U³CF : Unbiased, Unconfounding, and Unified Causal Framework for Multi-Target Domain Adaptation

Wenxu Wang, Yeqiang Liu, Rui Zhou, Jing Wang, Zhenbo Li†, Wenbo Gong

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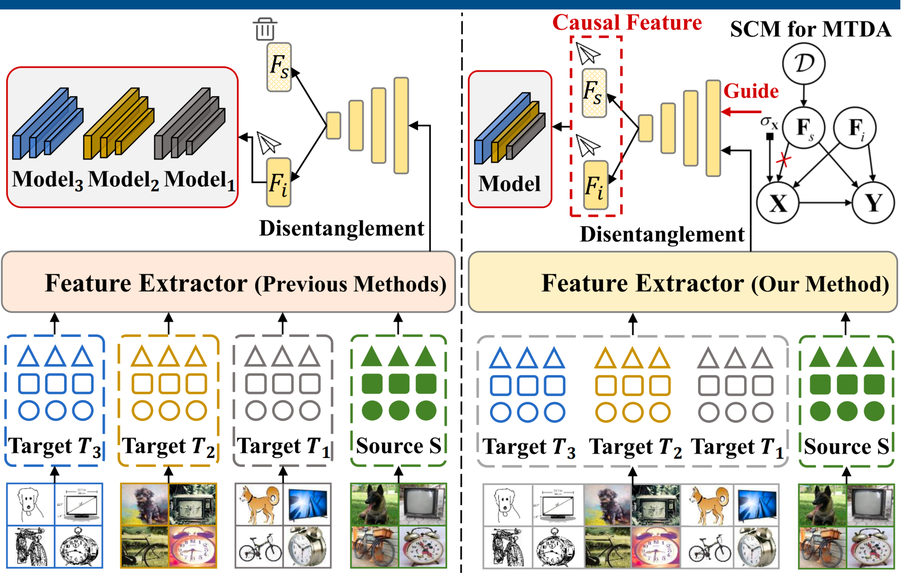
1. Motivation



2. Theoretical Perspective

P1: Contrastive MI Lower Bound

Each target feature $\mathbf{z}_{ti}$ is aligned with its positive source prototype $\mathbf{c}_s^{k+}$ against $K-1$ negative prototypes.

$$I\left(\mathbf{z}_{ti}; \mathbf{c}_s^{k+}\right) \geq \log K - \mathbb{E}[\mathcal{L}_{ali}(\mathbf{z}_{ti})]$$

Takeaway. Minimizing $\mathcal{L}_{ali}$ increases the mutual information between $\mathbf{z}_{ti}$ and $\mathbf{c}_s^{k+}$, promoting cross-domain semantic alignment.

P2: Conditional Intervention with Domain Averaging

F_s is a domain-specific confounder between X and Y, while F_i encodes domain-invariant information.

$$P(Y \mid F_i = \mathbf{f}_i; \sigma_X) = \frac{1}{K_D}\sum_{j=1}^{K_D} P\left(Y \mid F_s = \hat{\mathbf{f}}_{sj}, F_i = \mathbf{f}_i, X = g(\mathbf{f}_i)\right)$$

Takeaway. Averaging over domain prototypes mitigates domain-specific confounding and promotes invariant causal prediction.

P3: Invariant–Specific Feature Disentanglement Bound

The disentanglement loss provides an upper bound on the mutual information between invariant and domain-specific features:

$$I(\mathbf{f}_i; \mathbf{f}_s) \leq \mathcal{L}_{dis} - H(\mathbf{x})$$

Takeaway. Minimizing $\mathcal{L}_{dis}$ reduces the dependency between invariant feature $\mathbf{f}_i$ and domain-specific feature $\mathbf{f}_s$.

P4: Variational bounds for label relevance and label irrelevance

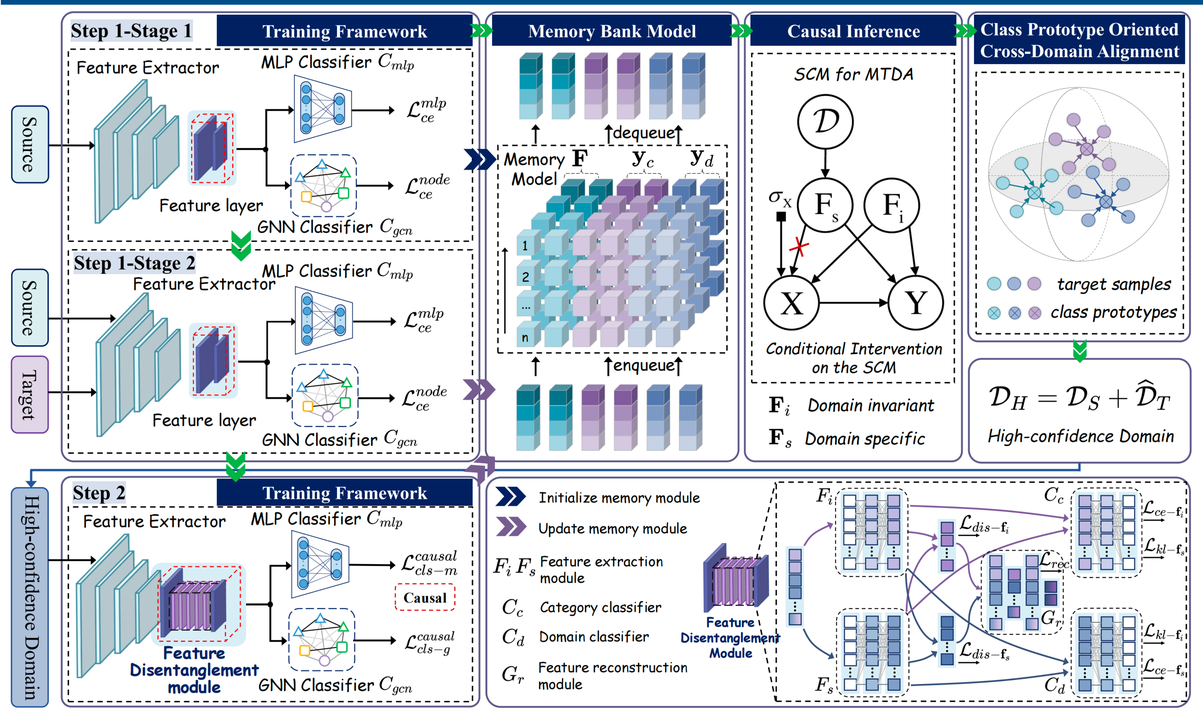
Takeaway. Cross-entropy minimization preserves label-discriminative information.

$$I(\mathbf{f}; \mathbf{y}) \geq H(\mathbf{y}) + \mathbb{E}_{p(\mathbf{f},\mathbf{y})}\left[\log q(\mathbf{y}|\mathbf{f})\right]$$

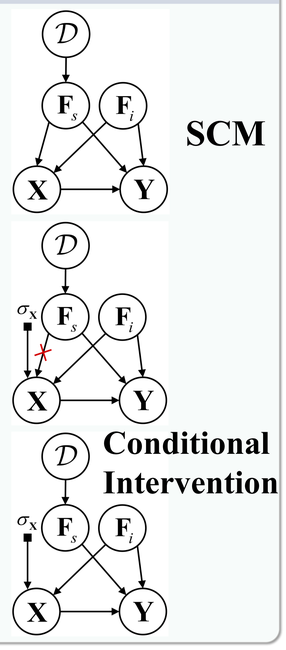
$$I(\mathbf{f}; \mathbf{y}) \leq \mathbb{E}_{p(\mathbf{f})}\left[D_{\mathrm{KL}}\left(p(\mathbf{y}|\mathbf{f}) \,\|\, r(\mathbf{y})\right)\right]$$

Takeaway. KL-based bound suppresses label information and encourages label-agnostic features.

3. Unbiased, Unconfounding, and Unified Causal Framework

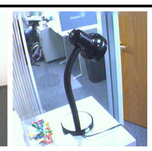
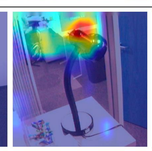
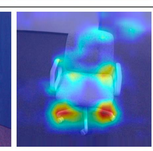
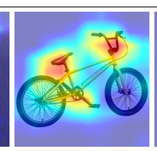
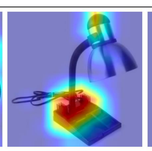
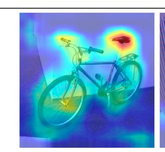
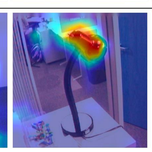
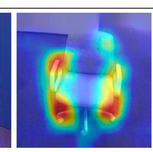


Soft Intervention



- **Causal perspective:** We propose a novel SCM for MTDA and introduce a soft intervention strategy.
- **Theoretical perspective:** We provide principled guarantees, including above four **Propositions**.
- **Methodological perspective:** We present U³CF, which integrates *Class Prototype Oriented Cross-Domain Alignment* and *Mutual Information-based Feature Disentanglement Mechanism.*
- **Experimental perspective:** Experiments show that U³CF consistently outperforms leading baselines.

4. Experments

Tasks	Office-31 (Amazon)			Office-31 (Webcam)		
Categories	bike	lamp	chair	bike	lamp	chair
Original Images						
CDAN (Long et al., 2018)						
U³CF (Ours)						

5. Contact

wangwenxu@ouc.edu.cn