Dual Energy-Based Model with Open-World Uncertainty Estimation for Out-of-distribution Detection

Supplementary Material

8. The derivation of Equation (20)

Based on Equation (3), we have

$$\partial_{\theta} D_{\mathrm{KL}} \left(p_{\mathrm{data}} \left(x, y^{+} \right) \| p_{\theta}(\tilde{x}, y^{+}) \right)$$

= $\mathbb{E}_{x, y^{+} \sim p_{\mathrm{data}}(x, y^{+})} \left[\partial_{\theta} E_{\theta}(x, y^{+}) \right]$
- $\mathbb{E}_{\tilde{x}, y^{+} \sim p_{\theta}(x, y^{+})} \left[\partial_{\theta} E_{\theta}(\tilde{x}, y^{+}) \right]$ (30)

Building upon the result presented in Equation (30), we can leverage this gradient to guide the model towards minimizing the discrepancy between the data distribution $p_{\text{data}}(x, y^+)$ and the model distribution $p_{\theta}(\tilde{x}, y^+)$. Then we have

$$\mathbb{E}_{x,y^{+} \sim p_{\text{data}}(x,y^{+})} \Big[E_{\theta}(x,y^{+}) \Big] - \mathbb{E}_{\tilde{x},y^{+} \sim p_{\theta}(x,y^{+})} \Big[E_{\theta}(\tilde{x},y^{+}) \Big]$$
(31)

$$= \mathbb{E}_{x,y^{+} \sim p_{\text{data}}(x,y^{+})} \left[\left(-\log \mathsf{P}_{\text{conf}}(y^{+}|x) \right) \right] \\ - \mathbb{E}_{\tilde{x},y^{+} \sim p_{\theta}(x,y^{+})} \left[-\log \mathsf{P}_{\text{conf}}(y^{+}|\tilde{x}) \right] \\ = \mathbb{E}_{x,y^{+} \sim p_{\text{data}}(x,y^{+})} \left[-\log \mathsf{P}_{\text{conf}}(y^{+}|x) \right] \\ + \mathbb{E}_{\tilde{x},y^{+} \sim p_{\theta}(x,y^{+})} \left[\log(1 - \sum_{k \neq y^{+}} \mathsf{P}_{\text{conf}}(y^{+}|\tilde{x})) \right] \\ \leq \mathbb{E}_{x,y^{+} \sim p_{\text{data}}(x,y^{+})} \left[\left(-\log \mathsf{P}_{\text{conf}}(y^{+}|x) \right) \right] \\ + \mathbb{E}_{\tilde{x},y^{+} \sim p_{\theta}(x,y^{+})} \left[\left(\log(1 - \mathsf{P}_{\text{conf}}(y^{-}|\tilde{x})) \right) \right]$$
(32)

The inequality in the final step arises from the fact that $\sum_{k \neq y^+} \mathsf{P}_{\mathsf{conf}}(y^+ | \tilde{x}) \geq \mathsf{P}_{\mathsf{conf}}(y^- | \tilde{x})$. This derivation provides an upper bound for the difference between the expectations under the data distribution and the model distribution.

9. More Results of DEBO

More results on different hyper-parameters λ_1 and λ_2 in Equation (25), as illustrated in Table 4.

The impact of hyperparameter γ . As shown in Figure 2, we investigate the influence of different hyperparameters γ in Equation (29) on the performance of OOD detection. The experimental results indicate that on the CIFAR10 and CIFAR100 datasets, when γ is fixed at 1, the AUROC performance metric exhibits more excellent performance. On the ImageNet-200 dataset, however, when γ takes a value of 0.3, the OOD detection performance reaches its

Datasets	λ_1	λ_2	$\text{FPR95}{\downarrow}$	AUROC↑	AUPR-In↑	AUPR-Out \uparrow	ID-ACC↑
	0.1	0.1	15.51	96.07	94.20	96.58	94.67
CIEA D 10	0.5	0.5	16.24	95.94	94.55	96.20	94.59
CIFARIO	1.0	1.0	16.69	96.10	93.54	96.65	94.49
	0.1	1.0	14.41	96.67	94.53	97.19	94.86
	0.1	0.1	47.93	85.77	80.94	87.11	75.98
CIEA D 100	0.5	0.5	38.13	88.42	83.45	89.45	75.48
CIFAR100	1.0	1.0	33.73	89.76	86.30	89.97	76.26
	0.1	1.0	43.68	87.35	81.72	88.39	75.06
ImageNet-200	0.1	0.1	41.12	88.10	83.24	87.03	86.26
	0.5	0.5	42.70	86.65	82.03	85.00	85.96
	1.0	1.0	42.59	86.99	82.46	86.16	85.27
	0.1	1.0	42.12	87.09	82.77	86.29	85.87

Table 4. More results on different hyper-parameters λ_1 and λ_2 in Equation (25).

optimum. This fully demonstrates that the introduction of the hyperparameter γ can significantly enhance the model's adaptability to different data distributions.



Figure 2. The impact of hyperparameter γ .

Different numbers of negative classes. We further conduct an ablation study to investigate the impact of varying the number of negative classes in our proposed DEBO, as illustrated in Table 5. Notably, when the number of negative classes is set to 1, we deviate from the conditional entropy minimization approach defined by C_{en} in Equation (24). Instead, we employ a cross-entropy loss function to maximize the confidence of the (K+1)-th class. This modification can be formally expressed as:

$$\mathbb{E}_{\tilde{x} \sim p_{\text{conf}}(x)} \left[-\log \mathbb{P}_{\text{conf}}(K+1|x) \right]$$
(33)

The remaining components of the DEBO loss function remain consistent across all configurations. We systematically adjust the negative classes to correspond with the dif-

	Number of negative classes	FPR95↓	AUROC↑	AUPR-In↑	AUPR-Out↑	ID-ACC↑
	1	16.11	96.18	94.22	96.73	93.97
CIFAR10	K	14.41	96.67	94.53	97.19	94.86
	2K	18.10	96.03	93.22	96.68	94.81
CIFAR100	1	45.22	85.27	81.60	85.77	75.48
	K	33.73	89.76	86.30	89.97	76.26
	2K	43.41	86.01	81.31	86.38	74.38
ImageNet-200	1	41.77	87.85	82.92	86.58	86.09
	K	41.12	88.10	83.24	87.03	86.26
	2K	41.44	87.93	83.06	86.79	81.81

Table 5. Ablation study on the number of negative classes inDEBO framework.

ferent class configurations examined in this analysis. As evidenced in Table 5, our results demonstrate that setting the number of negative classes to K yields the best performance.

Different model architectures. In this section, comparative experiments are further conducted using CIFAR100 as the ID training dataset on different model architectures, specifically ResNet-34. As shown in Table 6, compared with the comparison methods, our DEBO consistently demonstrates superior performance.

Methods	$FPR95\downarrow$	AUROC↑	AUPR-In↑	AUPR-Out↑	ID-ACC↑
MSP	55.76	78.97	73.71	81.03	77.32
EBO	55.65	80.17	73.54	82.39	77.32
CIDER	57.83	79.35	72.66	81.11	N/A
OE	53.13	83.18	76.02	86.05	77.93
EBO (w. D_{aux})	48.47	84.72	77.41	87.14	72.03
UDG	67.03	74.58	67.21	76.81	72.60
MIXOE	66.65	74.60	67.08	77.09	75.51
MCD	54.86	78.40	72.53	79.24	75.68
S_{dec} (ours)	42.75	87.63	82.46	88.86	77.17

Table 6. Comparative experiments using different model architectures (ResNet-34) with CIFAR100 as the ID training dataset.

Different OOD auxiliary training data. We further conduct comparative experiments using different auxiliary OOD training datasets with CIFAR100 as the ID training dataset. This OOD dataset consists of data generated by a generative model, as presented in the paper "DREAM-OOD"[6]. As shown in Table 7, compared with the baseline methods, our method consistently demonstrates superior performance.

Methods	$FPR95\downarrow$	AUROC↑	AUPR-In↑	AUPR-Out↑	ID-ACC↑
OE	42.40	83.81	78.07	87.50	76.76
EBO (w. D_{aux})	42.81	83.71	78.12	86.69	74.58
UDG	50.25	82.97	77.01	86.68	65.42
MIXOE	51.09	82.49	76.81	84.53	75.72
MCD	51.61	79.79	74.60	80.55	76.30
S_{dec} (ours)	38.91	86.25	81.40	88.42	76.24

Table 7. Comparative experiments using different auxiliary OOD training datasets with CIFAR100 as the ID training dataset.

Methods	ACC. \uparrow	IS↑
JEM [9]	92.9	8.76
Ours	92.34	8.77

Table 8. Results on CIFAR10. The ACC. denotes the classification accuracies and IS is widely used metric for evaluating the performance of generative models.

10. Results of Dual Energy-Based Model

We employ the proposed Dual Energy-Based Model to train a hybrid discriminative-generative model, demonstrating its capability to jointly model both label and data distributions. Table 8 presents the accuracy and generation performance of our Dual Energy-Based Model using a Wide-ResNet 28-10 backbone architecture on the CIFAR-10 dataset. Figure 3 illustrates the qualitative results of the generated data.

It is noteworthy that training this hybrid discriminativegenerative model necessitates increased computational resources and time due to the incorporation of SGLD sampling in the training process. Moreover, the primary focus of this paper remains on OOD detection, specifically the Dual Energy-Based Model for OOD Detection (DEBO) method proposed herein.



Figure 3. Generated images of our proposed Dual Energy-Based Model.

11. Hardware and Software

All experiments are conducted using PyTorch and Python 3.8, leveraging the computational capabilities of NVIDIA A6000 GPUs.

12. Results on Individual Datasets.

We present comprehensive comparative results of several representative methods on each OOD test dataset, as shown in Table 9, specifically for the CIFAR100 dataset.

MSPcifar1063.2777.1077.8274.75mnist51.3176.8355.1594.261syhn61.5775.8563.8189.94lexture65.2175.3484.1560.49places36557.6178.6860.2891.34LSUN-resize49.6882.8684.1881.71iSUN50.9982.0284.7678.67LSUN-resize49.6882.8684.1881.71mist51.2175.6353.8093.43syhn53.1384.1271.5392.64etxture66.4775.7384.0761.69places36558.2679.1460.0691.37LSUN-resize41.0187.8188.4987.11iSUN44.4886.4988.2584.10LSUN-resize41.0184.3686.7981.10EBO75.8777.7071.26mist46.0385.8362.5497.26syhn41.6188.8879.4190.29places36558.3278.8860.2491.52LSUN-resize48.4486.4988.2586.17places36558.2679.9285.8475.03places36558.2679.9285.8475.03places36558.2679.9285.8479.26LSUN-resize48.4486.4988.2589.71LSUN-resize48.4588.1787.90<	Methods	OOD test datasets	FPR95↓	AUROC↑	AUPR-In↑	AUPR-Out [↑]
MSP mnist 51.31 76.83 55.15 94.26 MSP svhn 61.57 78.58 63.81 89.94 Hexture 65.21 75.34 84.15 60.49 Jaces365 57.61 78.68 60.28 91.34 LSUN-resize 49.68 82.86 84.18 81.71 iSUN 50.99 82.02 84.76 78.55 LSUN-resize 49.68 82.86 84.18 81.71 iSUN 50.21 80.87 83.17 78.55 EBO cifar10 64.22 77.42 77.62 74.80 misit 51.21 75.63 53.80 93.43 syhn 53.13 84.12 71.53 92.64 LSUN-resize 41.13 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-resize 48.44 86.41 86.61 86.87 places365 58.22 78.88 <td rowspan="2"></td> <td>cifar10</td> <td>63.27</td> <td>77.10</td> <td>77.82</td> <td>74.75</td>		cifar10	63.27	77.10	77.82	74.75
MSP swhn 61.77 78.58 63.81 89.94 MSP texture 65.21 75.34 84.15 60.49 LSUN-resize 49.68 82.86 84.18 81.71 iSUN 50.99 82.02 84.76 78.67 LSUN-Crop 50.21 80.87 83.17 78.55 cifar10 64.22 77.42 77.62 74.80 mnist 51.21 75.63 53.80 93.43 svhn 53.13 84.12 71.53 92.64 texture 66.47 75.73 84.07 61.69 places365 58.26 79.14 60.06 91.37 LSUN-resize 41.01 84.36 86.79 81.10 LSUN-resize 41.01 84.36 86.79 81.10 LSUN-resize 48.44 86.49 85.51 75.37 efar10 62.58 75.87 77.70 71.26 misit 51.77 89.70		mnist	51.31	76.83	55.15	94.26
MSP texture places365 57.61 78.68 60.28 91.34 LSUN-resize 49.68 82.86 84.18 81.71 iSUN 50.99 82.02 84.76 78.67 LSUN-resize 49.68 82.86 84.18 81.71 iSUN 50.99 82.02 84.76 78.67 LSUN-resize 40.64 77.42 77.62 74.80 minist 51.21 75.33 83.07 61.69 places365 58.26 79.14 60.06 91.37 LSUN-resize 41.13 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-resize 41.01 88.88 79.41 95.17 LSUN-resize 44.03 85.83 60.24 91.52 iLSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 83.15 85.01 80.75 LSUN-resize 48.44 86.44		svhn	61.57	78.58	63.81	89.94
MSF places365 57.61 78.68 60.28 91.34 LSUN-resize 49.68 82.86 84.18 81.71 iSUN 50.99 82.02 84.76 78.67 LSUN-Crop 50.21 80.87 83.17 78.55 cifar10 64.22 77.42 77.62 74.80 mnist 51.21 75.63 53.80 93.43 syhn 53.13 84.12 71.53 92.64 betwire 66.47 75.73 84.07 61.69 places365 58.26 79.14 60.06 91.37 LSUN-resize 41.13 88.49 87.11 10 iSUN 44.48 86.49 88.25 84.10 LSUN-resize 41.13 84.36 86.79 81.10 LSUN-Crop 41.01 84.36 86.17 92.726 mist 46.03 85.83 67.51 93.70 DSUN-resize 88.25 88.35 75.03 <td>MCD</td> <td>texture</td> <td>65.21</td> <td>75.34</td> <td>84.15</td> <td>60.49</td>	MCD	texture	65.21	75.34	84.15	60.49
LSUN-resize iSUN 49.68 50.99 82.86 82.22 84.18 84.76 81.71 78.57 LSUN-Crop 50.21 80.87 83.17 78.57 cifar10 64.22 77.42 77.62 74.80 mist 51.21 75.63 53.80 93.43 svhn 53.13 84.12 71.53 92.64 texture 66.47 75.73 84.07 61.69 places365 58.26 79.14 60.06 91.37 LSUN-resize 41.13 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-resize 41.16 88.88 79.41 95.17 cifar10 62.58 75.87 77.70 71.26 mist 46.03 85.83 62.54 97.26 svhn 41.61 88.88 79.41 95.17 texture 56.76 82.45 83.15 85.01 LSUN-resize 48.44 86.41 86.61	MSP	places365	57.61	78.68	60.28	91.34
iSUN 50.99 82.02 84.76 78.67 LSUN-Crop 50.21 80.87 83.17 78.55 minist 51.21 75.63 53.80 93.43 svhn 53.13 84.12 71.53 92.64 texture 66.47 75.73 84.07 61.69 places365 58.26 79.14 60.06 91.37 LSUN-resize 41.13 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-resize 41.10 84.36 86.79 81.10 OE cifar10 62.58 75.87 77.70 71.26 minist 46.03 85.83 60.24 91.52 LSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 86.81 87.96 86.17 LSUN-resize 48.43 86.43 86.61 86.86 iSUN 47.30 74.40 70.28		LSUN-resize	49.68	82.86	84.18	81.71
LSUN-Crop 50.21 80.87 83.17 78.55 ecifar10 64.22 77.42 77.62 74.80 mnist 51.21 75.63 53.80 93.43 sumist 51.21 75.63 53.80 93.43 sumist 51.21 75.63 53.80 93.43 sumist 66.47 75.73 84.07 61.69 places365 58.26 79.14 60.06 91.37 LSUN-resize 41.13 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-Crop 41.01 84.36 86.79 81.10 DE cifar10 62.58 75.87 77.70 71.26 mnist 41.61 88.88 99.41 95.17 texture 56.76 82.45 88.35 75.03 places365 58.32 78.88 60.24 91.52 LSUN-Crop 47.56 83.15 85.01		iSUN	50.99	82.02	84.76	78.67
EBO cifar10 64.22 77.42 77.62 74.80 mnist 51.21 75.63 53.80 93.43 svhn 53.13 84.12 71.53 92.64 places365 58.26 79.14 60.06 91.37 LSUN-resize 41.13 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-Crop 41.01 84.36 86.79 81.10 Cifar10 62.58 75.87 77.70 71.26 mnist 46.03 85.83 62.54 97.26 svhn 41.61 88.88 79.41 95.17 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.41 86.61 86.86 iSUN 47.96 86.81 87.96 86.17 LSUN-resize 48.42 86.41 86.61 86.86 iSUN 47.96 84.73 74.40 93.91		LSUN-Crop	50.21	80.87	83.17	78.55
Best Book Single Signal S		cifar10	64.22	77.42	77.62	74.80
EBO svhn 53.13 84.12 71.53 92.64 texture 66.47 75.73 84.07 61.69 places365 58.26 79.14 60.06 91.37 LSUN-resize 41.13 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-Crop 41.01 84.36 86.79 81.10 order cifar10 62.58 75.87 77.70 71.26 mnist 46.03 85.83 62.54 95.17 texture 56.76 82.45 88.35 75.03 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.41 86.61 86.86 iSUN 47.96 86.11 85.30 80.75 LSUN-Crop 47.56 83.15 85.01 80.75 EBO (w. Daux) cifar10 68.38 73.94 74.46 70.28 Baushn 51.77		mnist	51.21	75.63	53.80	93.43
EBO texture 66.47 75.73 84.07 61.69 LSUN-resize 41.13 87.81 60.06 91.37 LSUN-resize 41.11 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-Crop 41.01 84.36 86.79 81.10 OE cifar10 62.58 75.87 77.70 71.26 minist 46.03 85.83 62.54 97.26 minist 46.03 85.83 62.54 97.26 minist 44.61 88.85 75.03 17 texture 56.76 82.45 88.55 75.03 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.41 86.61 86.81 EBO (w. Daux) cifar10 68.38 73.94 74.46 70.28 minist 51.77 89.70 57.40 98.31 syhn 47.80		svhn	53.13	84.12	71.53	92.64
BBO places365 58.26 79.14 60.06 91.37 LSUN-resize 41.13 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-Crop 41.01 84.36 86.79 81.10 cifar10 62.58 75.87 77.70 71.26 mnist 46.03 85.83 62.54 97.26 svhn 41.61 88.88 79.41 95.17 texture 56.76 82.45 88.35 75.03 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.61 86.61 86.86 iSUN 47.96 86.81 87.96 86.17 LSUN-Crop 47.56 83.15 85.01 80.75 EBO (w. D_aux) texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-Crop 27.72 92.80 <td>EDO</td> <td>texture</td> <td>66.47</td> <td>75.73</td> <td>84.07</td> <td>61.69</td>	EDO	texture	66.47	75.73	84.07	61.69
LSUN-resize 41.13 87.81 88.49 87.11 iSUN 44.48 86.49 88.25 84.10 LSUN-Crop 41.01 84.36 86.79 81.10 OE cifar10 62.58 75.87 77.70 71.26 minist 46.03 85.83 62.54 97.26 svhn 41.61 88.88 79.41 95.17 texture 56.76 82.45 88.35 75.03 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 86.17 85.01 80.75 LSUN-resize 48.43 86.47 74.46 70.28 mist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 57.2 90.9	EBU	places365	58.26	79.14	60.06	91.37
iSUN 44.48 86.49 88.25 84.10 LSUN-Crop 41.01 84.36 86.79 81.10 0E cifar10 62.58 75.87 77.70 71.26 mnist 46.03 85.83 62.54 97.26 svhn 41.61 88.88 79.41 95.17 texture 56.76 82.45 88.35 75.03 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 86.81 87.96 86.17 LSUN-resize 48.44 86.41 86.61 98.31 svbn 47.96 84.83 73.94 74.46 70.28 mnist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 57.27		LSUN-resize	41.13	87.81	88.49	87.11
LSUN-Crop 41.01 84.36 86.79 81.10 cifar10 62.58 75.87 77.70 71.26 mnist 46.03 85.83 62.54 97.26 svhn 41.61 88.88 79.41 95.17 jaces365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 86.81 87.96 86.17 LSUN-Crop 47.56 83.15 85.01 80.75 EBO (w. D_aux) cifar10 68.38 73.94 74.46 70.28 mnist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14		iSUN	44.48	86.49	88.25	84.10
Cifar10 62.58 75.87 77.70 71.26 mnist 46.03 85.83 62.54 97.26 svhn 41.61 88.88 79.41 95.17 ieture 56.76 82.45 88.35 75.03 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 86.81 87.96 86.17 LSUN-resize 48.44 86.44 86.41 93.31 mist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-resize 64.16 77.12 92.64 99.00		LSUN-Crop	41.01	84.36	86.79	81.10
OE mnist 46.03 85.83 62.54 97.26 svhn 41.61 88.88 79.41 95.17 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.41 86.64 96.86 iSUN 47.96 86.81 87.96 86.17 LSUN-resize 48.44 86.41 86.90 80.75 EBO (w. D_aux) cifar10 68.38 73.94 74.46 70.28 mnist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-resize 65.30 76.30 46.11 95.43 Svhn 19.12 97.06		cifar10	62.58	75.87	77.70	71.26
OE svhn 41.61 88.88 79.41 95.17 DE texture 56.76 82.45 88.35 75.03 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 86.81 87.96 86.71 LSUN-Crop 47.56 83.15 85.01 80.75 cifar10 68.38 73.94 74.46 70.28 mnist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-Crop 27.72 92.80 93.32 91.75 cifar10 81.24 68.06 66.54<		mnist	46.03	85.83	62.54	97.26
OE texture 56.76 82.45 88.35 75.03 places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 86.81 87.96 86.17 LSUN-Crop 47.56 83.15 85.01 80.75 ego (w. Daux) cifar10 68.38 73.94 74.46 70.28 mist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-Crop 27.72 92.80 93.32 91.75 cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30		svhn	41.61	88.88	79.41	95.17
OE places365 58.32 78.88 60.24 91.52 LSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 86.81 87.96 86.17 LSUN-Crop 47.56 83.15 85.01 80.75 EBO (w. D _{aux}) cifar10 68.38 73.94 74.46 70.28 mnist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-Crop 27.72 92.80 93.32 91.75 cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30 46.11 95.43 svhn 19.12 97.06	OF	texture	56.76	82.45	88.35	75.03
LSUN-resize 48.44 86.44 86.61 86.86 iSUN 47.96 86.81 87.96 86.17 LSUN-Crop 47.56 83.15 85.01 80.75 ecifar10 68.38 73.94 74.46 70.28 mnist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-crop 27.72 92.80 93.32 91.75 CIDER cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 <t< td=""><td>UE</td><td>places365</td><td>58.32</td><td>78.88</td><td>60.24</td><td>91.52</td></t<>	UE	places365	58.32	78.88	60.24	91.52
iSUN 47.96 86.81 87.96 86.17 LSUN-Crop 47.56 83.15 85.01 80.75 eifar10 68.38 73.94 74.46 70.28 mnist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-resize 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74		LSUN-resize	48.44	86.44	86.61	86.86
LSUN-Crop 47.56 83.15 85.01 80.75 cifar10 68.38 73.94 74.46 70.28 mnist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-Crop 27.72 92.80 93.32 91.75 cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10		iSUN	47.96	86.81	87.96	86.17
EBO (w. D _{aux}) cifar10 68.38 73.94 74.46 70.28 mnist 51.77 89.70 57.40 98.31 svhn 47.80 84.73 74.40 93.39 texture 65.06 79.92 85.84 72.44 places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-Crop 27.72 92.80 93.32 91.75 cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22		LSUN-Crop	47.56	83.15	85.01	80.75
BBO (w. D_{aux})mnist51.7789.7057.4098.31svhn47.8084.7374.4093.39texture65.0679.9285.8472.44places36564.1677.1255.7290.96LSUN-resize38.8287.9089.0885.61iSUN39.2288.3990.1485.61LSUN-Crop27.7292.8093.3291.75cifar1081.2468.0666.5465.94mnist65.3076.3046.1195.43svhn19.1297.0692.0499.00texture55.2984.4589.7177.71places36569.0075.5352.3690.74LSUN-resize64.1777.8178.1576.10iSUN69.2475.4877.2272.66LSUN64.5181.9980.4283.61ourscifar1063.0675.0975.9869.85mnist16.0296.9283.8799.47svhn20.1494.9090.6197.61texture50.0886.6191.1280.24places36554.4681.1664.0292.40LSUN-resize17.3996.1496.3595.49iSUN14.9196.6397.1195.65LSUN-Crop33.8290.6291.3789.04		cifar10	68.38	73.94	74.46	70.28
$ \begin{array}{c} {} { { \rm EBO} \left({{\rm w.}\;} {D_{aux}} \right) } \\ { { \rm EBO} \left({{\rm w.}\;} {D_{aux}} \right) } \\ { { \rm texture} } \\ { { \rm texture} } \\ { { \rm places}365 } \\ { { \rm texture} } \\ { { \rm places}365 } \\ { { \rm texture} } \\ { { \rm stan} } \\ \\ { { \rm stan} } \\ { { \rm stan} } \\ { { \rm stan} } \\ \\ { { \rm stan} } \\ \\ \\ \\ { { \rm stan} } \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ \\ $		mnist	51.77	89.70	57.40	98.31
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$		svhn	47.80	84.73	74.40	93.39
Libb (w. D_aux) places365 64.16 77.12 55.72 90.96 LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-Crop 27.72 92.80 93.32 91.75 cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN-resize 64.51 81.99 80.42 83.61 ours cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90	EPO(w, D)	texture	65.06	79.92	85.84	72.44
LSUN-resize 38.82 87.90 89.08 85.61 iSUN 39.22 88.39 90.14 85.61 LSUN-Crop 27.72 92.80 93.32 91.75 cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN 64.51 81.99 80.42 83.61 Ours cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47<	EBO (w. D_{aux})	places365	64.16	77.12	55.72	90.96
iSUN 39.22 88.39 90.14 85.61 LSUN-Crop 27.72 92.80 93.32 91.75 cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN 64.51 81.99 80.42 83.61 Ours cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90 90.61 97.61		LSUN-resize	38.82	87.90	89.08	85.61
LSUN-Crop 27.72 92.80 93.32 91.75 cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN 64.51 81.99 80.42 83.61 Ours cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90 90.61 97.61 texture 50.08 86.61 91.12 80.24		iSUN	39.22	88.39	90.14	85.61
cifar10 81.24 68.06 66.54 65.94 mnist 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN 64.51 81.99 80.42 83.61 Ours cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 ours cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 ours texture 50.08 86.61 91.12 80.24 places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 <td></td> <td>LSUN-Crop</td> <td>27.72</td> <td>92.80</td> <td>93.32</td> <td>91.75</td>		LSUN-Crop	27.72	92.80	93.32	91.75
mist 65.30 76.30 46.11 95.43 svhn 19.12 97.06 92.04 99.00 texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN 64.51 81.99 80.42 83.61 ours cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90 90.61 97.61 texture 50.08 86.61 91.12 80.24 places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 96.35 95.49 iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04 <td></td> <td>cifar10</td> <td>81.24</td> <td>68.06</td> <td>66.54</td> <td>65.94</td>		cifar10	81.24	68.06	66.54	65.94
CIDERsvhn19.1297.0692.0499.00texture55.2984.4589.7177.71places36569.0075.5352.3690.74LSUN-resize64.1777.8178.1576.10iSUN69.2475.4877.2272.66LSUN64.5181.9980.4283.61cifar1063.0675.0975.9869.85mnist16.0296.9283.8799.47svhn20.1494.9090.6197.61texture50.0886.6191.1280.24places36554.4681.1664.0292.40LSUN-resize17.3996.1496.3595.49iSUN14.9196.6397.1195.65LSUN-Crop33.8290.6291.3789.04		mnist	65.30	76.30	46.11	95.43
CIDER texture 55.29 84.45 89.71 77.71 places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN 64.51 81.99 80.42 83.61 cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90 90.61 97.61 texture 50.08 86.61 91.12 80.24 places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 96.35 95.49 iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04		svhn	19.12	97.06	92.04	99.00
Places365 69.00 75.53 52.36 90.74 LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN 64.51 81.99 80.42 83.61 cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90 90.61 97.61 texture 50.08 86.61 91.12 80.24 places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 96.35 95.49 iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04	CIDED	texture	55.29	84.45	89.71	77.71
LSUN-resize 64.17 77.81 78.15 76.10 iSUN 69.24 75.48 77.22 72.66 LSUN 64.51 81.99 80.42 83.61 cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90 90.61 97.61 texture 50.08 86.61 91.12 80.24 places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 96.35 95.49 iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04	CIDER	places365	69.00	75.53	52.36	90.74
iSUN 69.24 75.48 77.22 72.66 LSUN 64.51 81.99 80.42 83.61 cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90 90.61 97.61 texture 50.08 86.61 91.12 80.24 places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 96.35 95.49 iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04		LSUN-resize	64.17	77.81	78.15	76.10
LSUN 64.51 81.99 80.42 83.61 cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90 90.61 97.61 texture 50.08 86.61 91.12 80.24 places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 96.35 95.49 iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04		iSUN	69.24	75.48	77.22	72.66
cifar10 63.06 75.09 75.98 69.85 mnist 16.02 96.92 83.87 99.47 svhn 20.14 94.90 90.61 97.61 texture 50.08 86.61 91.12 80.24 places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 96.35 95.49 iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04		LSUN	64.51	81.99	80.42	83.61
mnist16.0296.9283.8799.47svhn20.1494.9090.6197.61texture50.0886.6191.1280.24places36554.4681.1664.0292.40LSUN-resize17.3996.1496.3595.49iSUN14.9196.6397.1195.65LSUN-Crop33.8290.6291.3789.04	Ours	cifar10	63.06	75.09	75.98	69.85
Svhn20.1494.9090.6197.61Ourstexture50.0886.6191.1280.24places36554.4681.1664.0292.40LSUN-resize17.3996.1496.3595.49iSUN14.9196.6397.1195.65LSUN-Crop33.8290.6291.3789.04		mnist	16.02	96.92	83.87	99.47
Ours texture 50.08 86.61 91.12 80.24 places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 96.35 95.49 iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04		svhn	20.14	94.90	90.61	97.61
places365 54.46 81.16 64.02 92.40 LSUN-resize 17.39 96.14 96.35 95.49 iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04		texture	50.08	86.61	91.12	80.24
LSUN-resize17.3996.1496.3595.49iSUN14.9196.6397.1195.65LSUN-Crop33.8290.6291.3789.04		places365	54.46	81.16	64.02	92.40
iSUN 14.91 96.63 97.11 95.65 LSUN-Crop 33.82 90.62 91.37 89.04		LSUN-resize	17.39	96.14	96.35	95.49
LSUN-Crop 33.82 90.62 91.37 89.04		iSUN	14.91	96.63	97.11	95.65
		LSUN-Crop	33.82	90.62	91.37	89.04

Table 9. Detailed comparative experiments using CIFAR100 as the ID training dataset.