VirDA: Reusing Backbone for Unsupervised Domain Adaptation with Visual Reprogramming

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Abstract

Image classification is the foundation of nearly all computer-vision pipelines. While state-of-the-art models excel within their training domains, their performance often deteriorates when transferred to a new, unlabeled setting. Unsupervised domain adaptation (UDA) addresses this challenge by repurposing a well-trained source classifier for the target domain, enabling strong downstream results without the need for additional labeled data. Existing UDA pipelines fine-tune already well-trained backbone parameters for every new source-and-target pair, resulting in the number of training parameters and storage memory growing linearly with each new pair, and also preventing the reuse of these well-trained backbone parameters.

Inspired by recent implications that existing backbones have textural biases, we propose making use of domain-specific textural bias for domain adaptation via visual reprogramming, namely VirDA. Instead of fine-tuning the full backbone, VirDA prepends a domain-specific visual reprogramming layer to the backbone. This layer produces visual prompts that act as an added textural bias to the input image, adapting its "style" to a target domain. To optimize these visual reprogramming layers, we use multiple objective functions that optimize the intra- and inter-domain distribution differences when domain-adapting visual prompts are applied. This process does not require modifying the backbone parameters, allowing the same backbone to be reused across different domains.

We evaluate VirDA on Office-31 and obtain 92.8% mean accuracy with only 1.5M trainable parameters. VirDA surpasses PDA, the state-of-the-art parameter-efficient UDA baseline, by +1.6% accuracy while using just 46% of its parameters. Compared with full-backbone fine-tuning, VirDA outperforms CDTrans and FixBi by +0.2% and +1.4%, respectively, while requiring only 1.7% and 2.8% of their trainable parameters. Relative to the strongest current methods (PMTrans and TVT), VirDA uses 1.7% of their parameters and trades off only 2.2% and 1.1% accuracy, respectively.

1 Introduction

Recent advancements in image classification have significantly enhanced model performance through supervised learning, driven primarily by large amounts of labeled data (He et al., 2016; Dosovitskiy et al., 2020; Liu et al., 2021; Han et al., 2022). However, these supervised approaches struggle when applied to new, unlabeled domains due to domain shifts (Ganin & Lempitsky, 2015). This challenge is particularly prominent in fields involving emerging technologies, such as medical imaging for newly discovered diseases, where acquiring labeled data is costly and time-consuming (Abedi et al., 2024).

To address this limitation, Unsupervised Domain Adaptation (UDA) (Ganin & Lempitsky, 2015; Ganin et al., 2016; Saito et al., 2018), aims to adapt well-trained source domain classifiers to the target domains, given that no labels of the target domain are available. Prior UDA methods aim to transfer well-learned representations, the hidden features that are shareable between the source and target domains, and are invariant to the domain-specific style (e.g., differences in studio-lighting versus practical lighting condition (Venkateswara et al., 2017), coloring style between synthetic versus real-world imagery (Saenko et al., 2010)). Existing

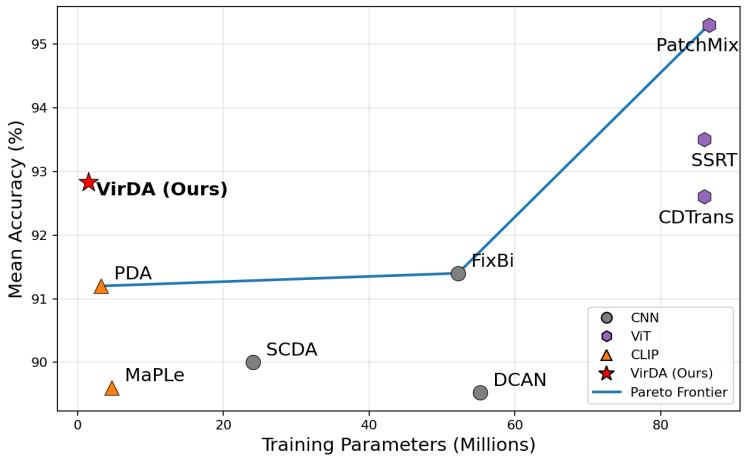

Figure 1: The Pareto chart of existing methods, with VirDA displaying the trade-off between accuracy and the number of training parameters. Notably, our method excels over other parameter-efficient fine-tuning methods using CLIP as the backbone (e.g., PDA and MaPLe), as well as other methods that require full fine-tuning (e.g., FixBi and CDTrans) at minimal computation cost. Moreover, VirDA required only 1.7% training parameters (1.5M to 86.6M) while sacrificing 2.2% accuracy compared to the SoTA method.

works (Zhang et al., 2019; Yang et al., 2023b; Na et al., 2021) facilitate this transfer by adapting the hidden features produced by the backbone in a typical image classification framework (Deng et al., 2009; Krizhevsky et al., 2012) through various means, e.g., feature distribution alignment (Chen et al., 2019a;b; Sun et al., 2017) and adversarial training (Long et al., 2018; Ganin & Lempitsky, 2015). Others utilize the pretrained Vision-Language models to use the common textual label set to guide the adaptation (Ge et al., 2022b; Du et al., 2024b; Bai et al., 2024b).

While these methods work well and achieve high accuracies, the transfer requires fine-tuning both the well-trained classifier along with fine-tuning the backbone, either a convolutional neural network (CNNs) (Long et al., 2018; Ganin & Lempitsky, 2015) or Vision Transformer backbones (Yang et al., 2023b; Zhu et al., 2023b; Xu et al., 2021; Liang et al., 2020), for each new domain. This limits backbone reusability, as well as requiring a large amount of storage to store the trained backbone across different source-target domain pairs.

In this paper, we propose Visually Reprogrammed Domain Adaptation (VirDA), which aims to facilitate backbone reuses through a lightweight visual reprogramming layer. Recent findings show that even well-trained backbones that produce robust features still have textural bias, making them overly reliant on textural patterns for each domain and each category inside the domain (Geirhos et al., 2018). We thus exploit these textural biases for domain adaptation through visual reprogramming (Cai et al., 2024b): each visual reprogramming layer consists of a domain-specific textural pattern that aims to capture the domain-specific textural bias, and a per-instance mask generator that adaptively applies this textural pattern over the input image. Applying this visual reprogramming layer is thus equivalent to shifting the style of the input image (either from the source or the target domain) towards a common style, learned by the backbone (Figure 2 for an illustration). More specifically, this visual reprogramming is prepended to the backbone and thus does not require backbone modification or fine-tuning. Thus, our resulting architecture for each domain is composed of three modules in a cascaded manner: (1) a domain-specific visual reprogramming layer, (2) a frozen, reusable backbone, and (3) a domain-specific classifier. To perform UDA and to train these visual-reprogramming layers and domain-specific classifiers, we design two key objectives: (1) an inter-domain alignment objective that aligns the learned hidden features and classification uncertainty from both the source and target domains, and (2) an intra-domain alignment objective that aims to learn domain-specific features through self-supervised loss.

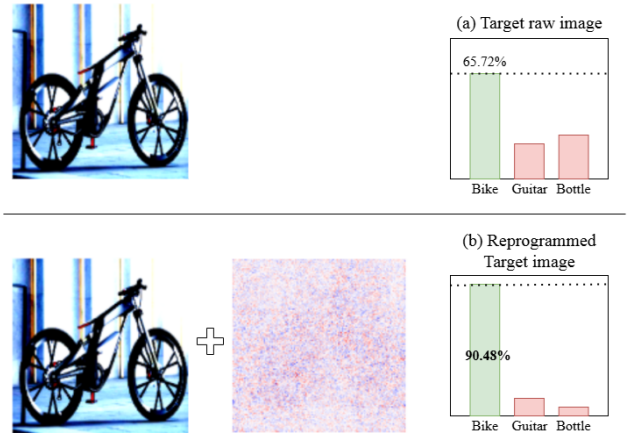

Figure 2: Classification result of a well-trained model on the source domain enhances when applied to the target domain, due to using a pixel-wise textural mask.

We conduct experiments to evaluate VirDA's capability in classification effectiveness, training parameter size, and storage requirement for each source and target domain pair. Our experiments demonstrate that the proposed VirDA, requiring only a maximum of 1.5 million of training parameters (less than 2% of PMTrans (Zhu et al., 2023b)) and only 6 MB for storage per domain (compared to over 340 MB of both PMTrans and CDTrans (Xu et al., 2021)), and fully reusing the backbone's parameters, achieves comparable performance to state-of-the-art (SOTA) methods across standard domain adaptation benchmarks, including Office-31 (Saenko et al., 2010), Office-Home (Venkateswara et al., 2017), and Digits (MNIST (LeCun et al., 1998), USPS (Netzer et al., 2011), SVHN (Hull, 1994)). The main contributions of this paper are summarized as follows.

- We propose a novel UDA method that efficiently addresses domain shifts by exploiting inherent textural biases in pretrained models, enabling lightweight yet effective domain adaptation.
- To the best of our knowledge, we are the first to perform domain adaptation with an entire single-modality frozen backbone by integrating visual reprogramming within the framework.
- We evaluate our method on three widely used benchmarks, confirming the effectiveness of our method with only a fraction of the training parameters, while achieving competitive performance compared to existing methods (as shown in Figure 1).

The remaining of this paper is structured as follows: Section 2 reviews related works to ours; Section 3 presents the detailed architecture and methodology of VirDA; Section 4 provides comprehensive experimental results and extensive ablation studies; and finally, Section 5 summarizes our conclusion as well as future research directions.

2 Related Works

In this section, we summarize three related research directions to VirDA, namely, unsupervised domain adaptation, parameter-efficient fine-tuning for domain adaptation, and visual reprogramming.

Unsupervised Domain Adaptation As introduced in Section 1, existing UDA methods aim to align the well-learned hidden representation of the backbone's output. (Long et al., 2015) and (Long et al., 2017) proposes Deep Adaptation Network (DAN) and Joint Adaptation Network (JAN) that align different task-specific hidden representations by aligning their embedding distances with Maximum Mean Discrepancy (MMD), (Wen et al., 2019) instead uses uncertainty matching to align hidden features. (Ganin & Lempitsky, 2015), on the other hand, performs feature alignments through the use of inverse gradient from an adversarial domain discriminator, aiming to make the source and target features indistinguishable. (Long et al., 2018)

improves per-class feature representation by clustering hidden features for adversarial training. (Tzeng et al., 2017) combines both feature distribution alignment and adversarial training. (Saito et al., 2018) and (Li et al., 2020) aim to further improve the precision of feature alignment using the classifier's disagreement to pinpoint and domain-specific attention modules (Saito et al., 2018; Li et al., 2020). Other works employ self-ensembling frameworks, improving consistency of predictions under perturbations with contrastive losses and self-supervised losses (Cui et al., 2020b; Yue et al., 2021; Xu et al., 2021), leveraging temporal smoothing to stabilize representations (Tarvainen & Valpola, 2017), and adapting Batch Nuclear-norm Maximization on the output matrix to improve prediction results (Cui et al., 2020a). Finally, recent methods combine both inter- and intra-domain alignment strategies (Na et al., 2021; Yang et al., 2023b). We adapt these alignment strategies, specifically, we perform inter-domain alignments on the visual reprogramming layers with uncertainty matching and adversarial training, as well as intra-domain alignment with self-supervised loss and consistency objectives.

Parameter-efficient fine-tuning (PEFT) for domain adaptation As an alternative to fully fine-tuning the backbone, recent PEFT approaches leverage large vision–language models' multimodal inference capability and instead learn a small number of prompt or fine-tuning image-text adapter modules. MaPLe (Khattak et al., 2023) injects and finetunes a small set of context prompting tokens for each text-encoding layer to better align the hidden representation of domain-specific visual and text-based tokens. DAPL (Ge et al., 2022a) also aims to modify CLIP for UDA, however, they finetune class-aware and domain-aware textual prompts with pseudo-labels. PDA (Bai et al., 2024a) aims to better learn cross-domain shift by combining learned prompts with a lightweight image-guided feature tuning branch that performs distribution alignment under pseudo-labels. DAMP (Du et al., 2024a) pushed the idea further by replacing image-guided feature tuning with a more powerful multi-domain transformer decoder. Our method can also be seen as fine-tuning "prompts" as a means to perform UDA. However, instead of learning a textual prompt that applies to a large pretrained multimodal model, we apply the visual prompt to highlight that domain adaptation is feasible via lightweight visual reprogramming of the input/patch-embedding space, where a small set of learnable image-side tokens steers a (mostly) frozen backbone—achieving parameter-efficient, backbone-agnostic adaptation. Because our approach does not make the assumption of using a multi-modal vision-language model, it can be applied to any of the existing backbones, i.e., both convolutional neural network-based backbone or vision transformer-based backbone.

Visual Reprogramming Visual Reprogramming (VR) is a method that repurposes pretrained vision backbones by learning small input-side modifications (e.g., additive prompts or adversarial "programs") so that the fixed or lightly adapted model performs a new downstream task without full retraining (Cai et al., 2024b). Recent works in VR focusing on learning perturbations guided by descriptive and distinctive attributes to improve alignment in Vision-Language Model (Cai et al., 2025), or incorporating adversarial examples to improve the robustness of re-programmed models (Zhou et al., 2025). However, these methods are only applicable to supervised training, and leave a research gap when applied to the unsupervised characteristics of UDA. Other visual prompting techniques have been applied to UDA, for example, in image classification (Gao et al., 2022), or image segmentation (Ma et al., 2023), employing visual prompting inside transformer architectures by inserting prompts into intermediate layers to facilitate cross-domain alignment. While VirDA also uses visual reprogramming for UDA, we aim to leave the backbone unmodified to facilitate its reuse; instead, we rely on the aforementioned domain alignment objectives to train the visual reprogramming layers.

3 Methodology

The unsupervised domain adaptation (UDA) problem for image classification (Ganin & Lempitsky, 2015) takes as input two datasets: a labeled dataset $\mathcal{D}_S = \{(\mathbf{x}_i^{(s)}, \mathbf{y}_i^{(s)})\}_{i=1}^{N_s}$ from a source domain $\mathcal{S}$ along with an unlabeled target domain $\mathcal{T}$'s dataset $\mathcal{D}_T = \{\mathbf{x}_j^{(t)}\}_{j=1}^{N_t}$, where each $\mathbf{x}^{(s)}$ and $\mathbf{x}^{(t)}$ is the input data samples (i.e., images) from the source and target domain respectively, and $\mathbf{y}^{(s)}$ is the sample label (i.e., image labels). We denote the mini-batch of input images be $\mathbf{B}^{(s)} = \{\mathbf{x}_1^{(s)}, \mathbf{x}_2^{(s)}, \ldots, \mathbf{x}_k^{(s)}\}$ and $\mathbf{B}^{(t)} = \{\mathbf{x}_1^{(t)}, \mathbf{x}_2^{(t)}, \ldots, \mathbf{x}_k^{(t)}\}$ for the source and target domains, respectively, with the $y^{(s)} = \{\mathbf{y}_1^{(s)}, \mathbf{y}_2^{(s)}, \ldots, \mathbf{y}_k^{(s)}\}$ be the corresponding source labels. Although the unsupervised setting of the target domain $\mathcal{T}$, we assume that the two domains

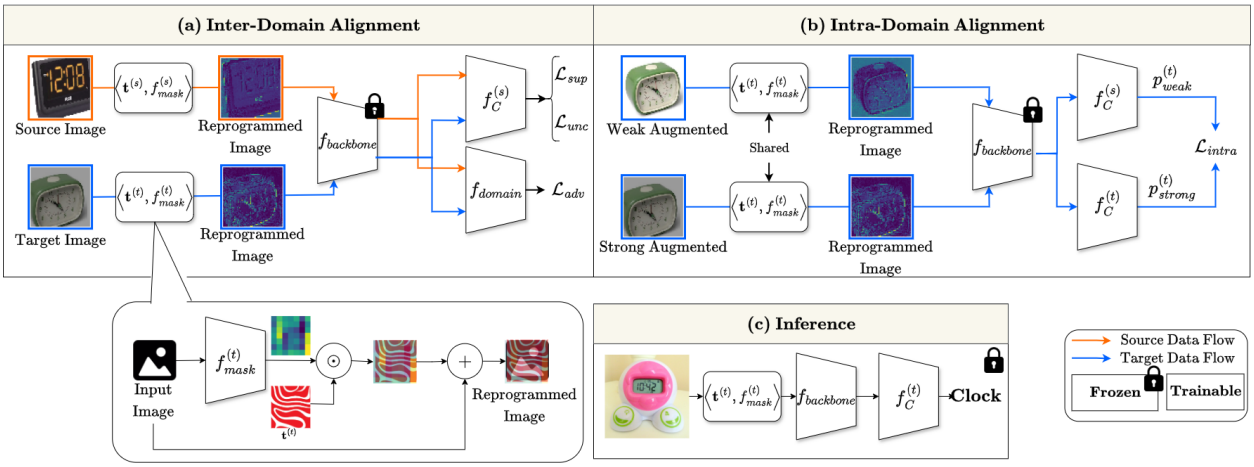

Figure 3: The overall pipeline of VIRDA.

share an identical label space $\mathcal{Y}$. As previously described, VIRDA consists of a visual reprogramming layer that produces visual prompts describing textural and spatial shifts between different domains. We describe this representation briefly in Section 3.1.

To optimize this visual reprogramming layer, we follow the formulation of existing works and attempt to align the hidden features produced by applying these layers in Section 3.2. (See Figure 3). These hidden features are aligned intra-domain with domain-specific data augmentations, and inter-domain by aligning hidden features produced with different domain-specific visual reprogramming layers.

3.1 Encoding Domain-specific Textural and Transformational Visual Prompt

Visual Prompt Representation Assuming the input image is represented as a tensor $\mathbf{x} \in \mathbb{R}^{w \times h \times c}$, where c is the number of color channels (usually 3), a visual reprogramming module is a pair $\langle \mathbf{t}, f_{mask} \rangle$, where $\mathbf{t} \in \mathrm{R}^{w \times h \times c}$ is the domain-specific textural pattern, while $f_{mask} : \mathbb{R}^{w \times h \times c} \rightarrow [0,1]^{w \times h \times c}$ is the mask producer.

Visual mask-producing Layer A mask-producing layer f_{mask} is a function that takes as input an image and produces the mask, is a fully convolutional subnetwork of L_{vr} layers, where each layer $l \in \{1, ..., L_{vr}\}$ performs a 3×3 convolution with padding of 1. The feature map is then downsampled into non-overlapping patches of size $2^{N_{vr}} \times 2^{N_{vr}}$, allowing the network to learn a compact summary of local texture and shape cues within each patch. In our experiments, we follow Cai et al. (2024b) to set $L_{vr} \in \{5, 6\}$, while $N_{vr} \in [1, 5]$. While deeper reprogramming layers with larger patches excel at capturing coarse, object-level patterns, shallower layers with smaller patches preserve finer, more detailed features.

Structural mask-producing Layer Although a visual reprogramming layer can mask visual appearance shifts, the cross-domain mismatches are also displayed in spatial layout and feature dependency, so that the downstream model still learns the wrong structural priors. For instance, images captured for production purposes often feature the object placed in the center, whereas real-world images typically show objects in random positions. To model this structural shift, we follow Hou et al. (2021), specifically, we add two cascaded learnable position-shifting masks, namely, $\mathbf{A_h}$ for vertical shift and $\mathbf{A_w}$ for horizontal shift. Applying these position-shifting masks is analogous to shifting different parts of the input images. We apply these masks as follow:

$$f_{coord}(\mathbf{x}) = \mathbf{x} \odot \mathbf{A_h} \odot \mathbf{A_w} \tag{1}$$

where $\odot$ is the element-wise multiplication operation, $\mathbf{A_h} \in \mathbb{R}^{c \times h \times 1}$ and $\mathbf{A_w} \in \mathbb{R}^{c \times 1 \times w}$ are the position-sensitive channel attentions derived from axis-wise pooled features.

Visual reprogramming layer The visual re-programming layer f_{pre} works as follows:

$$f_{pre}(\mathbf{x}) = f_{coord}(\mathbf{x}) + \mathbf{t} \odot f_{mask}(f_{coord}(\mathbf{x})) \tag{2}$$

The textural pattern $\mathbf{t}$ and both the mask-producing layers f_{mask}, f_{coord} are domain-specific. Hence, for each domain $d \in \{s, t\}$ we denote $\mathbf{t}^{(d)}$, $f_{mask}^{(d)}$ and $f_{coord}^{(d)}$ for domain d's pattern and mask-producing layers, and $f_{pre}^{(d)}$ as the visual reprogramming layer for domain d.

Intuitively, each visual prompt is an added structural-aware textural bias, where the specific application is produced per instance. The textural bias, hypothetically, should capture the domain-specific style that the backbone has biases towards, following the finding of the existing work (Geirhos et al., 2018).

3.2 Visually-aligning Model

Unlike previous visual reprogramming works (Cai et al., 2024b;a; Zhou et al., 2025; Cai et al., 2025) that assume the availability of target-domain labels, our approach must function in an unsupervised setting. Consequently, our classifier architecture requires sufficient flexibility to leverage both shared (domain-invariant) and unique (domain-specific) features effectively (Xiao et al., 2021). To achieve this, we introduce a visual reprogramming module that explicitly couples domain-invariant features, combined with loosely coupled, domain-specific classifier heads that capture specialized features.

Full model architecture Thus, we design an architecture that couples the common features through a visual-reprogramming module, while also enabling learning to make use of domain-specific features, through lowly-coupled domain-specific classifiers. Following Eq. 2, we denote the domain-specific visual-reprogramming module for the source domain s and the target domain t as $f_{pre}^{(s)}$ and $f_{pre}^{(t)}$, respectively. We also denote the domain-specific classifiers for the source and target domains as $f_C^{(s)}$ and $f_C^{(t)}$, respectively. Thus, our model architecture is as depicted in Figure 3: for each domain, we cascade three modules: a domain-specific visual-reprogramming module f_{pre}, a reused domain-invariant backbone $f_{backbone}$, and finally a domain-specific classifier f_C. To train this architecture, we have to model two goals: (1) we have to perform inter-domain alignment, and (2) we have to perform intra-domain alignment.

Inter-domain alignment Since we do not re-train our backbone, as such, inter-domain alignment implies different objectives for the visual reprogramming modules and the domain-specific classifier, respectively. For the source and target visual re-programming modules $f_{pre}^{(s)}$ and $f_{pre}^{(t)}$, this alignment means that these modules have to be able to "shift" the input image style from their respective domain to that of a common image style that was learned by the shared backbone. For the domain-specific classifiers $f_C^{(s)}$ and $f_C^{(t)}$, this means that they have to learn to use the shared or aligned inter-domain features. Concretely, the inter-domain loss is implemented via three objectives:

$$\mathcal{L}_{inter} = \mathcal{L}_{sup} + \mathcal{L}_{adv} + \mathcal{L}_{unc} \tag{3}$$

To keep the source classifier well-trained during adaptation, which is crucial to transfer the feature-label information when $f_{pre}^{(s)}$ learned the common style, we first implement supervised loss on the source data:

$$\mathcal{L}_{sup} = \frac{1}{k} \sum_{i=1}^{k} \mathbf{CE}(\mathbf{y}_i^{(s)}, p_i^{(s)}), \tag{4}$$

where $p_i^{(d)} = f_C^{(d)}(\mathbf{z}_i^{(d)})$ and $\mathbf{z}_i^{(d)} = \big(f_{backbone} \circ f_{pre}^{(d)}\big)(\mathbf{x}_i^{(d)})$ is the prediction and features obtained for each sample in the domain d's batch $\mathbf{B}^{(d)}$, respectively. The $\mathcal{L}_{adv}$ is the adversarial domain discriminator loss, used to help the visual-reprogramming modules to shift their respective domain images into a common domain and produce indistinguishable hidden features. This loss is modeled via binary cross-entropy over the predictions produced by a domain-specific discriminator f_{domain}. Hypothetically, both the source- and target- visual reprogramming modules will produce aligned hidden features that can "fool" the domain discriminator f_{domain}, defined as:

$$\mathcal{L}_{adv} = \frac{1}{k} \sum_{i=1}^{k} \big[\log f_{domain}(\mathbf{z}_i^{(s)}) + \log\big(1 - f_{domain}(\mathbf{z}_i^{(t)})\big)\big] \tag{5}$$

If the domain discriminator can still distinguish the produced features, then the backpropagated signals will be used to train both f_{domain} and the visual-reprogramming modules through reverse gradient (Ganin & Lempitsky, 2015). Given that the source and target domain hidden features are aligned, the source classifier $f_C^{(s)}$ should be generalized to both domains to leverage the use of labels. This means that it can both learn robust domain-invariant features produced by the target visual re-programming module $f_{pre}^{(t)}$, while remaining well-trained on source domain inputs. Following prior work (Wen et al., 2019), we propose to use the uncertainty loss $\mathcal{L}_{unc}$. This objective is implemented to align $f_C^{(s)}$'s uncertainty in different domains, i.e., the distribution of $f_C^{(s)}$'s uncertainty should be the same on both the source and target-reprogrammed domain. Indirectly, this objective will also enforce inter-domain alignment between two visual-reprogramming modules. Recall that we have a batch of input images from both domains, $\mathbf{B}^{(s)}$ and $\mathbf{B}^{(t)}$. We perform M stochastic forward passes of the full module and sample the per-instance, per-class uncertainty on both the reprogrammed source batch $\tilde{\mathbf{B}}^{(s)}$ and the reprogrammed target batch $\tilde{\mathbf{B}}^{(t)}$. For each instance i and class c, we collect the M predictive samples $\{p_{m,c}(y \mid \mathbf{x}_i)\}_{m=1}^{M}$ and treat them as draws from a per-instance, per-class uncertainty distribution. We use these point-wise uncertainty estimation to estimate the full uncertainty distributions $\hat{q}_{i,c}^{(s)}$ and $\hat{q}_{i,c}^{(t)}$. We then align uncertainties by minimizing the class-averaged KL divergence:

$$\mathcal{L}_{unc} = \frac{1}{k\,|\mathcal{Y}|} \sum_{i=1}^{k} \sum_{c \in \mathcal{Y}} \mathbb{KL}\big(\hat{q}_{i,c}^{(s)} \,\big\|\, \hat{q}_{i,c}^{(t)}\big), \tag{6}$$

This encourages matched predictive uncertainty across domains and indirectly aligns the two visual-reprogramming modules. In practice, we place Dropout layers with different probabilities p_{mask} and p_C in both $f_{mask}^{(d)}$ and $f_C^{(s)}$, respectively to measure uncertainty (Gal & Ghahramani, 2016).

Intra-domain alignment To enhance the performance of our model on the target domain, we employ intra-domain objectives to transfer the already-well-trained source classifier $f_C^{(s)}$'s classification capability to the target domain classifier $f_C^{(t)}$, while also allowing the target domain classifier to learn intra-domain robust feature. Specifically, the intra-domain alignment loss is:

$$\mathcal{L}_{intra} = \mathcal{L}_{unsup} + \mathcal{L}_{distrib} \tag{7}$$

where both of our objectives enforce consistency through different views of a sample. This is done by augmenting the target domain image through both strong augmentations, such as affine transformation or color jitter, and weak augmentations, which are the original image. The resulting augmented images' hidden features are then passed through both the source classifier $f_C^{(s)}$ and the target classifier $f_C^{(t)}$. Assuming the features are well aligned to a certain level through prior objectives, we use $f_C^{(s)}$ to produce pseudo labels for the target classifier $f_C^{(t)}$. The $\mathcal{L}_{unsup}$ is thus to optimize $f_C^{(t)}$ to minimize both the difference in prediction of $f_C^{(t)}$ and $f_C^{(s)}$, as well as reducing $f_C^{(t)}$'s uncertainty over augmented target images while the $\mathcal{L}_{distrib}$ penalises any disagreement between the target classifier $f_C^{(t)}$ and the source classifier $f_C^{(s)}$. More concretely, let f_{weak} denote the weak augmentation and f_{strong} denote the strong augmentation. From $\mathbf{B}^{(t)}$, we obtain the weak-view prediction $p_{i,weak}^{(t)} = \big(f_C^{(s)} \circ f_{backbone} \circ f_{pre}^{(t)} \circ f_{weak}\big)(\mathbf{x}_i^{(t)})$ and the strong-view prediction $p_{i,strong}^{(t)} = \big(f_C^{(t)} \circ f_{backbone} \circ f_{pre}^{(t)} \circ f_{strong}\big)(\mathbf{x}_i^{(t)})$. Thus, the distribution divergence loss is:

$$\mathcal{L}_{distrib} = \frac{1}{k} \sum_{i=1}^{k} \mathbb{KL}(p_{i,weak}^{(t)} \,\big\|\, p_{i,strong}^{(t)}) \tag{8}$$

We also perform threshold-based uncertainty filtering to keep the most confident pseudo labels, which we obtain as $\hat{y}_i^{(t)} = \arg\max p_{i,weak}^{(t)}$. The unsupervised loss is defined as:

$$\mathcal{L}_{unsup} = \frac{1}{k} \sum_{i=1}^{k} \mathbf{CE}(\hat{y}_i^{(t)}, p_{i,strong}^{(t)}) \tag{9}$$

3.3 Inference

At inference time, we perform on the target domain using both the target visual reprogramming layer and the target classifier for label prediction:

$$\hat{y}_i = \arg\max\big(f_C^{(t)} \circ f_{backbone} \circ f_{pre}^{(t)}(x_i)\big), \tag{10}$$

where $\hat{y}_i$ is the predicted class of the unlabeled target sample.

4 Experiments

We evaluate our proposed method on widely used three domain adaptation benchmarks, namely Office-31, Office-Home, and Digits, compared with state-of-the-art UDA methods in both accuracy and number of training parameters. In addition, we validate the contributions of the proposed method through extensive ablation studies. We describe detailed dataset characteristics and implementation details below.

4.1 Datasets

Digits is a dataset composed from three other digit datasets, which are MNIST (LeCun et al., 1998), USPS (Hull, 1994), and Street View House Numbers (SVHN) (Netzer et al., 2011). In terms of domain characteristics, MNIST (M) contains grayscale digit images with a clean background; SVHN (S) consists of cropped coloured digits from real scenes with extremely blurred appearance; USPS (U) provides grayscale handwritten digit images with unconstrained writing styles. Whilst sharing the same 10 (0-9) digit classes, the three datasets present significantly different data distributions, therefore suitable for UDA evaluation. For the UDA test, we adopted three commonly used cross-dataset transfer settings with the standard data split: S→M, U→M, M→U.

Office-31 (Saenko et al., 2010) is the most popular dataset for real-world domain adaptation. It contains 4,110 images of 31 categories in three domains: Amazon (A), Webcam (W), DSLR (D). We evaluated all methods on six domain adaptation tasks.

Office-Home (Venkateswara et al., 2017) is a more challenging benchmark than Office-31. It consists of images of everyday objects organized into four domains: artistic images (Ar), CLIP art (Cl), product images (Pr), and real-world images (Rw). It contains 15,500 images of 65 classes.

4.2 Implementation Details

In all experiments, we use both Resnet (He et al., 2016) and ViT (Dosovitskiy et al., 2020) models pre-trained on ImageNet (Deng et al., 2009) as the fixed backbone for VirDA. For the Digits tasks, we use ResNet-18 with a learning rate of $3e^{-4}$ for the classifier heads and $5e^{-4}$ for the visual reprogramming modules, using a batch size of 128. The dropout rate for the classifier and the mask generator is set as $p_{mask} = 0.5$ and $p_C = 0.3$, respectively. On the Office-Home and Office-31 datasets, we adopt ViT-B/32 as the backbone for all transfer tasks. We set the same learning rate as above, using a batch size of 32 and $p_{mask} = 0.3$ with $p_C = 0.1$. For all experiments, we adopt AdamW (Loshchilov & Hutter, 2017) with the default configuration of (β_1, β_2) is $(0.9, 0.999)$, and a weight decay of $1e^{-5}$. On the Office-31 and Office-Home datasets, we set L_{vr} and N_{vr} corresponding to 6 and 5, for coarse object-level mask, while on Digits we set $L_{vr} = 5$ and $N_{vr} = 4$, as the dataset's characteristics demonstrate mild transformation. On all tasks, we set the number of forward passes to estimate uncertainty $M = 8$.

4.3 Results

To provide comparison, we compare VirDA with the widely-recognized state-of-the-art methods on Office-31 and Office-Home datasets that use different backbones. Specifically, we include MSTN (Xie et al., 2018), DCAN (Li et al., 2020), SCDA (Li et al., 2020), FixBi (Na et al., 2021) as baselines for the Resnet backbone; ViT-based, SSRT (Sun et al., 2022), PMTrans (Zhu et al., 2023a), CDTrans (Xu et al., 2022), TVT (Yang et al., 2023a) as the baselines for the ViT backbone; DAMP (Du et al., 2024a), PDA (Bai et al., 2024a),

MaPLe (Khattak et al., 2023), DAPL (Ge et al., 2022a) as the baselines for parameter-efficient fine-tuning on the CLIP backbone. Note that on all of our transfer tasks, we keep the backbone frozen, and we estimate the number of training parameters of our method on the visual prompt layers and the classifier heads.

Results on Digits. We display the performance of VirDA on Digits tasks in Tab. 1, where it achieves a mean accuracy of 93.4% on the benchmark using only 0.2M training parameters. VirDA records 96.8% on M→U, 97.1% on U→M, and 86.4% on S→M. This performance is on par with or better than CyCADA (Hoffman et al., 2018), GTA (Sankaranarayanan et al., 2018), and MCD (Saito et al., 2018), all of which use twice the number of parameters. Compared to DANN, which uses the most parameters in our benchmarks, VirDA delivers higher accuracy on all tasks. While MCD achieves a slightly higher mean (95.6%), VirDA remains competitive across all shifts while operating with the smallest model size among the compared methods.

Table 1: Accuracy (%) on Digits for UDA (ResNet backbone). The best result is marked in **bold**.

Method	Training Params (M)	M→U	U→M	S→VM	Mean
DANN	21.0	90.4	94.7	84.2	89.8
CyCADA	0.4	95.6	96.5	90.4	94.2
GTA	0.4	95.3	96.4	92.4	94.7
MCD	0.4	96.5	94.1	**96.2**	**95.6**
VirDA (Ours)	**0.2**	**96.8**	**97.1**	86.4	93.4

Results on Office-31. As shown in Tab. 2, our method is capable of achieving 100% and 99.0% on mild shift tasks D→W and W→D while requiring only 1.5 training parameters. We also achieve strong results on A→W (94.7%) and A→D (98.1%), similar to the performance of fine-tuning methods such as SCDA and FixBi, while outperforming PEFT methods, namely PDA and MaPLe. VirDA lags SoTA on the toughest reverse shifts by 2 to 4% (D→A at 81.3% and W→A at 84.1%), however, outperforming all ResNet fine-tune methods and PEFT methods, with a fraction of training parameters.

Table 2: Accuracy (%) on Office-31 for UDA with ResNet, ViT, and CLIP backbones. The best results are in **bold**.

Method		**Parameter size (M)**	**Training params (M)**	**A→W**	**D→W**	**W→D**	**A→D**	**D→A**	**W→A**	**Mean**
MSTN	ResNet	59.24	59.2	91.3	98.9	**100.0**	90.4	72.7	65.6	86.5
DCAN	ResNet	55.2	55.2	95.0	97.5	**100.0**	92.6	77.2	74.9	89.5
SCDA	ResNet	24.0	24.0	94.2	98.7	99.8	95.2	75.7	76.2	90.0
FixBi	ResNet	52.2	52.2	96.1	99.3	**100.0**	95.0	78.7	79.4	91.4
ViT-based	ViT	86.0	86.0	91.2	99.2	**100.0**	90.4	81.1	80.6	90.4
SSRT	ViT	86.0	86.0	97.7	99.2	**100.0**	98.6	83.5	82.2	93.5
CDTrans	ViT	86.0	86.0	96.7	99.0	**100.0**	97.0	81.1	81.9	92.6
TVT	ViT	86.0	86.0	96.4	99.4	**100.0**	96.4	84.9	86.0	93.9
PMTrans	ViT	86.6	86.6	**99.1**	**99.6**	**100.0**	**99.6**	**85.7**	**86.3**	**95.0**
PDA	CLIP	153.0	3.2	92.1	98.1	99.8	91.2	83.5	82.5	91.2
MaPLe	CLIP	154.4	4.7	88.6	97.7	99.4	86.9	83.0	82.0	89.6
DAPL	CLIP	124.3	0.3	80.3	81.8	81.8	81.3	81.2	81.0	81.2
VirDA (Ours)		87.6	1.5	94.7	99.0	**100.0**	98.1	81.3	84.1	92.8

Results on Office-Home. VirDA attains a **79.6%** mean accuracy on Office-Home while updating only **3.2M** training parameters, i.e., about **27×fewer** than full ViT/PMTrans fine-tuning (86.6M), as shown in Tab. 3. It decisively outperforms classic ResNet baselines—e.g., +9.1% over DCAN (70.5%) and +6.9% over FixBi (72.7%)—and is competitive with CLIP adapters on several transfers, achieving 85.7% (Ar→Pr), 88.5% (Pr→Rw), and 88.6% (Rw→Pr). VirDA remains robust on harder directions such as Rw→Ar (80.3%),

narrowing the gap to heavier ViT/CLIP methods. The primary weakness is on tasks where the target dataset is Clipart (e.g., Pr→Cl 61.4%, Rw→Cl 63.6%), where specialized adapters like PMTrans and DAMP still lead. Overall, VIRDA offers a standout accuracy–efficiency trade-off—delivering near-ViT performance while updating about **4%** of PMTrans's trainable parameters.

Table 3: Accuracy (%) on Office-Home for UDA with ResNet, ViT, and CLIP backbones. The best results are in **bold**.

Method		Parameter size (M)	Training params (M)	Ar→Cl	Ar→Pr	Ar→Rw	Cl→Ar	Cl→Pr	Cl→Rw	Pr→Ar	Pr→Cl	Pr→Rw	Rw→Ar	Rw→Cl	Rw→Pr	Mean
MSTN	ResNet	59.24	59.2	49.8	70.3	76.3	60.4	68.5	69.6	61.4	48.9	75.7	70.9	55.0	81.1	65.7
DCAN	ResNet	55.2	55.2	54.5	75.7	81.2	67.4	74.0	76.3	67.4	52.7	80.6	74.1	59.1	83.5	70.5
SCDA	ResNet	24.0	24.0	57.5	76.9	80.3	65.7	74.9	74.5	65.5	53.6	79.8	74.5	59.6	83.7	70.5
FixBi	ResNet	52.2	52.2	58.1	77.3	80.4	67.7	79.5	78.1	65.8	57.9	81.7	76.4	62.9	86.7	72.7
ViT-based	ViT	86.0	86.0	67.0	85.7	88.1	80.1	84.1	86.7	79.5	67.0	89.4	83.6	70.2	91.2	81.1
SSRT	ViT	86.0	86.0	75.2	89.0	91.1	85.1	88.3	89.9	85.0	74.2	91.2	85.7	78.6	91.8	85.4
CDTrans	ViT	86.0	86.0	68.8	85.0	86.7	81.5	87.1	87.3	79.6	63.3	88.2	82.0	66.0	90.6	80.5
TVT	ViT	86.0	86.0	74.9	86.8	89.5	82.8	88.0	88.3	79.8	71.9	90.1	85.5	74.6	90.6	83.6
PMTrans	ViT	86.6	86.6	**81.2**	91.6	**92.4**	**88.9**	91.6	**93.0**	**88.5**	**80.0**	**93.4**	**89.5**	**82.4**	**94.5**	**88.9**
PDA	CLIP	153.0	3.2	73.5	91.4	91.3	86.0	91.6	91.5	86.0	73.5	91.7	86.4	73.0	92.4	85.7
MaPLe	CLIP	154.4	4.7	72.2	**91.6**	90.3	82.6	90.9	89.8	82.4	71.6	90.1	85.1	72.0	92.1	84.2
DAPL	CLIP	124.3	0.3	70.7	91.0	90.9	85.2	91.0	90.9	85.1	70.7	90.9	85.3	70.4	91.4	84.5
DAMP	CLIP	131.1	6.7	75.7	**94.2**	92.0	86.3	**94.2**	91.9	86.2	76.3	92.4	86.1	75.6	94.0	87.1
VirDA (Ours)		87.6	1.5	62.8	85.7	88.9	80.9	87.0	86.4	81.5	61.4	88.5	80.3	63.6	88.6	79.6

4.4 Ablation studies

Effect of Losses. Tab. 4 illustrates how different combinations of loss functions affect the accuracy of A→D task on the Office-31 dataset. Using only $\mathcal{L}_{sup}$, which improves the source-only model by a small margin, about 1.6% (from 90.6% to 92.2%). The incorporation of $\mathcal{L}_{adv}$ decreases the overall accuracy by 2%, indicating that enforcing to bridge between the representation of source and target features is inadequate. This would make the visual appearance of source and target data look similar, but neglect the intra-label appearance boundaries. Introducing the inter-domain alignment loss, $\mathcal{L}_{unc}$, significantly improves accuracy to 93.8%, demonstrating its effectiveness in narrowing the domain gap. Employing a single intra-domain alignment signal, either $\mathcal{L}_{unsup}$ or $\mathcal{L}_{distrib}$, yields marginal improvements of 3.1% and 1.9%, respectively. However, combining both intra-domain alignment losses enhances performance notably by 4.3%, resulting in the highest accuracy achieved in this task.

Table 4: Incremental accuracy gains for each additional loss term on A→D task on Office-31. The best results are in **bold**.

Added Loss	Included Losses	Δ Acc. (%)	Total Acc. (%)
Source-only	–	–	90.6
$\mathcal{L}_{sup}$	$\mathcal{L}_{sup}$	+1.6	92.2
$\mathcal{L}_{adv}$	$\mathcal{L}_{sup} + \mathcal{L}_{adv}$	−2.0	90.2
$\mathcal{L}_{unc}$	$\mathcal{L}_{inter}$	+3.6	93.8
$\mathcal{L}_{unsup}$	$\mathcal{L}_{inter} + \mathcal{L}_{unsup}$	+3.1	96.9
$\mathcal{L}_{distrib}$	$\mathcal{L}_{inter} + \mathcal{L}_{distrib}$	+1.9	95.7
$\mathcal{L}_{intra}$	$\mathcal{L}_{inter} + \mathcal{L}_{intra}$	+4.3	**98.1**

Effect of Structural mask-producing layer. We evaluate the effectiveness of f_{coord} on 3 out of 6 most challenging tasks in Office-31 dataset, specifically D→A, W→A and A→W in Tab.5. With ResNet50, adding f_{coord} yields a modest gain on W→A (+2.10%) and a small lift on D→A (+0.32%), with a negligible change on A→W (−0.26%). Critically, when paired with ViT-B/32, f_{coord} delivers substantial improvements across all three shifts, D→A (+7.1%), W→A (+2.70%), and A→W (+3.77%), setting the best results in every column. This highlights that our coordination module scales especially well with transformer backbones, offering clear, consistent gains on the hardest transfers.

Table 5: Ablation on Office-31 with/without the structural mask-producing layer f_{coord}. The best results are in **bold**.

Backbone	f_{coord}	**D→A**	**W→A**	**A→W**
ResNet50	×	63.17	62.32	83.07
ResNet50	✓	63.49	64.42	82.81
ViT-B/32	×	74.15	81.36	90.89
ViT-B/32	✓	**81.25**	**84.06**	**94.66**

Figure 4: Visualization of the original image, the reprogrammed mask before (upper row) and after (lower row) UDA task on Rw→Pr. The source domain masks focus on encoding the surrounding areas, while the target domain masks highlight the main object.

Visualization. Figure 4 visualizes reprogrammed masks before and after training on source and target samples. Initially (upper rows), the masks exhibit diffuse, unclear patterns. Post-adaptation, source masks emphasize background regions, while target masks focus on modifying primary objects. Masks effectively alter simpler objects like "Soda" or "Telephone", but face challenges with visually different objects like "Computer" or "Printer", and multiple-object scenarios such as "Scissors".

5 Conclusion and Future Work

In this paper, we propose a novel method, VIRDA, a parameter-efficient solution for UDA that's capable of reusing a single pretrained backbone for all transfer settings. By introducing lightweight, domain-specific visual reprogramming layers that prepend to the frozen backbone, VIRDA adapts source knowledge to target domains through texture-level transformations rather than full network fine-tuning. We add intra- and inter-domain losses to guide the reprogramming function under the unsupervised constraint. Moreover, we leverage the prediction uncertainty to stabilize the training procedure. Our experiments demonstrate that VIRDA achieves competitive or superior performance compared to prior methods, and approaches the performance of state-of-the-art approaches while using only a fraction of the parameters. In the future, we

plan to implement our VirDA to tackle the challenging downstream tasks, e.g., semantic segmentation and object detection.

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