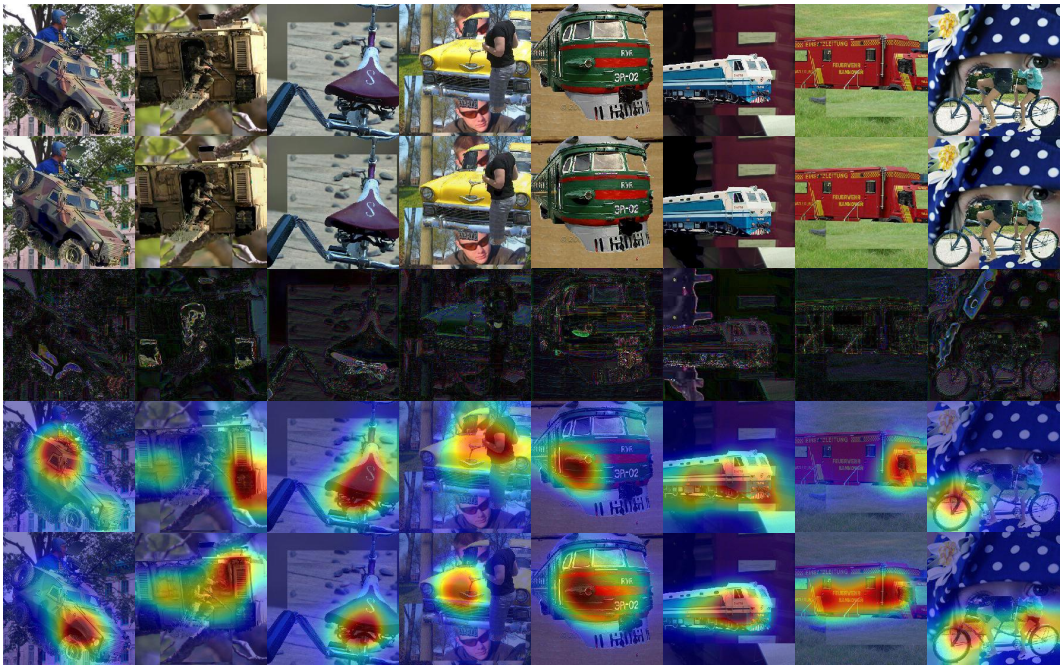


Figure 16: Visualizations on ImageNet-9.