Variational Disentanglement for Domain Generalization

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Abstract

Domain generalization aims to learn a domain-invariant model that can generalize well to the unseen target domain. In this paper, based on the assumption that there exists an invariant feature mapping, we propose an evidence upper bound of the divergence between the category-specific feature and its invariant ground-truth using variational inference. To optimize this upper bound, we further propose an efficient Variational Disentanglement Network (VDN) that is capable of disentangling the domain-specific features and category-specific features (which generalize well to the unseen samples). Besides, the generated novel images from VDN are used to further improve the generalization ability. We conduct extensive experiments to verify our method on three benchmarks, and both quantitative and qualitative results illustrate the effectiveness of our method.

1 Introduction

Nowadays, deep neural networks are widely used in numerous tasks and exhibit remarkable performance. However, their performance may degrade rapidly when the deployed environment is different from the training one. How to obtain a domain invariant network that can generalize to the data collected from an unseen environment is always a research hotspot (Zhang et al., 2016; Kawaguchi et al., 2017).

Domain generalization (DG) aims to tackle the generalization problem where the data from the target domain is inaccessible. Generally, existing DG research works can be categorized into two streams, invariant feature representation learning and data augmentation. The objective of invariant feature representation learning is to extract shareable information across different domains, as such, the learned model is expected to be better generalized to the unseen but related domain during evaluation. For example, Li et al. (2018b;c) aims to minimize the divergence of the latent features between different domains or the divergence with a pre-defined prior distribution. Dou et al. (2019) further proposes to minimize the divergence of the distributions conditioned on the category label. Although some desired performances have been reported through aforementioned methods, they may face the risk of overfitting to the source domains without carefully specifying the invariant information to learn. On the other hand, data augmentation based methods have also been proved to be effective in the domain generalization setting by enlarging the scale of training data with different augmentation strategies, e.g., data augmentation through adversarial training (Volpi et al., 2018; Zhou et al., 2020b), MixUp (Wang et al., 2020c), stacked transformation (Zhang et al., 2020), and Fourier transformation (Xu et al., 2021). However, these augmentation strategies can be limited since they only focus on some specific types of data augmentation, as such, the diversity of augmented data may be constrained.

In this paper, we propose to learn an invariant feature representation by matching the distribution of the feature space across domains to a distribution which is expected to represent the ground truth (i.e., invariant information) for the problem of domain generalization on a specific task. We first propose to derive the evidence upper bound of the divergence between the distribution of the feature space across domains and its unknown ground-truth distribution. To further optimize the upper bound, we develop an efficient framework named Variational Disentanglement Network (VDN), which is capable of alleviating the aforementioned limitations jointly. More specifically, instead of optimizing the latent feature z alone, we propose to optimize the category-specific feature z_c and domain-specific feature z_d at the same time. The optimization of z_c and z_d are twofold: minimizing the redundant information in the task-specific features and maximizing the posterior probability of the generated samples with random styles. By maximizing the posterior probability term, z_c and z_d are impelled to be disentangled and contain all necessary information to avoid a trivial solution that overfits to source domains. Meanwhile, by further minimizing our proposed information term which is to filter out redundant information, z_c is expected to have less domain-specific information. Last but not the least, our VDN is also capable of generating different and diverse data across domains based on the specific task by

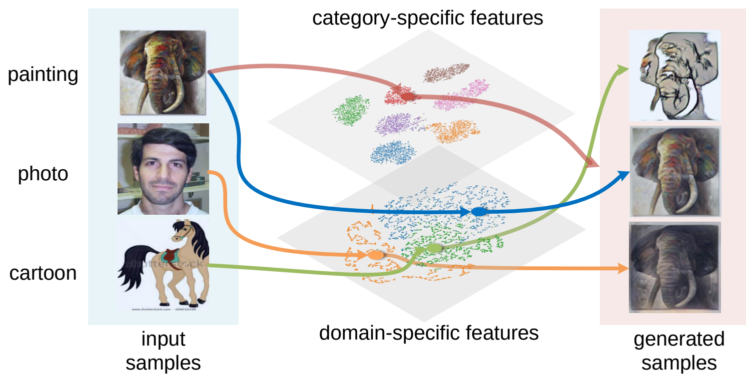


Figure 1: Given data from multiple source domains, we propose to learn a domain invariant embedding for classification and a domain-specific embedding to encode the style information. The arrows from images to embeddings indicate the encoding process, and the arrows from features to the generated samples represent the generation process. Invariant category-specific features are learned using the proposed variational disentanglement framework.

swapping z_d across domains. The generated novel images can be further used to improve the generalization ability of the model, and are also compatible with existing augmentation-based methods. Extensive experiments are conducted on widely-used benchmarks, and both quantitative and qualitative results show the effectiveness of our method.

In summary, our contributions are as follows:

- We provide a theoretical insight of how variational disentanglement can benefit the task of domain generalization based on the basic assumption of the invariant feature representation learning.
- We propose to derive a novel evidence upper bound of the divergence between the distribution of task-specific features and its invariant ground truth for domain generalization. Our proposed evidence upper bound further supports the rationality and build the tie between previous feature alignment-based methods (Li et al., 2018b) and disentangle-based methods, e.g., Li et al. (2017); Peng et al. (2019b).
- A novel framework is proposed to optimize the proposed evidence upper bound of the divergence. Extensive experiments demonstrate the effectiveness and superiority of our proposed method.

2 Related works

2.1 Domain generalization

The core ideas of domain generalization (DG) are inherited from domain adaptation (Huang et al., 2006; Pan et al., 2011; Zhang et al., 2015; Ghifary et al., 2017; Blanchard et al., 2021) to some extent, e.g., they assume that there exists something in common between different domains even if they can look quite different. For example, Khosla et al. (2012); Seo et al. (2020) aims to jointly learn an unbiased model and a set of bias vectors for each domain, Yang & Gao (2013) used Canonical Correlation Analysis (CCA) to extract the shared feature, Muandet et al. (2013) proposes a domain invariant analysis method which used MMD and was further extended by Li et al. (2018b), multi-task autoencoders were also used by Ghifary et al. (2015) to learn a shared feature extractor with multiple decoders. Moreover, various regularization methods of latent code are proposed (Zhao et al., 2020; Wang et al., 2020b), e.g., low-rank regularization (Xu et al., 2014; Li et al., 2017; 2020; Piratla et al., 2020). In addition, data augmentation based methods are also proved to be effective in the domain generalization setting, e.g., GAN generated samples (Volpi et al., 2018; Zhou et al., 2020b), domain mixup (Wang et al., 2020c; Zhou et al., 2021), stacked transformations (Zhang et al., 2020), domain-guided perturbation direction (Shankar et al., 2018), Fourier augmentation (Xu et al., 2021), and solving a jigsaw puzzle problem (Carlucci et al., 2019). Meta-learning based methods (Li et al., 2018a; Balaji et al., 2018; Li et al., 2019b;a; Dou et al., 2019; Du et al., 2020) are also explored by learning from episodes that simulate the domain gaps. Recently, invariant risk minimization (IRM) is proposed to eliminate spurious correlations as such the models are expected to have better generalization performance (Arjovsky et al., 2019; Ahuja et al., 2020; Bellot & van der Schaar, 2020; Zunino et al., 2020). As for feature disentanglement, current methods are usually based on decomposition (Li et al., 2017; Khosla et al., 2012; Piratla et al., 2020; Chattopadhyay et al., 2020). Generation based disentanglement methods are also explored. For instance, Peng et al. (2019b) conducts the single domain generalization using adversarial disentangled auto-encoder and Wang et al. (2020a) provide a pair of encoders for disentangled features in each domain.

2.2 Feature disentanglement and image translation

Our proposed method is related to the feature disentanglement, which has also been widely adopted in the problem of cross-domain learning (Bousmalis et al., 2017; Hoffman et al., 2018; Russo et al., 2018; Saito et al., 2018). A lot of progress in domain generalization has been made by applying feature disentanglement (Peng et al., 2019b; Khosla et al., 2012; Li et al., 2017; Piratla et al., 2020). For instance, Peng et al. (2019b) proposes a domain agnostic learning method based on VAE and adversarial learning, and Khosla et al. (2012); Li et al. (2017); Piratla et al. (2020) assume that there exists a shared model which is regarded as domain invariant and a set of domain-specific weights.

Our work is also related to the image translation (Isola et al., 2017; Choi et al., 2018; Zhu et al., 2017; Liu et al., 2019), which can be treated as conducting feature disentanglement by separating the style feature and content feature. Generally, the existing translation methods can be categorized into two streams, supervised/paired (Isola et al., 2017) and unsupervised/unpaired (Zhu et al., 2017; Choi et al., 2018). While some progress has been achieved, most of the existing models require a large amount of data. Recently, some efforts have been made to improve the capability of the translation model by utilizing few samples (Liu et al., 2019; Saito et al., 2020). Specifically, the framework we propose conducts translation tasks in a more efficient manner given limited and diverse data. This helps us obtain a more accurate posterior probability estimation. In addition, the generated high-quality samples with different combinations of image attributes (e.g., samples with a new combination of angles, shape, and color (Zhao et al., 2018)) based on our proposed framework are also used for data augmentation purpose for better generalization capability.

3 Methodology

3.1 Preliminary

Assume we observe K domains and there are N_i labeled samples $\{(x_j, y_j)\}_{j=1}^{N_i}$ in the domain $\mathbf{D}_i$. The distributions of the input image and its corresponding label in the domain $\mathbf{D}_i$ and all source domains are represented as X_i, Y_i and X, Y respectively. We first introduce the assumption regarding the invariant feature representation for the task of DG.

Assumption 1 *(Learnability) Denote the dimension of the image x and the latent feature z_c by d_x and d_c, respectively, let $\phi_c : \mathbb{R}^{d_x} \to L^1(\mathbb{R}^{d_c})$ be the mapping between an image x and its probability density function (PDF) $f(z_c|x)$, where L^1 denotes 1-norm integrable function space. A deterministic mapping $\phi_g : \mathbb{R}^{d_c} \to \mathbb{N}$ acts as a classifier to predict the category of the image based on its latent feature z_c. For a domain generalization problem with n_s source domains ($X_s = X_1 \cup X_2 ... \cup X_{n_s}$) and a target domain X_t, we say it learnable if*

$$\begin{aligned} &\exists \phi_c, \quad s.t. \\ &\mathbb{E}_{x \sim X_{i|y}}[\phi_c(x)] = \mathbb{E}_{x \sim X_{j|y}}[\phi_c(x)], \forall y \in Y, \forall i, j \in \{1, 2, ..., n_s, t\} \\ &\phi_g(\psi(\phi_c(x))) = y, \forall x \in X_s \cup X_t \end{aligned} \tag{1}$$

where $X_{i|y}$ represents the conditional distribution of images with the category y in the domain i, $\psi(\cdot)$ returns the mean value of the distribution.

Such an assumption is mild and is commonly adopted in the community of domain generalization

3.2 Motivation

To approximate the conditional distribution of domain-invariant features ϕ_c, we propose to minimize the evidence upper bound of the KL divergence $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$[1] derived by Bayes variational inference, where $Q(\mathbf{z_c}|x)$ denotes the feature distribution obtained from the category-specific encoder E_c and $P(\mathbf{z_c}|x)$ is the invariant ground

[1]For consistency, we represent distributions using upper case letter, e.g., $Q(\mathbf{z_c}|x)$ means the distribution of random variable $\mathbf{z_c}$ conditioned on x and it is also abbreviated as $Q_{z_c|x}$. The lower case represent the exact probability density value, e.g., $p(x|z_c, z_d)$.

truth distribution. Since we aim to find a deterministic classifier, we set $E_c(x) = \psi(Q(\mathbf{z_c}|x))$ for simplicity. We now introduce the rationality of learning invariant feature representation by minimizing the upper bound of KL divergence. Due to the limited space, proofs of Theorem 1 and 2, and additional details are placed in the Appendix.

Lemma 1 *The KL divergence $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$ can be represented as*

$$\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - E_{z_c \sim Q_{z_c|x}}[\log p(x|z_c)] + \log p(x),$$

where $p(x|z_c)$ is the PDF of the distribution $P(\mathbf{x}|z_c)$. Based on Lemma 1, we can derive the evidence upper bound of $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$.

Theorem 1 *The evidence upper bound of KL divergence $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$ between the distribution $Q(\mathbf{z_c}|x)$ and the ground-truth $P(\mathbf{z_c}|x)$ is as follows:*

$$\underbrace{\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}))}_{\text{① information gain term}} - \underbrace{E_{z_c \sim Q_{z_c|x}, z_d \sim P_{z_d}}[\log p(x|z)]}_{\text{② posterior probability term}} + C$$

where C is a constant, $z = [z_c, z_d]$ and P_d can be an arbitrary prior distribution.

We further show that the performance in the unseen target domain can also be benefited from the optimization of the given upper bound in source domains.

Assumption 2 *Given a sample x^t from the target domain X_t, there exists a non-empty feasible set $\mathcal{I}$ which is defined as*

$$\mathcal{I} = \{I|q(z_c|x) \leq \sum_{i \in I} \beta_i q(z_c|x_i^s), \forall z_c \in \mathbb{R}^{d_c}\} \cap \{I|\phi_c(x^t) = \phi_c(x_i^s), \forall i \in I\},$$

where I is the index set, x_i^s denotes an arbitrary sample with index i in any source domains, and $q(z_c|x)$ is the probability density function value of z_c conditioned on x from distribution $Q(\mathbf{z_c}|x)$.

Theorem 2 *Based on Assumption 2, the KL divergence between $Q(\mathbf{z_c}|x^t)$ and the unknown domain-invariant ground truth distribution $P(\mathbf{z_c}|x^t)$ can be bounded as follows*

$$\mathcal{D}(Q(\mathbf{z_c}|x^t)||P(\mathbf{z_c}|x^t)) \leq \inf_{I \in \mathcal{I}} [\sum_{i \in I} \beta_i \mathcal{D}(Q(\mathbf{z_c}|x_i^s)||P(\mathbf{z_c}|x_i^s))].$$

The above theorem demonstrates that the KL divergence between $Q(\mathbf{z_c}|x)$ and $P(\mathbf{z_c}|x)$ from source domains constitutes the divergence upper bound in the unseen target domain. Therefore, it further supports the rationale and effectiveness of our method.

3.3 Optimization strategies

In this section, we introduce the overall framework and the optimization details of each term in our proposed evidence upper bound.

3.3.1 Overall framework

The whole framework of our proposed method is illustrated in Fig. 2 which consists of a task-specific encoder E_c, a domain-specific encoder E_d, a generator G, a discriminator D_x to distinguish real and generated images, a discriminator D_c to justify whether the task-specific feature comes from a predefined distribution, and a task-specific network E_t for classification purpose. The overall optimization objective is given as

$$L = \underbrace{\lambda_{reg} L_{reg}}_{\text{To minimize ①}} + \underbrace{L_{posterior}}_{\text{To minimize ②}} \tag{2}$$

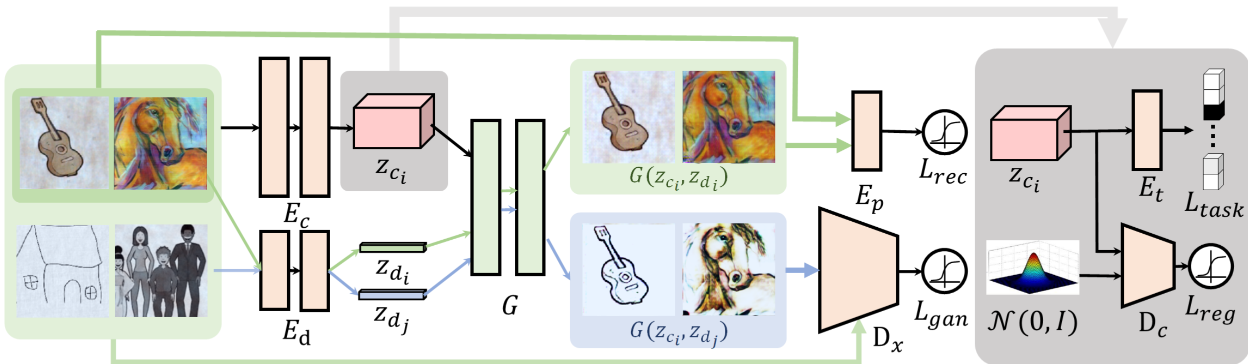


Figure 2: Framework of our method for training. For a random sample (x_i, y_i) in the training set, we random select another sample (x_j, y_j) that does not require the same category. We feed the two samples into the task-specific encoder E_c and domain-specific encoder E_d and get the corresponding code z_{c_i}, z_{c_j} and z_{d_i}, z_{d_j}. Then we use the generator G to obtain the reconstructed samples $G(z_{c_i}, z_{d_i})$ and samples with random style $G(z_{c_i}, z_{d_j})$. The perceptual loss and discriminator loss are used to enhance the quality of generated samples which further guarantee good disentanglement between class-specific feature z_c and domain-specific feature z_d. In addition, for the task-specific feature z_c, it is supervised by the specific task, e.g., classification, and regularized by the information gain term $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}))$.

where the loss L_{reg} is defined in equation 7 which acts as a regularization term that aligns the task-specific feature to a predefined distribution, and $L_{posterior}$ is defined as

$$L_{posterior} = L_{task} + \lambda_{rec} L_{rec} + \lambda_{gan} L_{gan} \tag{3}$$

where L_{gan}, L_{rec} and L_{task} are defined in equation 9, equation 10 and equation 11 in Sec. 3.3.3 respectively and are optimized jointly to disentangle the task-specific feature z_c and domain-specific feature z_d.

In the test phase, an image from an unseen but related target domain is pass through the task-specific encoder E_c and the task-specific network E_t, and the other networks will not be involved. Therefore, our network is supposed to have the same inference complexity as the vanilla model.

3.3.2 Optimizing the information gain term

To reduce the risk of learned task-specific feature overfitting to the source domains, similar to Li et al. (2018b), we minimize the divergence between $Q(\mathbf{z_c}|x)$ which is introduced by the task-specific encoder E_c, and a predefined prior distribution $P(\mathbf{z_c})$. The divergence $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}))$ can be interpreted as the information gain by introducing a specific image x. Ideally, the optimal features only contain the necessary information for classification, and domain-specific information will be ruled out. To this end, we minimize the task-specific loss, i.e., classification loss in equation 11, and information gain term in our framework simultaneously. For the minimization of information gain term, we empirically find that directly optimizing this term using the reparameterization trick Kingma & Welling (2013) may not be feasible due to the high dimensionality of z_c. To this end, we propose to optimize $\mathcal{D}(Q(\mathbf{z_c})||P(\mathbf{z_c}))$, which is equivalent to optimize the upper bound of the information gain term L_{reg} in Theorem 1. The proof is in Lemma A.2 and the optimization of the proposed upper bound also supports the core idea of the previous work Li et al. (2018b) that aligns the latent feature to a pre-defined distribution. More specifically, we optimize its dual form following the core idea of F-GAN Nowozin et al. (2016) given as

$$\mathcal{D}(Q(\mathbf{z_c})||P(\mathbf{z_c})) = D_f(P(\mathbf{z_c})||Q(\mathbf{z_c})) = \int q(z_c) \sup_{t \in \mathrm{dom}_{f^*}} \left\{ t\frac{p(z_c)}{q(z_c)} - f^*(t) \right\} \mathrm{d}z_c \tag{4}$$

where $p(\cdot)$ and $q(\cdot)$ are PDFs of P and Q respectively, $f(u) = -\log(u)$, and $f^*(t)$ denotes its Fenchel conjugate (Hiriart-Urruty & Lemaréchal, 2004) which is defined as

$$f^*(t) = \sup_{u \in \mathrm{dom}_f} \{ut - f(u)\} = -1 - \log(-t). \tag{5}$$

Algorithm 1 Variational Disentanglement for domain generalization.

Input: $X = \{x_i\}_{i=1}^N$, $Y = \{y_i\}_{i=1}^N$, initialized parameters G, D_c, D_x, E_c, E_d and E_t.
Output: Learned parameters G^*, D_c^*, D_x^*, E_c^*, E_d^* and E_t^*.

while Stopping criterion is not met **do**
  Sample a *minibatch* $\tilde{X}$ and $\tilde{Y}$ from X and Y respectively.
  Calculate the task-specific feature $Z_c = E_c(\tilde{X})$ and domain-specific feature $Z_d = E_d(\tilde{X})$.
  Shuffle the domain-specific feature $\hat{Z}_d = \text{shuffle}(Z_d)$
  Generate the reconstructed samples $X_{rec} = G(Z_c, Z_d)$ and the samples with the random style $X_{rand} = G(Z_c, \hat{Z}_d)$.
  Calculate the weighted loss $L_{gen} = L_{task} + \lambda_{reg} L_{reg} + \lambda_{gan} L_{gan} + \lambda_{rec} L_{rec}$
  Compute the gradient of L_{gen} w.r.t G, E_c, E_d and E_t and then do the update.
  if Update frequency is met **then**
    Calculate the weighted loss $L_{dis} = -(\lambda_{reg} L_{reg} + \lambda_{gan} L_{gan})$
    Compute the gradient of L_{dis} w.r.t D_c and D_x and then do the update.
  end if
end while

One can replace t in equation 5 using an arbitrary class of functions T, as such, the term ① can be represented as

$$\mathcal{D}(Q(\mathbf{z_c})||P(\mathbf{z_c})) = \sup_{T \in \mathcal{T}} \left(\mathbb{E}_{z_c \sim P_{z_c}} \left[T(z_c) \right] - \mathbb{E}_{z_c \sim Q_{z_c|x}} \left[f^*(T(z_c)) \right] \right) \tag{6}$$

if the capacity of $\mathcal{T}$ is large enough.

To optimize equation 6, an adversarial training manner is used. Specifically, we optimize the task-specific encoder E_c to maximize this term and the discriminator D_c to minimize it. The final goal of the training for the regularization term is as follows

$$\min_{E_c} \max_{D_c} L_{reg} = \mathbb{E}_{z_c \sim P_{z_c}} \left[D_c(z_c) \right] + \mathbb{E}_{x \sim X} \left[\log(-D_c(E_c(x))) \right] + 1 \tag{7}$$

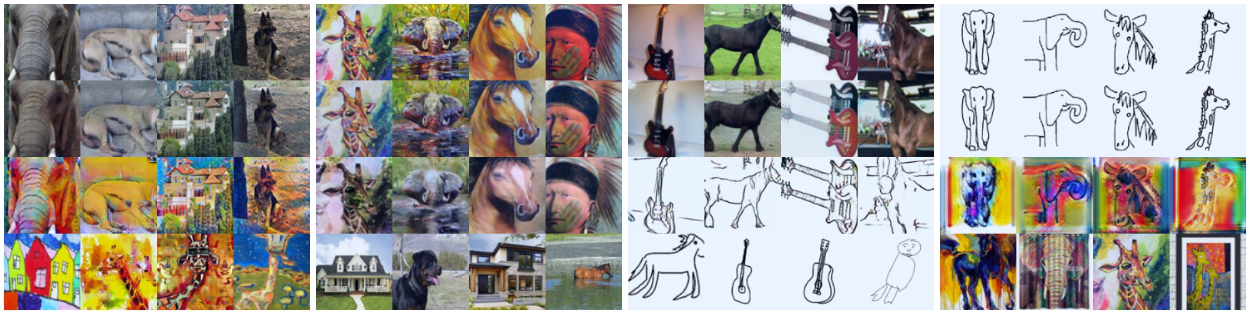
where the function T in equation 6 is implemented by a deep neural network D_c with the activation function $g_f(v) = -\exp(-v)$ at the output to retain the original domain dom_{f^*}.

3.3.3 Optimizing the posterior probability term

For better disentanglement, we propose to maximize the posterior probability term $p(x|z_c, z_d)$. The advantages of maximizing this term can be roughly summarized into two points: first, directly minimizing the information gain term and task-specific term may cause the overfitting to the training samples. For instance, when the dataset is not large enough, directly memorizing all the datasets may has less information gain comparing with extracting discriminate features for classification. By maximizing the posterior probability, we can guarantee that z_c and z_d together contain almost all the information of the image which avoid the loss of discriminative features caused by minimizing the information gain term. Second, by improving the quality of generated samples using random combined task-specific feature z_c and style feature z_d, the task-specific and domain-specific features will be disentangled since our discriminator can not only distinguish real and fake images but can also differentiate whether the generated samples are from the specific domains thanks to the domain labels.

To maximize the posterior probability term, two obstacles need to be solved. First, an efficient sampling strategy is needed on account that the space of z_c and z_d is large and intractable and it is not feasible to sample ergodically from them. To this end, inspired by VAE (Kingma & Welling, 2013), we propose to adopt the task-specific encoder E_c and domain-specific encoder E_d instead, i.e., $Q_{z_c} \sim E_c(X)$ and $Q_{z_d} \sim E_d(X)$, to conduct code sampling of z_c and z_d which are most likely to generate a realistic sample. To sample in Q_c and Q_d independently, we shuffle the domain-specific features in a batch and ensure the generated samples $G(z_{c_i}, z_{d_j})$ using randomly combined features as realistic as possible. More details can be found in Algorithm 1.

Unlike VAE Kingma & Welling (2013) which only computes the reconstruction term $p(x|z_{c_i}, z_{d_i})$, we also need to compute the probability of the generated one $G(z_{c_i}, z_{d_j})$ using the generator G for $\forall i \neq j$ without a corresponding



(a) photo → art painting (b) art painting → photo (c) photo → sketch (d) sketch → art painting

Figure 3: The generated samples in source domains. The images in the first row are the input images that we want to keep the category information and in the last row are the input images that provide the style information. The second row is the reconstructed one and the third row is the translated one.

ground-truth. To this end, we estimate the probability $p(x|z_c, z_d)$ using the following equations

$$p(x|z_c, z_d) = \begin{cases} La(x|G(z_c, z_d), \beta)) & \text{w/ ground-truth} \\ D_x(G(z_c, z_d)) & \text{w/o ground-truth} \end{cases} \tag{8}$$

where La denotes the PDF of Laplace distribution (corresponding to the L1 norm) to measure the pixel reconstruction loss. To optimize the term in equation 8, D_x needs to have the capability to distinguish between the real and generated images $G(z_{c_i}, z_{d_j})$ through random combined latent features and the generator G is also required to produce realistic outputs. To this end, we train the model in an adversarial manner given below

$$\max_{D_x} \min_{E_c, E_d, G} L_{gan} = E_{x \sim X}[D(x)] - E_{z_c \sim Q_c, z_d \sim Q_d}[D(G(z_c, z_d))]. \tag{9}$$

For the reconstructed images with ground-truth, we empirically find that directly minimizing the pixel level divergence can lead to a performance degradation. To this end, we minimize the divergence of semantic features through a pre-trained perceptual network E_p instead. Therefore, we maximize the improved version $La(E_p(x)|E_p(G(z_c, z_d)), \beta))$ by minimizing its corresponding L1 loss given as

$$\min_{E_c, E_d, G} L_{rec} = E_{x \sim X}||E_p(x) - E_p(G(E_c(x), E_d(x)))||_1. \tag{10}$$

Last but not least, to further enforce the task-specific encoder E_c to generate more meaningful embeddings, we use label information to guide the model training by minimizing the following equation

$$\begin{aligned} \min_{E_c, E_t} L_{task} = & E_{x \sim X}[l_{task}(E_t \circ E_c(x), y)] \\ & + E_{z_c \sim Q_c, z_d \sim Q_d}[l_{task}(E_t \circ E_c(G(z_c, z_d)), y)] \end{aligned} \tag{11}$$

where y denotes the ground-truth label of the input x or its task-specific feature z_c, l_{task} is the task-specific loss, e.g., cross entropy is used in our work for classification tasks. Besides, we also consider the generated samples for data augmentation purpose, which is the second term of equation 11.

4 Experiments

We evaluate our method using three benchmarks including Digits-DG (Zhou et al., 2020b), PACS (Li et al., 2017) and mini-DomainNet (Zhou et al., 2020c; Peng et al., 2019a). For the hyper-parameters, we set λ_{reg}, λ_{rec} and λ_{gan} as 0.1, 1.0 and 1.0, respectively, for all experiments. The network architectures and training details are illustrated in the supplementary materials. We report the accuracy of the model at the end of the training.

4.1 Digits-DG

Settings: Digits-DG (Zhou et al., 2020b) is a benchmark composed of MNIST, MNIST-M, SVHN, and SYN where the font and background of the samples are diverse. Except that we additionally use the Fourier-based data

Table 1: Evaluation of DG on the Digits-DG benchmark. The average target domain accuracy are reported.

Method	Reference	MNIST	MNIST-M	SVHN	SYN	Avg.
DeepAll	-	95.8	58.8	61.7	78.6	73.7
MMD-AAE (Li et al., 2018a)	CVPR 2018	96.5	58.4	65.0	78.4	74.6
CrossGrad (Shankar et al., 2018)	ICLR 2018	96.7	61.1	65.3	80.2	75.8
DDAIG (Zhou et al., 2020b)	AAAI 2020	96.6	64.1	68.6	81.0	77.6
L2A-OT (Zhou et al., 2020a)	ECCV 2020	96.7	63.9	68.6	83.2	78.1
MixStyle (Zhou et al., 2021)	ICLR 2021	96.5	63.5	64.7	81.2	76.5
FACT (Xu et al., 2021)	CVPR 2021	**97.9**	65.6	72.4	**90.3**	81.5
VDN	Ours	97.6	**68.1**	**72.9**	87.6	**81.6**

augmentation (Xu et al., 2021), we follow the experiment setting in Zhou et al. (2020b). More specifically, the input images are resized to 32×32 based on RGB channels. The ConvNet is used as the backbone for all methods and is divided into two parts: the task-specific encoder E_c which includes the first three conv blocks except for the last max-pooling layer and the rest are regarded as the task-specific network E_t. For the E_c and E_t, we use the same learning parameters with Zhou et al. (2020b). SGD is used as the optimizer with an initial learning rate of 0.05 and weight decay of 5e-5. For the rest of the networks, we use RmsProp without momentum as the optimizer with the initial learning rate of 5e-5 and the same weight decay. We train the model for 60 epochs using the batch size of 128 and all the learning rate is decayed by 0.1 at the 50th epoch.

Results: We repeat the experiment 3 times and report the average accuracy in Table 1. Our method has about 10% percent improvements in MNIST-M, SVHN, and SYN domains compared with the DeepAll method. In addition, the results demonstrate that our method achieves the best overall performance, especially in the domain of MNIST-M with about 3% improvement compared with other competitors.

4.2 PACS

Settings: PACS (Li et al., 2017) is a benchmark for domain generalization task collected from four different domains: photo, art painting, sketch, and cartoon with relatively large domain gaps. Following the widely used setting in Carlucci et al. (2019), we only used the official split of the training set to train the model and all the images from the target domain are used for the test. RmsProp is used to train all the networks with an initial learning rate of 5e-5 without momentum and decrease the learning rate by a factor of 10 at the 50th epoch. The batch size is set to 24 and we sample the same number of images from each domain at the training phase. All the images are cropped to 224×224 for training and the data augmentations including random crop with a scale factor of 1.25, amplitude mix (Xu et al., 2021) , and random horizontal flip. Other augmentations such as random grayscale are not used as it may conceal the true performance of the model by introducing prior knowledge of the target domain. More specifically, the part from the beginning to the second residual block inclusive is regarded as the task-specific encoder E_c, and the remaining part acts as the task-specific network E_t. The discriminators D_c and D_x are updated once after every 5 updates of other parts in the framework.

Results: The results based on Resnet-18 are reported in Table 2. As we can observe, our method outperforms other state-of-the-art methods. Moreover, we observe that we can achieve much better performance in the sketch domain in a large margin compared with other baseline methods. We conjecture the reason that the Sketch domain may contain less domain-specific information. As shown in Fig. 4, shuffling domain-specific features has less impact on image generation in the domain of Sketch. Due to limited space, the results based on Resnet-50 are reported in the Appendix.

4.3 mini-DomainNet

Settings: We then consider a larger benchmark mini-DomainNet (Zhou et al., 2020c), which is a subset of DomainNet (Peng et al., 2019a) without noisy labels, for evaluation purpose. In mini-DomainNet, there are more than 140k images in total belonging to 4 different domains, namely sketch, real, clipart, and painting.

For the task-specific encoder E_c and task-specific network E_t, we use SGD with a momentum of 0.9 and an initial learning rate of 0.005 as the optimizer. For other parts of our framework, RmsProp without momentum is used with

Table 2: Evaluation of DG on the PACS benchmark. The average target domain accuracy of five repeated experiments is reported.

Method	Reference	Art	Cartoon	Photo	Sketch	Avg.
DeepAll	-	77.0	75.9	95.5	70.3	79.5
MASF (Dou et al., 2019)	NIPS 2019	80.3	77.2	93.9	71.7	81.0
Epi-FCR (Li et al., 2019a)	ICCV 2019	82.1	77.0	93.9	73.0	81.5
L2A-OT (Zhou et al., 2020a)	ECCV 2020	83.3	78.2	**96.2**	73.6	82.8
RSC (Huang et al., 2020)	ECCV 2020	78.9	76.9	94.1	76.8	81.7
MixStyle (Zhou et al., 2021)	ICLR 2021	84.1	78.8	96.1	75.9	83.7
DAML (Shu et al., 2021)	CVPR 2021	83.0	74.1	95.6	78.1	82.7
FACT (Xu et al., 2021)	CVPR 2021	**85.4**	78.4	95.2	79.2	84.5
DSU (Li et al., 2022)	ICLR 2022	83.6	79.6	95.8	77.6	84.1
VDN	Ours	84.3	**79.8**	94.6	**82.8**	**85.4**

Table 3: Evaluation of DG on mini-DomainNet benchmark. We repeat the experiments three times and report the average accuracy in the unseen target domain in the table.

Method	Reference	Clipart	Real	Painting	Sketch	Avg.
DeepAll	-	62.86	58.73	47.94	43.02	53.14
MLDG (Li et al., 2018a)	AAAI 2018	63.54	**59.49**	48.68	43.41	53.78
JiGen (Carlucci et al., 2019)	CVPR 2019	63.84	58.80	48.40	44.26	53.83
MASF (Dou et al., 2019)	NIPS 2019	63.05	59.22	48.34	43.67	53.58
RSC (Huang et al., 2020)	ECCV 2020	64.65	59.37	46.71	42.38	53.94
DSU (Li et al., 2022)	ICLR 2022	63.17	56.03	47.46	47.14	53.45
VDN	Ours	**65.08**	59.05	**48.89**	**49.21**	**55.56**

the initial learning rate of 0.0001. For the learning rate scheduler towards all the optimizers, we use the same cosine annealing rule (Loshchilov & Hutter, 2016) with the minimum learning rate of 0 after 100 epochs. The batch size is 128 with a random sampler that roughly samples the same number of images in each domain. We consider data augmentations including the random clip with a probability of 0.5, and random crop the data to the size 96×96 using the scale factor of 1.25. For a fair comparison, we use the same backbone network Resnet-18 for all the methods and the division of E_c and E_t for our model is the same as the setting in PACS. The update frequency of D_c and D_x is the same with PACS that discriminators update once after every 5 updates of other parts in the framework.

Results: We compare our method with MLDG (Li et al., 2018a), JiGen (Carlucci et al., 2019), MASF (Dou et al., 2019), RSC (Huang et al., 2020), and DSU (Li et al., 2022). The results are shown in Table 3. As we can observe, we can achieve better performance compared with other baselines, especially in the sketch domain in a large margin. There is an interesting finding that similar to the PACS benchmark, the performance improvement in the sketch domain is huge, but in the real domain, the performance of our method has some degradation. This may reveal the potential inductive bias of the model. However, our method still has the best overall performance.

4.4 Ablation study and perceptual results

In this section, we first present the results of the ablation study to illustrate the effectiveness of each component in our proposed method. We further provide some perceptual results of image generation to show the significance of feature disentanglement.

4.4.1 Ablation study

We conduct the ablation study using the PACS benchmark. We first explore the effectiveness of each term in the evidence upper bound we proposed in Theorem 1. Then, the impacts of optimization strategies for each term are evaluated.

Table 4: Ablation study regarding the effectiveness of each term in the evidence upper bound we proposed. The first row is the DeepAll baseline and the last is the complete version of our method.

+①	+②	+DAug	+FAug	Art	Cartoon	Photo	Sketch	Avg.
-	-	-	-	77.0	75.9	**95.5**	70.3	79.5
✓	-	-	-	77.6	77.8	93.5	71.8	80.2
-	✓	-	-	79.7	78.4	94.3	75.2	81.9
✓	✓	-	-	81.5	78.2	93.8	77.6	82.8
✓	✓	✓	-	82.6	78.5	94.0	82.7	84.5
✓	✓	✓	✓	**84.3**	**79.8**	94.6	**82.8**	**85.4**

(a) art painting (b) cartoon (c) photo (d) sketch

Figure 4: The generated samples in the unseen target domains. The rows from up to down denote the input image provide the task-specific features, reconstructed images, transformed images, and the images that provide the style features, respectively. Note that the input images all come from the unknown target domain.

Effectiveness of each term: We first evaluate the effectiveness of optimizing each term we proposed in the EUB. The results are shown in Table 4 where '+①' and '+②' represent that we utilize the information gain term ① defined in equation 7 and the posterior probability term ② defined in equation 3 but without data augmentation respectively. '+DAug' means we use the generated samples from our generator G for data augmentation, and '+FAug' represents that we adopt Fourier-based data augmentation strategy (Xu et al., 2021) to do the data augmentation. The results demonstrate that both the information gain term and posterior probability term can improve the generalization capability of the model. In addition, combining these two together can attain larger performance improvements. The results also demonstrate that using the generated samples as augmented data can effectively improve the generalization ability of the model.

Impacts of different optimization strategies: As for the evidence upper bound we proposed, there are different optimization strategies for each term. For instance, reparameterization trick (Kingma & Welling, 2013) is a widely used method to optimize the term ①. In addition, directly optimizing the L1 reconstruction loss is a usual way to generate sharp reconstructed images. We investigate the impacts of different optimization strategies and the results are shown in Table 5 where the ✓one is the strategy we adopt. As we can see, directly using the reparameterization trick to align the high-dimensional features can lead to side effects. In addition, optimizing the perceptual loss can lead to better performance compared with replacing the reconstruction loss in equation 10 with L1 loss.

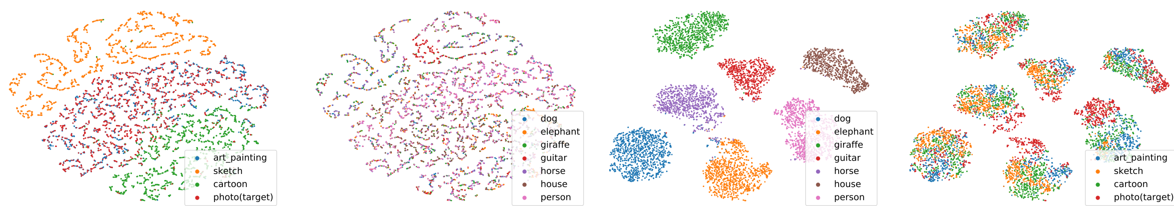
4.4.2 Perceptual results

To provide an intuitive way to understand the effect of disentangling, we further give some perceptual results. For limited space, more visualization results are placed in the supplementary materials.

Generated samples based on source-domain images: To demonstrate the effectiveness of our method, we first visualize the generated samples in a cross-domain setting that the pairs of input samples are from different source domains on account that the quality of the samples can reflect the accuracy of the estimated posterior probability and the degree of disentanglement. Some of the generated samples are shown in Fig. 3. The visualization results demonstrate that our method can disentangle the domain-specific features and task-specific features well and generate

Table 5: Ablation study regarding the effects of different optimization strategies. '✓': the strategy we use in the paper. 'reparam': the reparameterization trick (Kingma & Welling, 2013). 'L1 loss': replacing the reconstruction loss in equation 10 with L1 loss.

+①	+②	Art	Cartoon	Photo	Sketch	Avg.
-	-	77.0	75.9	**95.5**	70.3	79.5
reparam	-	74.4	77.6	92.4	68.3	78.2
✓	-	77.6	77.8	93.5	71.8	80.2
-	L1 loss	78.2	78.3	93.9	73.4	81.0
-	✓	**79.7**	**78.4**	94.3	**75.2**	**81.9**



(a) w/o domain label (b) w/o category label (c) w/o category label (d) w/o domain label

Figure 5: The unsupervised t-SNE visualization results of extracted features from our model. The features in (a,b) are collected from the domain-specific encoder E_d and features in (c,d) are collected from the task-specific encoder E_c. PACS benchmark is used for visualization and photo domain is selected as the target domain. (Best viewed in color.)

realistic novel samples with high quality and different styles. In addition, we observe that the reconstructed samples may not necessarily be the same as the original one, mainly due to the perceptual loss we adopt, as such, we can prevent the latent features from overfitting to the source domain.

Generated samples based on target-domain images: To further demonstrate the effectiveness of our proposed framework, we conduct image generation based on the unseen target domain, where the generated samples using the pairs from the same unseen target domain are shown in Fig. 4 based on leave-one-domain-out training manner. From the visualization results, we find that our method can still separate the task-specific features and domain-specific features well even if the networks have never seen the samples from the target domain. More specifically, it can encode the intra-domain style variance based on the observation that the model can generate samples with different styles using the domain-specific features from the same target domain.Meanwhile, the results in Fig. 4 also illustrate that the sketch domain may have little domain-specific features and intra-domain style variance on account that the translated and reconstructed samples are almost the same. This observation further demonstrates the effectiveness of our proposed method by using Sketch as the target domain where a significant performance improvement can be achieved.

4.4.3 The visualization of feature embeddings:

In addition to the perceptual results of generated samples, we also utilize t-SNE (Van der Maaten & Hinton, 2008) to conduct analysis on the features extracted from two different branches E_c and E_d using our framework by using PACS where Photo is treated as the target domain. The visualization results are shown in Fig. 5 and several findings are observed: in Fig. 5(a) and 5(b), the features from source domains extracted by E_d can be well separated in terms of domain information but cannot be separated in terms of category information. On the contrary, as we can observe from Fig. 5(c) and 5(d), E_c can separate the features in terms of the category information instead of the domain information, which shows the effectiveness of our disentanglement framework.

5 Conclusion

In this paper, we propose to tackle the problem of domain generalization from the perspective of variational disentangling. Specifically, we first provide an evidence upper bound regarding the divergence between the distribution of category-specific feature and its invariant ground-truth through Bayes variational inference. Then, we propose an efficient framework to optimize the proposed evidence upper bound for domain generalization. Extensive experiments are conducted to verify the significance of our proposed method. Besides, we conduct experiments of image generation which further justify the effectiveness of our proposed disentanglement framework.

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A Detailed proof

A.1 Preliminary

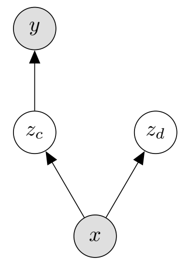

Figure 6: The graphical structure of our proposed model. The shaded nodes represent the observed random variables and others are latent random variables. There exist conditional dependences between the image x and the category-specific feature z_c and domain-specific feature z_d, respectively. We expect z_c and z_d are independent. In addition, the ground-truth label y only depends on the category-specific feature z_c.

Our probabilistic graphical model is represented as Fig. 6. It is notable that the mapping between z_c and x, and the mapping between z_d and x are all many-to-many, e.g., there are many plausible images if specify z_c or z_d alone. In addition, given an image x, there should exist many possible z_c and z_d, i.e., there exist conditional distributions $p(z_c|x)$ and $p(z_d|x)$ instead of a deterministic mapping. Or in other word, given a specific latent code pair $z = [z_c, z_d]$, there exists a conditional distribution $p(x|z)$. This assumption is reasonable since the latent codes $z = [z_c, z_d]$ are usually constrained into a lower-dimensional subspace compared with the image-space so that there may not exist a latent code z that can deterministically correspond to an image x.

Assumption A.1 *(Learnability) Denote the dimension of the image x and the latent feature z_c by d_x and d_c, respectively, let $\phi_c : \mathbb{R}^{d_x} \to L^1(\mathbb{R}^{d_c})$ be the mapping between an image x and its probability density function (PDF) $f(z_c|x)$, where L^1 denotes 1-norm integrable function space. A deterministic mapping $\phi_g : \mathbb{R}^{d_c} \to \mathbb{N}$ acts as a classifier to predict the category of the image based on its latent feature z_c. For a domain generalization problem with n_s source domains ($X_s = X_1 \cup X_2 ... \cup X_{n_s}$) and a target domain X_t, we say it learnable if*

$$\begin{aligned} &\exists \phi_c, \quad s.t. \\ &\mathbb{E}_{x \sim X_{i|y}}[\phi_c(x)] = \mathbb{E}_{x \sim X_{j|y}}[\phi_c(x)], \forall y \in Y, \forall i, j \in \{1, 2, ..., n_s, t\} \\ &\phi_g(\psi(\phi_c(x))) = y, \forall x \in X_s \cup X_t \end{aligned} \tag{12}$$

where $X_{i|y}$ represents the conditional distribution of images with the category y in the domain i, $\psi(\cdot)$ returns the mean value of the distribution.

In other words, we say the task is learnable if there exists a domain invariant category-specific encoder ϕ_c among source and unseen target domains that can achieve the same marginal distribution $p(z_c|y)$ for each domain. In addition, the extracted category-specific features can be used to correctly predict labels of the images from both source and unseen target domains. This assumption is mild since we only assume that the task is feasible. In addition, we have no additional constraints on the form of the solution.

For a learnable domain generalization task, we aim to find out the domain invariant mapping $\phi_c(\cdot)$ so that we could further train a domain-agnostic classifier. However, given limited data and limited function space, the mapping ϕ_c is intractable. To this end, we propose to use an encoder E_c to approximate the unknown ground truth mapping ϕ_c by Bayes variational inference. More specifically, we give an upper bound of $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$ where $P(\mathbf{z_c}|x) = \phi_c(x)$ and $Q(\mathbf{z_c}|x)$ is the conditional distribution embedded by the encoder E_c implemented by a deep neural network. A corresponding framework is further proposed to optimize the proposed evidence upper bound.

Our motivation is summarized as follows

- We first give an evidence upper bound of the KL divergence $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$ between the approximated conditional distribution of category-specific features z_c and its intractable ground-truth distribution in Lemma A.1 and Theorem A.1.

- We further relax the information gain term of the derived upper bound to make a balance between the two terms in the upper bound. Our relaxed loss is proved to be an upper bound of the original one as shown in Lemma A.2.
- Finally, we demonstrate that under a mild assumption, the upper bound of the divergence $\mathcal{D}(Q(\mathbf{z_c}|x^t)||P(\mathbf{z_c}|x^t))$ in the unseen target domain can also be bounded in Theorem A.2.

A.2 The upper bound of $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$

Lemma A.1 *The KL divergence $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$ can be represented as*

$$\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - E_{z_c \sim Q_{z_c|x}}[\log p(x|z_c)] + \log p(x). \tag{13}$$

Proof A.1

$$\begin{aligned}
\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x)) &= \int q(z_c|x) \log \frac{q(z_c|x)}{p(z_c|x)} \mathrm{d}z_c \\
&= \int q(z_c|x)[\log q(z_c|x) - \log p(z_c|x)] \mathrm{d}z_c \\
&= \int q(z_c|x)[\log q(z_c|x) - \log p(x|z_c) - \log p(z_c) + \log p(x)] \mathrm{d}z_c \\
&= \mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - E_{z_c \sim Q_{z_c|x}}[\log p(x|z_c)] + \log p(x)
\end{aligned} \tag{14}$$

The term $p(x)$ can come out of the expectation $E_{z_c \sim Q_{z_c|x}}$ on account that it does not depend on z_c. This completes the proof.

Based on Lemma 1, we can derive the evidence upper bound of $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$.

Theorem A.1 *The evidence upper bound of KL divergence $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$ between the distribution $Q(\mathbf{z_c}|x)$ and the ground-truth $P(\mathbf{z_c}|x)$ is as follows:*

$$\underbrace{\mathcal{D}(Q(\mathbf{z_c}|x)||P(z_c))}_{\text{① information gain term}} - \underbrace{E_{z_c \sim Q_{z_c|x}, z_d \sim P_d}[\log p(x|z)]}_{\text{② posterior probability term}} + C \tag{15}$$

where C is a constant, $z = [z_c, z_d]$, and P_d can be an arbitrary prior distribution.

Proof A.2

$$\begin{aligned}
&\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x)) \\
&= \underbrace{\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - E_{z_c \sim Q_{z_c|x}}[\log p(x|z_c)] + \log p(x)}_{\text{Using lemma 1}} \\
&= \mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - E_{z_c \sim Q_{z_c|x}}[\log[\int p(x, z_d|z_c) \mathrm{d}z_d]] + \log p(x) \\
&= \mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - E_{z_c \sim Q_{z_c|x}}[\log[\int \frac{p(x, z_d, z_c)}{p(z_c)}]] + \log p(x) \\
&= \mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - E_{z_c \sim Q_{z_c|x}}[\log[\int \frac{p(z_d)p(z_c|z_d)p(x|z)}{p(z_c)}]] + \log p(x) \\
&= \mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - E_{z_c \sim Q_{z_c|x}}\{\log[E_{z_d \sim P_d} \frac{p(z_c|z_d)}{p(z_c)} p(x|z)]\} + \log p(x) \\
&\leq \mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - \underbrace{E_{z_c \sim Q_{z_c|x}, z_d \sim P_d} \log[\frac{p(z_c|z_d)}{p(z_c)} p(x|z)]}_{\text{Using Jensen's inequality on account that } -\log \text{ is convex}} + \log p(x) \\
&= \mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) - \underbrace{E_{z_c \sim Q_{z_c|x}, z_d \sim P_d}[\log p(x|z_c, z_d)]}_{p(z_c|z_d) = p(z_c) \text{ because } z_c \text{ and } z_d \text{ are independent}} + \log p(x) \\
&= \underbrace{\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}))}_{\text{① information gain term}} - \underbrace{E_{z_c \sim Q_{z_c|x}, z_d \sim P_d}[\log p(x|z)]}_{\text{② posterior probability term}} + C
\end{aligned} \tag{16}$$

This completes the proof.

Assumption A.2 *$q(x|z_c)$ is bounded, i.e., for an image x there exists a constant M that satisfies $\frac{q(x|z_c)}{q(x)} < M$ for $\forall z_c$.*

The Assumption A.2 is mild due to the following reasons. First, x is generated based on both z_c and z_d. Therefore, the mapping between z_c and x is not deterministic, i.e., $q(x|z_c)$ can not be the impulse function δ. Second, when the random variables z_c and z_d extracted from two encoders E_c and E_d are disentangled in some degree, *i.e.*, $\sup_{z_c,z_d} \frac{q(z_c|z_d)}{q(z_c)} < k$ where k is a constant, we can obtain the following upper bound

$$\begin{aligned}
\frac{q(x|z_c)}{q(x)} &= \int \frac{q(x, z_d|z_c)}{q(x)} \mathrm{d}z_d \\
&= \int \frac{q(z_d)q(z_c|z_d)q(x|z_c, z_d)}{q(z_c)q(x)} \mathrm{d}z_d \\
&\leq kE_{z_d \sim Q_{z_d}} \frac{q(x|z_c, z_d)}{q(x)} \\
&\leq k \sup_{z_c,z_d} \frac{q(x|z_c, z_d)}{q(x)} = M
\end{aligned} \tag{17}$$

where $q(x|z_c, z_d)$ is the PDF of a predefined Laplace/Gaussian distribution so that it is bounded, and $q(x)$ is a constant for a given x. Thus, $\frac{q(x|z_c)}{q(x)}$ is bounded when z_c and z_d is disentangled to some degree. In addition, Eq. equation 17 also demonstrates that the better the disentanglement, the tighter upper bound we can obtain.

Lemma A.2 *The upper bound of the KL divergence $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}))$ based on Assumption A.2 can be represented as*

$$M\mathcal{D}(Q(\mathbf{z_c})||P(\mathbf{z_c})) + M \log M. \tag{18}$$

Proof A.3

$$\begin{aligned}
\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c})) &= \int q(z_c|x) \log \frac{q(z_c|x)}{p(z_c)} \mathrm{d}z_c \\
&= \int \frac{q(x|z_c)q(z_c)}{q(x)} \log \frac{q(x|z_c)q(z_c)}{q(x)p(z_c)} \mathrm{d}z_c \\
&\leq M[\int q(z_c) \log \frac{q(z_c)}{p(z_c)} \mathrm{d}z_c + \log M] \\
&= M\mathcal{D}(Q(z_c)||P(z_c)) + M \log M
\end{aligned} \tag{19}$$

The upper bound given in Lemma A.2 is used to balance the weight of two terms in the upper bound of $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}|x))$ given in Theorem A.1. It is difficult to accurately estimate the posterior probability term in Eq. 15 since the high dimensionality of the image and limited data. On the contrary, the calculation of $\mathcal{D}(Q(\mathbf{z_c}|x)||P(\mathbf{z_c}))$ is trivial and accurate, so it leads to a stable gradient. If we do not loose the information gain term in Eq. 15, the gradient accumulation will cause a over- sparse embedding of z_c. The ablation study in the main paper also demonstrate the necessity of the relaxation.

A.3 The upper bound in the unseen target domain

Assumption A.3 *Given a sample x^t from the target domain X_t, there exists a non-empty feasible set $\mathcal{I}$ which is defined as*

$$\mathcal{I} = \{I | q(z_c|x) \leq \sum_{i \in I} \beta_i q(z_c|x_i^s), \forall z_c \in \mathbb{R}^{d_c}\} \cap \{I | \phi_c(x^t) = \phi_c(x_i^s), \forall i \in I\},$$

where I is the index set, x_i^s denotes an arbitrary sample with index i in any source domains, and $q(z_c|x)$ is the probability density function value of z_c conditioned on x from distribution $Q(\mathbf{z_c}|x)$.

Theorem A.2 *Based on Assumption A.3, the KL divergence between $Q(\mathbf{z_c}|x^t)$ and the unknown domain-invariant ground truth distribution $P(\mathbf{z_c}|x^t)$ can be bounded as follows*

$$\mathcal{D}(Q(\mathbf{z_c}|x^t)||P(\mathbf{z_c}|x^t)) \leq \inf_{I\in\mathcal{I}}[\sum_{i\in I}\beta_i\mathcal{D}(Q(\mathbf{z_c}|x_i^s)||P(\mathbf{z_c}|x_i^s))].$$

The above theorem demonstrates that the KL divergence between $Q(\mathbf{z_c}|x)$ and $P(\mathbf{z_c}|x)$ from source domains constitutes the divergence upper bound in the unseen target domain. Therefore, it further supports the rationale and effectiveness of our method.

B Detailed architectures of the networks

To be more clear about the architecture of our framework, we give a simplified diagram about the relationship between class-specific encoder E_c, domain-specific encoder E_d and generator G. More details about the architecture of each network are elaborated in the following sub-sections.

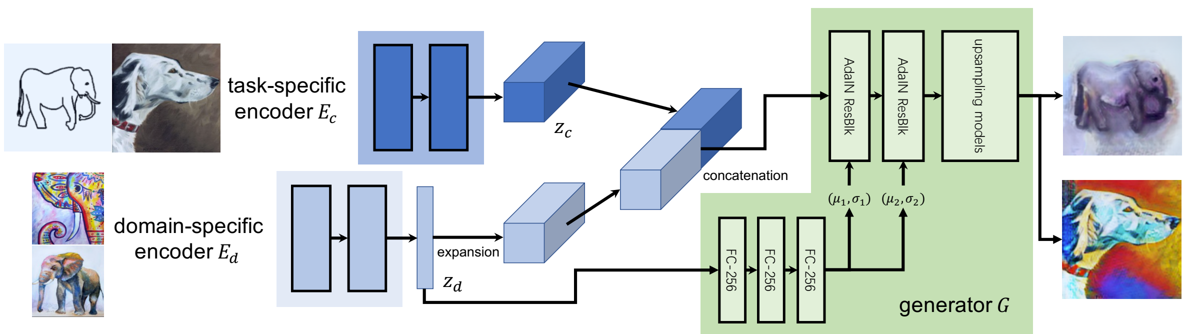

Figure 7: A simplified diagram regarding E_c, E_d and G. The input of the generator G consists of two parts: the output of the task-specific encoder z_c and the output of the domain-specific encoder z_d. The feature z_d is fed into a three-layer network to obtain the mean and variance used by AdaIN ResBlk following Liu et al. (2019). In addition, we reshape z_d to the same size with the feature map of z_c and then concatenate them together.

B.1 The architectures of E_c and E_t

B.1.1 The architectures of E_c and E_t for Digits-DG

We use ConvNet as the backbone for Digits-DG and divide it into two parts. The details about the division for E_c and E_t are illustrated in Table 6.

B.1.2 The architectures of E_c and E_t for PACS and mini-Domainnet

For PACS and mini-Domainnet, we use Resnet-18 as the backbone network and adopt the same division regarding E_c and E_t. The details about the division for E_c and E_t are illustrated in Table 7.

B.2 The architecture of the domain-specific encoder E_d

For all the experiments, we use the same domain-specific encoder. The details of the architecture are shown in Table 8. On account that we use a global average pooling layer to reduce the size of the feature map to 1×1, the domain-specific code z_d will lose the spatial information and hence only embed the global appearance which is relevant to the domain.

	#	Layer
task-specific encoder E_c	1	Conv2D(in=3, out=64, kernel_size=3, stride=1,padding=1)
	2	Relu
	3	MaxPool2D(kernel_size=2)
	4	Conv2D(in=64, out=64, kernel_size=3, stride=1,padding=1)
	5	Relu
	6	MaxPool2D(kernel_size=2)
	7	Conv2D(in=64, out=64, kernel_size=3, stride=1,padding=1)
	8	Relu
task-specific network E_t	9	MaxPool2D(kernel_size=2)
	10	Conv2D(in=64, out=64, kernel_size=3, stride=1,padding=1)
	11	Relu
	12	MaxPool2D(kernel_size=2)
	13	flatten the feature
	14	Fully connected layer(in=64*2*2, category number)

Table 6: The architecture of task-specific encoder E_c and task-specific network E_t for Digits-DG. They are obtained by separating the backbone ConvNet into two parts.

	#	Layer
task-specific encoder E_c	1	Conv2D(in=3, out=64, kernel_size=7, stride=2,padding=3)
	2	BatchNorm2d
	3	Relu
	4	MaxPool2d(kernel_size=3,stride=2,padding=1)
	5	Relu
	6	layer1 $\begin{bmatrix} 3\times 3 & 64 \\ 3\times 3 & 64 \end{bmatrix}$
	7	layer2 $\begin{bmatrix} 3\times 3 & 128 \\ 3\times 3 & 128 \end{bmatrix}$
task-specific network E_t	8	layer3 $\begin{bmatrix} 3\times 3 & 256 \\ 3\times 3 & 256 \end{bmatrix}$
	9	layer4 $\begin{bmatrix} 3\times 3 & 512 \\ 3\times 3 & 512 \end{bmatrix}$
	10	global average pooling
	11	Fully connected layer(in=512, category number)

Table 7: The architecture of the task-specific encoder E_c and the task-specific network E_t for PACS and mini-DomainNet. They are obtained by separating the backbone Resnet-18 into two parts.

#	Layer
1	Conv2D(in=3, out=64, kernel_size=7, stride=1,padding=3)
2	Relu
3	Conv2D(in=64, out=128, kernel_size=4, stride=2,padding=1)
4	Relu
5	Conv2D(in=128, out=256, kernel_size=4, stride=2,padding=1)
6	Relu
7	Conv2D(in=256, out=256, kernel_size=4, stride=2,padding=1)
8	Relu
9	global average pooling
10	Conv2D(in=256, out=128, kernel_size=1, stride=1,padding=0)

Table 8: The architecture of the domain-specific encoder E_d.

B.3 The architecture of the discriminator D_x

PatchGan discriminator (Isola et al., 2017) is adopted as D_x for all experiments. More specifically, the discriminator D_x which is responsible to distinguish real and generated images includes one convolutional layer and 8 activation first residual blocks (Mescheder et al., 2018) as shown in Table 9.

#	Layer
1	Conv2D(in=3, out=64, kernel_size=7, stride=1,padding=3)
2	ActFirstResBlock(in=64, out=128, activation=leakyRelu, norm=None)
2	ActFirstResBlock(in=128, out=128, activation=leakyRelu, norm=None)
3	ReflectionPad2d(padding=1)
4	AvgPool2d(kernel_size=3, stride=2)
5	ActFirstResBlock(in=128, out=256, activation=leakyRelu, norm=None)
6	ActFirstResBlock(in=256, out=256, activation=leakyRelu, norm=None)
7	ReflectionPad2d(padding=1)
8	AvgPool2d(kernel_size=3, stride=2)
9	ActFirstResBlock(in=256, out=512, activation=leakyRelu, norm=None)
10	ActFirstResBlock(in=512, out=512, activation=leakyRelu, norm=None)
11	ReflectionPad2d(padding=1)
12	AvgPool2d(kernel_size=3, stride=2)
13	ActFirstResBlock(in=512, out=1024, activation=leakyRelu, norm=None)
14	ActFirstResBlock(in=1024, out=1024, activation=leakyRelu, norm=None)
15	ReflectionPad2d(padding=1)
16	AvgPool2d(kernel_size=3, stride=2)
17	LeakyRelu(1024)
18	Conv2D(in=1024, out=domain number, kernel_size=1, stride=1,padding=1)

Table 9: The architecture of the discriminator D_x. **ActFirstResBlock**: activation first residual blocks (Mescheder et al., 2018)

Our discriminator is not only capable of distinguishing real and fake, but it can also distinguish whether the image comes from the specified domain (the number of output channel of our discriminator is the domain number as illustrated in Table 9). If z_c and z_d are not disentangled well, the arbitrarily combined pairs may not generate realistic images with corresponding domain labels, i.e., the disentanglement is supervised by the posterior probability term.

B.4 The architecture of the discriminator D_c

The discriminator D_c is built by multiple fully connected layers. The details are illustrated in Table 10. For the fake sample, the input of the discriminator D_c is the task-specific feature z_c after average-pooling and is concated with the domain label which acts as supervised information. For the real one, the input is the random variable sampling from a standard Gaussian distribution and concated with a random domain label.

B.5 The architecture of the generator G

We use roughly the same architecture of the generator G for Digits-DG and PACS/mini-DomainNet. The difference is mainly in the number of channels and the number of upsampling modules. The architecture of the generator is shown in Table 11. Note that the three-layer network for AdaIN ResBlk (Huang et al., 2018) is not included in the table.

#	Layer
1	Linear(in=input dim, out=512, bias=True)
2	Relu
3	Dropout(probability=0.2)
4	Linear(in=512, out=512, bias=True)
5	Relu
6	Dropout(probability=0.2)
7	Linear(512, 2)
8	activation layer $g_f(v) = -\exp(-v)$

Table 10: The architecture of the discriminator D_c. **input dim**: the number of source domains + the channel number of the feature $z_c = E_c(x)$

(a) The generator for Digits-DG

#	layer
1	AdaIN ResBlk(192)
2	AdaIN ResBlk(192)
3	Upsample(scale_factor=2, nearest)
4	Conv2D(in=192, out=96, kernal_size=5, s=1, p=2)
5	InstanceNorm
6	Relu
7	Upsample(scale_factor=2, nearest)
8	Conv2D(in=96, out=48, kernal_size=5, s=1, p=2)
9	InstanceNorm
10	Relu
11	Conv2D(in=48, out=3, kernal_size=5, s=1, p=2)
12	Tanh & Normalize

(b) The generator for PACS and mini-DomainNet

#	layer
1	AdaIN ResBlk(256)
2	AdaIN ResBlk(256)
3	Upsample(scale_factor=2, nearest)
4	Conv2D(in=256, out=128, kernal_size=5, s=1, p=2)
5	InstanceNorm
6	Relu
7	Upsample(scale_factor=2, nearest)
8	Conv2D(in=128, out=64, kernal_size=5, s=1, p=2)
9	InstanceNorm
10	Relu
11	Upsample(scale_factor=2, nearest)
12	Conv2D(in=64, out=32, kernal_size=5, s=1, p=2)
13	InstanceNorm
14	Relu
15	Conv2D(in=32, out=3, kernal_size=5, s=1, p=2)
16	Tanh & Normalize

Table 11: The architecture of the generator G except the three-layer network for AdaIn ResBlk (Liu et al., 2019).

Algorithm	A	C	P	S	Avg
ERM	83.2 ± 1.3	76.8 ± 1.7	**97.2** ± 0.3	74.8 ± 1.3	83.0
IRM	81.7 ± 2.4	77.0 ± 1.3	96.3 ± 0.2	71.1 ± 2.2	81.5
GroupDRO	84.4 ± 0.7	77.3 ± 0.8	96.8 ± 0.8	75.6 ± 1.4	83.5
Mixup	85.2 ± 1.9	77.0 ± 1.7	96.8 ± 0.8	73.9 ± 1.6	83.2
MLDG	81.4 ± 3.6	77.9 ± 2.3	96.2 ± 0.3	76.1 ± 2.1	82.9
CORAL	80.5 ± 2.8	74.5 ± 0.4	96.8 ± 0.3	78.6 ± 1.4	82.6
MMD	84.9 ± 1.7	75.1 ± 2.0	96.1 ± 0.9	76.5 ± 1.5	83.2
DANN	84.3 ± 2.8	72.4 ± 2.8	96.5 ± 0.8	70.8 ± 1.3	81.0
CDANN	78.3 ± 2.8	73.8 ± 1.6	96.4 ± 0.5	66.8 ± 5.5	78.8
MTL	85.6 ± 1.5	78.9 ± 0.6	97.1 ± 0.3	73.1 ± 2.7	83.7
SagNet	81.1 ± 1.9	75.4 ± 1.3	95.7 ± 0.9	77.2 ± 0.6	82.3
ARM	**85.9** ± 0.3	73.3 ± 1.9	95.6 ± 0.4	72.1 ± 2.4	81.7
VREx	81.6 ± 4.0	74.1 ± 0.3	96.9 ± 0.4	72.8 ± 2.1	81.3
RSC	83.7 ± 1.7	82.9 ± 1.1	95.6 ± 0.7	68.1 ± 1.5	82.6
VDN(Ours)	85.8 ± 0.6	**83.5** ± 0.7	96.7 ± 0.3	**85.6** ± 0.6	87.9

Table 12: Evaluation of domain generalization performance on PACS benchmark using ResNet-50 backbone. The mean value and corresponding standard error of the test accuracy are reported.

C Extra results

C.1 Results on PACS benchmark using Resnet-50 backbone

We further conduct experiments using ResNet-50 backbone and report the mean accuracy and std in the target domain when finish the training. The results of 5 repeated experiments are shown in Table 12 and the results demonstrate that our method achieves better performance than SOTA methods[2].

C.2 Extra visualization results

Besides the image generation task in the source domains or in the target domain that we have shown the results in the paper, we are also interested in the "cross-domain" performance, i.e., from source domains to unseen target domain and from unseen target domain to source domains. Assuming that we have two images x_i and x_j and their corresponding task-specific features z_{c_i}, z_{c_j} and domain-specific features z_{d_i}, z_{d_j}, the translated images with different mixture degrees are generated using $G(z_{c_i}, \lambda z_{d_i} + (1-\lambda) z_{d_j})$ where λ in $[0.0, 0.1, 0.2, ..., 1.0]$. Note that in this work, we do not use the generated samples with a mixture style for data augmentation nor use the discriminator to supervise the generated images with a mixture style. How to effectively utilize the sample of mixed style may be a potential research direction.

C.2.1 From the target domain to source domains

We first investigate the performance of our framework that translates the samples from the unseen target domain to source domains. The results are shown in Fig. 8. As we can observe, even if the framework has never seen the samples in the unseen target domain, it can still extract task-specific features that are compatible with the domain-specific features from source domains and then generate the samples with the style of source domains. This further verifies the robustness and generalization ability of our method.

C.2.2 From source domains to the target domain

We then explore the performance of our proposed framework that translates the image from source domains to the unseen target domain. The visualization results are shown in Fig. 9. As we can see, the framework may be difficult to generate samples of the unseen target domain. This is reasonable because our framework has never seen the sample distribution of the target domain and it is difficult to generate OOD samples with large domain gaps. However, our

[2]The results of other methods are from the camera ready version of the paper "In search of lost domain generalization", ICLR 2021.

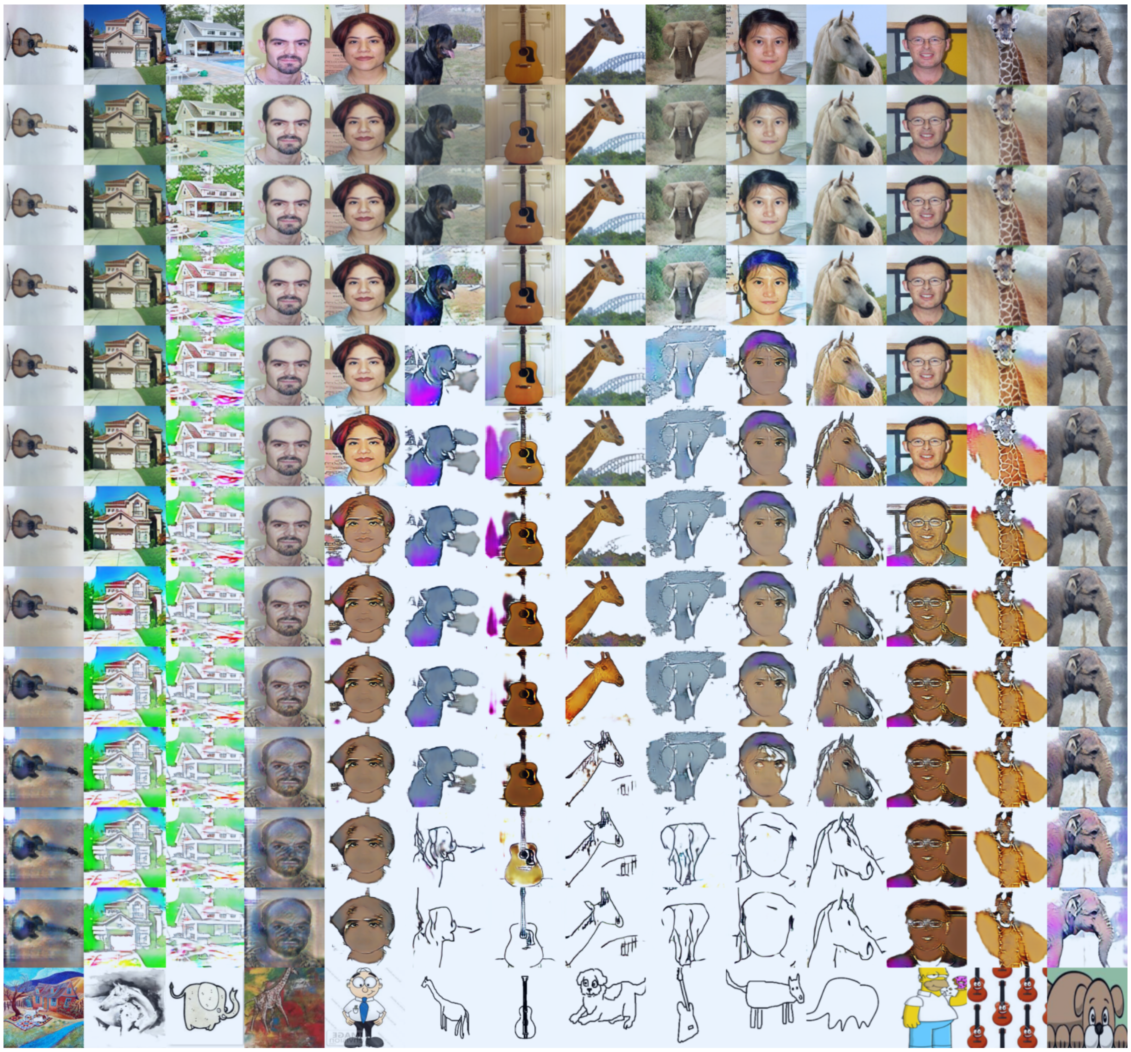

Figure 8: The visualization results of the image translation from the unseen target domain to source domains. The photo domain in PACS is used as the unseen target domain. The first row is the input image from the unseen target domain that provides the task-specific features and the last row is from source domains that provide the domain-specific features. Other rows are images that are generated images $G(z_{c_i}, \lambda z_{d_i} + (1 - \lambda) z_{d_j})$ using different mixture degrees.

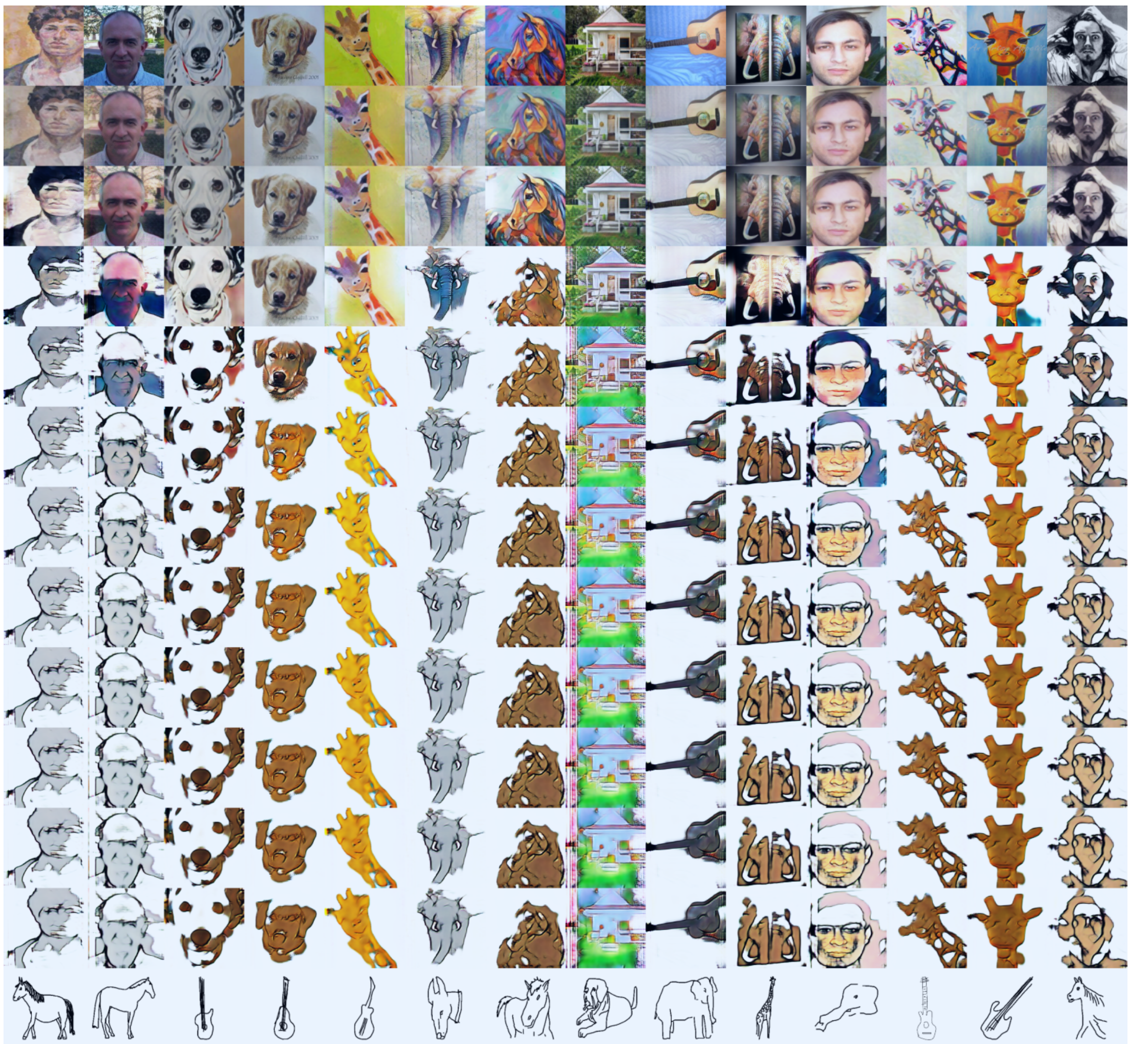

Figure 9: The visualization results of the image translation from source domains to the uneen target domain. The domain sketch in PACS is used as the unseen target domain. The first row is the input image from source domains that provide the task-specific features and the last row is from the unseen target domain that provides the domain-specific features. Other rows are images $G(z_{c_i}, \lambda z_{d_i} + (1-\lambda) z_{d_j})$ using different mixture degree.

proposed framework can generate samples from a new domain, i.e., the image that is not exactly the same as the sketch domain but has some similar characters such as having little task-irrelevant information.

D Experiment environment

We will release the code after the paper is accepted. Parts of the experiments are conducted on a Windows workstation with Ryzen 5900X, 64GB RAM, and an Nvidia RTX 3090. Others are conducted on a Linux server with Intel(R) Xeon(R) Silver 4210R CPU, 256GB RAM, and RTX 2080-TIs. For the software, PyTorch 1.9 is used. We do not find a significant difference of trained models under two different environments.