NON-NEGATIVE BREGMAN DIVERGENCE MINIMIZATION FOR DEEP DIRECT DENSITY RATIO ESTIMATION

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ABSTRACT

The estimation of the ratio of two probability densities has garnered attention as the *density ratio* is useful in various machine learning tasks, such as anomaly detection and domain adaptation. To estimate the density ratio, methods collectively known as *direct density ratio estimation* (DRE) have been explored. These methods are based on the minimization of the *Bregman* (BR) divergence between a density ratio model and the true density ratio. However, existing direct DRE suffers from serious *train-loss hacking* when using *flexible models* such as neural networks. In this paper, we introduce a *non-negative correction* for empirical risk using only the prior knowledge of the *upper bound of the density ratio*. This correction makes a DRE method more robust against train-loss hacking and enables the use of flexible models. In the theoretical analysis, we discuss the consistency of the empirical risk. In our experiments, the proposed estimators show favorable performance in inlier-based outlier detection and covariate shift adaptation.

1 INTRODUCTION

The ratio of probability densities has been used in various industrial applications (Sugiyama et al., 2009; 2012), such as anomaly detection (Hido et al., 2011; Smola et al., 2009; Abe & Sugiyama, 2019), two-sample testing (Keziou & Leoni-Aubin, 2005; Sugiyama et al., 2011a), off-policy evaluation (Kato et al., 2020), change detection in time series (Kawahara & Sugiyama, 2009), and binary classification only from positive and unlabeled data (PU learning; Kato et al., 2019). Thus, the estimation of the density ratio has attracted a great deal of attention. A naive approach is to estimate the two densities of the numerator and denominator separately, then take the ratio of the estimated densities. However, this approach is difficult to apply to high-dimensional data as division by an estimated quantity can magnify the estimation error in the numerator. To overcome this drawback, various approaches of direct DRE have been explored without undergoing density estimation. These approaches include the moment matching (Huang et al., 2007; Gretton et al., 2009), the probabilistic classification (Qin, 1998; Cheng & Chu, 2004), the density matching (Nguyen et al., 2011; Yamada et al., 2010), and the density-ratio fitting (Kanamori et al., 2009). Sugiyama et al. (2011b) showed that these methods could be generalized as density ratio matching under the Bregman (BR) divergence (Bregman, 1967). Recently, Kato et al. (2019) also proposed using the risk for PU learning proposed by du Plessis et al. (2015) for DRE, which also can be generalized from the viewpoint of BR divergence minimization as we show below.

However, a serious *train-loss hacking* problem is often observed when we minimize an empirically approximated BR divergence with respect to a flexible density ratio model such as neural networks. This is caused because there is no lower bound in the empirically approximated BR divergence, i.e., we can achieve an infinitely negative value in minimization. Similar train-loss hacking is first reported by Kiryo et al. (2017) in PU learning. In Kiryo et al. (2017), they call the phenomena *over-fitting*, but we refer to it as train-loss hacking because the nuance is a bit different from the standard one. In existing DRE methods, this problem has been rarely discussed. One reason for this is that the existing method often assumes a linear-in-parameter model to approximate the density ratio (Kanamori et al., 2012), which is not so flexible compared with neural networks. On the other hand, recent developments in machine learning suggest that using neural networks has significantly improved the performances for various tasks, such as computer vision (Krizhevsky et al., 2012) and natural language processing (Bengio et al., 2001) motivating the use of neural networks for density ratio estimation.

Table 1: Summary of methods for DRE(Sugiyama et al., 2011b). For PULogLoss, we use $C < \frac{1}{\overline{R}}$.

Method	$f(t)$	Reference
LSIF	$(t-1)^2/2$	Kanamori et al. (2009)
KLIEP (UKL)	$t\log(t) - t$	Sugiyama et al. (2008)
Kernel Mean Matching	$(t-1)^2/2$	Gretton et al. (2009)
Logistic Regression (BKL)	$t\log(t) - (1+t)\log(1+t)$	Hastie et al. (2001)
PULogLoss	$\log(1-t) + Ct(\log(t) - \log(1-t))$ for $0 < t < 1$	Kato et al. (2019)

To mitigate the train-loss hacking, we propose a general procedure to modify the empirical BR divergence using only the prior knowledge of the upper bound of the density ratio. Our idea of the correction has been inspired by Kiryo et al. (2017), which proposed using non-negative correction to the empirical risk of classification for using neural networks in PU learning. However, the idea of non-negative correction is only immediately applicable to the binary classification, thus we require a non-trivial rewriting of the BR divergence to generalize the approach to our problem. In analogy to Kiryo et al. (2017), we call the proposed empirical risk the *non-negative BR* (nnBR) divergence, and it can be regarded as a generalization of PU learning with flexible models (Kiryo et al., 2017).

Our main contributions are: (1) the proposal of a general procedure to modify a BR divergence to enable DRE with flexible models, (2) theoretical justification of the proposed estimator, and (3) the experimental validation of the proposed method using benchmark data.

2 Problem Setting

Let $\mathcal{X}^{\mathrm{nu}} \subseteq \mathbb{R}^d$ and $\mathcal{X}^{\mathrm{de}} \subseteq \mathbb{R}^d$ be the spaces of the d-dimensional *covariates* $\{\boldsymbol{x}_i^{\mathrm{nu}}\}_{i=1}^{n_{\mathrm{nu}}}$ and $\{\boldsymbol{x}_i^{\mathrm{de}}\}_{i=1}^{n_{\mathrm{de}}}$, respectively, which are independent and identically distributed (i.i.d.) as $\{\boldsymbol{x}_i^{\mathrm{nu}}\}_{i=1}^{n_{\mathrm{nu}}} \overset{\mathrm{i.i.d.}}{\sim} p_{\mathrm{nu}}(\boldsymbol{x})$ and $\{\boldsymbol{x}_i^{\mathrm{de}}\}_{i=1}^{n_{\mathrm{de}}} \overset{\mathrm{i.i.d.}}{\sim} p_{\mathrm{de}}(\boldsymbol{x})$, where $p_{\mathrm{nu}}(\boldsymbol{x})$ and $p_{\mathrm{de}}(\boldsymbol{x})$ are probability densities over $\mathcal{X}^{\mathrm{nu}}$ and $\mathcal{X}^{\mathrm{de}}$, respectively. Here, "nu" and "de" indicate the numerator and the denominator. Our goal is to estimate the density ratio $r^*(\boldsymbol{x}) = \frac{p_{\mathrm{nu}}(\boldsymbol{x})}{p_{\mathrm{de}}(\boldsymbol{x})}$. To identify the density ratio, we assume the following:

Assumption 1. The density $p_{\mathrm{nu}}(\boldsymbol{x})$ is strictly positive over the space $\mathcal{X}^{\mathrm{nu}}$, the density $p_{\mathrm{de}}(\boldsymbol{x})$ is strictly positive over the space $\mathcal{X}^{\mathrm{de}}$, and $\mathcal{X}^{\mathrm{nu}} \subseteq \mathcal{X}^{\mathrm{de}}$. In addition, the density ratio r^* is bounded from above on $\mathcal{X}^{\mathrm{de}}$: $\overline{R} = \sup_{\boldsymbol{x}\in\mathcal{X}^{\mathrm{de}}} r^*(\boldsymbol{x}) < \infty$.

Note that the assumption $\mathcal{X}^{\mathrm{nu}} \subseteq \mathcal{X}^{\mathrm{de}}$ is typical in the context of DRE.

Notation: Let $\mathbb{E}_{\mathrm{nu}}$ and $\mathbb{E}_{\mathrm{de}}$ denote the expectations over $p_{\mathrm{nu}}(\boldsymbol{x})$ and $p_{\mathrm{de}}(\boldsymbol{x})$, respectively. Let $\hat{\mathbb{E}}_{\mathrm{nu}}$ and $\hat{\mathbb{E}}_{\mathrm{de}}$ denote the sample average over $\{\boldsymbol{x}_i^{\mathrm{nu}}\}_{i=1}^{n_{\mathrm{nu}}}$ and $\{\boldsymbol{x}_i^{\mathrm{de}}\}_{i=1}^{n_{\mathrm{de}}}$, respectively. Let $\mathcal{H} \subset \{r : \mathbb{R}^d \to (b_r, B_r)\}$ be the hypothesis class of the density ratio, where $0 \leq b_r < \overline{R} < B_r$.

2.1 Density Ratio Matching under the Bregman Divergence

A naive way to implement DRE would be to estimate the numerator and the denominator densities separately and take the ratio. However, according to Vapnik's principle, we should avoid solving a more difficult intermediate problem than the target problem (Vapnik, 1998). Therefore, various methods for directly estimating the density ratio model have been proposed (Sugiyama et al., 2012), and Sugiyama et al. (2011b) showed that those methods can be generalized from the viewpoint of the *density ratio matching under the BR divergence*.

The BR divergence is an extension of the Euclidean distance to a class of divergences that share similar properties (Bregman, 1967). Formally, let $f : (b_r, B_r) \to \mathbb{R}$ be a twice continuously differentiable convex function with a bounded derivative. Then, the point-wise BR divergence associated with f from t^* to t is defined as $\mathrm{BR}'_f(t^*\|t) := f(t^*) - f(t) - \partial f(t)(t^* - t)$, where ∂f is the derivative of f. Now, the discrepancy from the true density ratio function r^* to a density ratio model r is measured by integrating the point-wise BR divergence as follows (Sugiyama et al., 2011b):

$$\mathrm{BR}'_f(r^*\|r) := \int p_{\mathrm{de}}(\boldsymbol{x})\big(f(r^*(\boldsymbol{x})) - f(r(\boldsymbol{x})) - \partial f(r(\boldsymbol{x}))\{r^*(\boldsymbol{x}) - r(\boldsymbol{x})\}\big)d\boldsymbol{x}. \tag{1}$$

We estimate the density ratio by finding a function r that minimizes the BR divergence defined in (1). Here, we subtract the constant $\overline{\mathrm{BR}} = \mathbb{E}_{\mathrm{de}}\left[f(r^*(\boldsymbol{x}))\right]$ from (1) to obtain

$$\mathrm{BR}_f(r^* \| r) := \int p_{\mathrm{de}}(\boldsymbol{x})\Big(\partial f(r(\boldsymbol{x}))r(\boldsymbol{x}) - f(r(\boldsymbol{x}))\Big)d\boldsymbol{x} - \int p_{\mathrm{nu}}(\boldsymbol{x})\partial f(r(\boldsymbol{x}))d\boldsymbol{x}. \tag{2}$$

Since $\overline{\mathrm{BR}}$ is constant with respect to r, we have $\arg\min_r \mathrm{BR}'_f(r^* \| r) = \arg\min_r \mathrm{BR}_f(r^* \| r)$. Then, let us define the sample analogue of (2) as

$$\widehat{\mathrm{BR}}_f(r) := \hat{\mathbb{E}}_{\mathrm{de}}\Big[\partial f\big(r(\boldsymbol{x}_i)\big)r(\boldsymbol{x}_i) - f\big(r(\boldsymbol{x}_i)\big)\Big] - \hat{\mathbb{E}}_{\mathrm{nu}}\Big[\partial f\big(r(\boldsymbol{x}_j)\big)\Big]. \tag{3}$$

For a hypothesis class $\mathcal{H}$, we estimate the density ratio by solving $\min_{r\in\mathcal{H}} \widehat{\mathrm{BR}}_f(r^* \| r)$.

2.2 Examples of DRE

Sugiyama et al. (2011b) showed that various DRE methods can be unified from the viewpoint of BR divergence minimization. Furthermore, Menon & Ong (2016) showed an equivalence between conditional probability estimation and DRE by BR divergence minimization. In addition, we can derive a novel method for DRE from the proposed method of du Plessis et al. (2015) and Kato et al. (2019). We summarize the DRE methods in Table 1. Here, the empirical risks of *least-square importance fitting* (LSIF), the *Kullback–Leibler importance estimation procedure* (KLIEP), logistic regression (LR), and *PU learning with log Loss* (PU-LogLoss) is given as $\widehat{\mathrm{BR}}_{\mathrm{LSIF}}(r) := -\hat{\mathbb{E}}_{\mathrm{nu}}[r(X)] + \frac{1}{2}\hat{\mathbb{E}}_{\mathrm{de}}[(r(X))^2]$, $\widehat{\mathrm{BR}}_{\mathrm{UKL}}(r) := \hat{\mathbb{E}}_{\mathrm{de}}\left[r(X)\right] - \hat{\mathbb{E}}_{\mathrm{nu}}\left[\log\left(r(\boldsymbol{x})\right)\right]$, $\widehat{\mathrm{BR}}_{\mathrm{BKL}}(r) := -\hat{\mathbb{E}}_{\mathrm{de}}\left[\log\left(\frac{1}{1+r(X)}\right)\right] - \hat{\mathbb{E}}_{\mathrm{nu}}\left[\log\left(\frac{r(X)}{1+r(\boldsymbol{x})}\right)\right]$, and $\widehat{\mathrm{BR}}_{\mathrm{PU}}(r) := -\hat{\mathbb{E}}_{\mathrm{de}}\left[\log\left(1 - r(\boldsymbol{x}_i)\right)\right] + C\hat{\mathbb{E}}_{\mathrm{nu}}\left[-\log\left(r(\boldsymbol{x}_i)\right) + \log\left(1 - r(\boldsymbol{x}_j)\right)\right]$, where $0 < C < \frac{1}{R}$. Here, $\widehat{\mathrm{BR}}_{\mathrm{LSIF}}(r)$ and $\widehat{\mathrm{BR}}_{\mathrm{PU}}(r)$ correspond to LSIF and PULogLoss, respectively. We can derive the KLIEP and LR from $\widehat{\mathrm{BR}}_{\mathrm{UKL}}(r)$ and $\widehat{\mathrm{BR}}_{\mathrm{BKL}}(r)$, which are called unnormalized Kullback–Leibler (UKL) divergence and binary Kullback–Leibler (BKL) divergence, respectively (Sugiyama et al., 2011b). In $\widehat{\mathrm{BR}}_{\mathrm{PU}}(r)$, we restrict the model as $r \in (0, 1)$ and we obtain an estimator of Cr^* as a result of the minimization of the risk. Details of the existing methods are shown in Appendix A.

3 Deep Direct DRE based on Non-negative Risk Estimator

In this section, we develop methods for DRE with flexible models such as neural networks.

3.1 Difficulties of DRE using Neural Networks

Training neural networks for DRE by minimizing the empirical BR divergence tends to suffer from an overfitting phenomenon. For example, we show in Section 5 that the LSIF with neural networks (Nam & Sugiyama, 2015) suffers from a serious overfitting issue. One possible cause of overfitting of flexible models has been identified to be the train-loss hacking as shown by Kiryo et al. (2017) in the context of PU learning (Figure 1). In DRE, the train-loss hacking is also sensible: the term $-\hat{\mathbb{E}}_{\mathrm{nu}}\left[\partial f\big(r(\boldsymbol{x}_j)\big)\right]$ can easily diverge to $-\infty$ if we try to minimize empirical BR divergence (3) over a highly flexible hypothesis class $\mathcal{H}$. This is because the term is not lower bounded, unlike the loss functions for other machine learning tasks such as classification. Here, note that the other term $\hat{\mathbb{E}}_{\mathrm{de}}\Big[\partial f\big(r(\boldsymbol{x}_i)\big)r(\boldsymbol{x}_i) - f\big(r(\boldsymbol{x}_i)\big)\Big]$ does not introduce a sufficient trade-off to prevent the divergence to $-\infty$ when the hypothesis class is highly flexible (Figure 1).

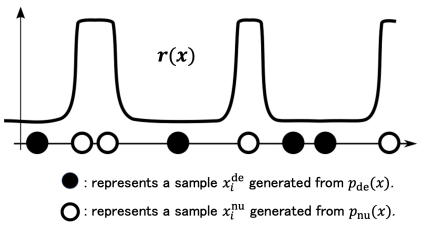

Figure 1: Illustration of the train-loss hacking phenomenon. Given finite data points, a sufficiently flexible model r can easily make the training loss, e.g., $\widehat{\mathrm{BR}}_{\mathrm{LSIF}}(r)$, diverge to $-\infty$.

3.2 NON-NEGATIVE BR DIVERGENCE

Although DRE using flexible models suffers from serious train-loss hacking, we still have a strong motivation to use those models for analyzing data such as computer vision and text data. For example, Nam & Sugiyama (2015) and Abe & Sugiyama (2019) approximated the density ratio with neural networks, and Uehara et al. (2016) applied direct DRE for generative adversarial nets (GANs; Goodfellow et al., 2014), both by minimizing the empirical BR divergence (3). To alleviate the train-loss hacking problem, we propose the *non-negative BR divergence estimator*. The proposed method is inspired by Kiryo et al. (2017), which suggested a non-negative correction to the empirical risk of PU learning based on the knowledge that a part of the population risk is non-negative. On the other hand, in DRE, it is not obvious how to correct the empirical risk because we do not know which part of the population risk (2) is non-negative. However, this can be alleviated by determining the upper bound $\overline{R}$ of the density ratio r^*. With the prior knowledge of $\overline{R}$, we can determine part of the risk of DRE (2) is non-negative and conduct a non-negative correction to the empirical risk (3) based on the non-negativity of the population risk. Let us define $\tilde{f}$ to be a function such that $\partial f(t) = C\big(\partial f(t)t - f(t)\big) + \tilde{f}(t)$, where $0 < C < \frac{1}{\overline{R}}$ and put the following assumption.

Assumption 2. Assume that $\tilde{f}(t)$ is bounded from above, and that there exists a constant A such that $\partial f(t)t - f(t) + A \geq 0$ for $t \in (b_r, B_r)$.

Assumption 2 is satisfied by most of the loss functions which appear in the previously proposed DRE methods (see Appendix B for examples). Under Assumption 2, because $\tilde{f}(t)$ is bounded above, the train-loss hacking $-\hat{\mathbb{E}}_{\mathrm{nu}}\Big[\partial f\big(r(\boldsymbol{x}_j)\big)\Big] \to -\infty$ in the minimization of the empirical risk (3) is caused by $-\hat{\mathbb{E}}_{\mathrm{nu}}\Big[C\left\{\partial f(r(\boldsymbol{x}_j))r(\boldsymbol{x}_j) - f(r(\boldsymbol{x}_j))\right\}\Big] \to -\infty$. Thus, we succeeded in identifying the part of the empirical risk causing the train-loss hacking. Next, to avoid the train-loss hacking, we impose a non-negative correction to the empirical risk (3). First, we rewrite the population risk (2) as $\mathrm{BR}_f(r^*\|r) = \int \Big\{p_{\mathrm{de}}(\boldsymbol{x}) - Cp_{\mathrm{nu}}(\boldsymbol{x})\Big\}\Big\{\partial f(r(\boldsymbol{x}))r(\boldsymbol{x}) - f(r(\boldsymbol{x})) + A\Big\}d\boldsymbol{x} - \int p_{\mathrm{nu}}(\boldsymbol{x})\Big\{\tilde{f}(r(\boldsymbol{x}))\Big\}d\boldsymbol{x}$. Note that we introduce a constant A, which is irrelevant to the original optimization problem. Here, let us define $\ell_1(t) := \partial f(t)t - f(t) + A$, and $\ell_2(t) := -\tilde{f}(t)$. In the above equation, since Assumption 2 implies $\ell_1(t) \geq 0$, and $0 < C < \frac{1}{\overline{R}}$ and $\frac{p_{\mathrm{nu}}(\boldsymbol{x})}{p_{\mathrm{de}}(\boldsymbol{x})} \leq \overline{R}$ imply $p_{\mathrm{de}}(\boldsymbol{x}) - Cp_{\mathrm{nu}}(\boldsymbol{x}) > 0$ for all $\boldsymbol{x} \in \mathcal{X}$, we have $\int \Big\{p_{\mathrm{de}}(\boldsymbol{x}) - Cp_{\mathrm{nu}}(\boldsymbol{x})\Big\}\Big\{\ell_1(r(\boldsymbol{x}))\Big\}d\boldsymbol{x} > 0$. Motivated by this inequality, we propose an empirical risk with the non-negative correction defined as $\widehat{\mathrm{nnBR}}_f(r) := \hat{\mathbb{E}}_{\mathrm{nu}}\big[\ell_2(r(X))\big] + \Big(\hat{\mathbb{E}}_{\mathrm{de}}\big[\ell_1(r(X))\big] - C\hat{\mathbb{E}}_{\mathrm{nu}}\big[\ell_1(r(X))\big]\Big)_+$, where $(\cdot)_+ := \max\{0, \cdot\}$. Our *deep direct DRE* (D3RE) is based on minimizing $\widehat{\mathrm{nnBR}}_f(r)$.

Remark 1 (Choice of C)**.** In practice, selecting the hyper-parameter C does not require accurate knowledge of $\overline{R}$ because any $0 < C < 1/\overline{R}$ is sufficient to justify the non-negative correction. However, selecting C that is too small may damage the empirical performance. See Section 5.2.

nnBR Divergence with Existing Methods: The above strategy can be instantiated in various methods previously proposed for DRE. Here, we introduce the non-negative BR divergence estimators that correspond to LSIF, UKL, BKL, and PULogLoss as follows:

$$\widehat{\mathrm{nnBR}}_{\mathrm{LSIF}}(r) := -\hat{\mathbb{E}}_{\mathrm{nu}}\left[r(X) - \frac{C}{2}r^2(X)\right] + \left(\frac{1}{2}\hat{\mathbb{E}}_{\mathrm{de}}\left[r^2(X)\right] - \frac{C}{2}\hat{\mathbb{E}}_{\mathrm{nu}}\left[r^2(X)\right]\right)_+.$$

$$\widehat{\mathrm{nnBR}}_{\mathrm{UKL}}(r) = -\hat{\mathbb{E}}_{\mathrm{nu}}\left[\log\big(r(X)\big) - Cr(X)\right] + \Big(\hat{\mathbb{E}}_{\mathrm{de}}\left[r(X)\right] - C\hat{\mathbb{E}}_{\mathrm{nu}}\left[r(X)\right]\Big)_+,$$

$$\begin{aligned}\widehat{\mathrm{nnBR}}_{\mathrm{BKL}}(r) = &-\hat{\mathbb{E}}_{\mathrm{nu}}\left[\log\left(\frac{r(X)}{1+r(X)}\right) + C\log\left(\frac{1}{1+r(X)}\right)\right] \\ &+ \left(-\hat{\mathbb{E}}_{\mathrm{de}}\left[\log\left(\frac{1}{1+r(X)}\right)\right] + C\hat{\mathbb{E}}_{\mathrm{nu}}\left[\log\left(\frac{1}{1+r(X)}\right)\right]\right)_+,\end{aligned}$$

$$\widehat{\mathrm{nnBR}}_{\mathrm{PU}}(r) := -C\hat{\mathbb{E}}_{\mathrm{nu}}\left[\log\big(r(X)\big)\right] + \Big(C\hat{\mathbb{E}}_{\mathrm{nu}}\left[\log\big(1 - r(X)\big)\right] - \hat{\mathbb{E}}_{\mathrm{de}}\left[\log\big(1 - r(X)\right]\Big)_+.$$

More detailed derivation of $\tilde{f}$ is in Appendix B. In practice, using flexible models for KLIEP poses another problem that the constrained optimization is no longer convex and is difficult to solve. Therefore, we experiment with UKL, unconstrained minimization of the objective function of KLIEP. In Appendix C, we provide the pseudo code of D3RE. For improving the performance heuristically, we use gradient ascending.

4 Theoretical Justification of D3RE

In this section, we confirm the validity of the proposed method by providing an estimation error bound. Given $n \in \mathbb{N}$ and a distribution p, we define the *Rademacher complexity* $\mathcal{R}_n^p$ of a function class $\mathcal{H}$ as $\mathcal{R}_n^p(\mathcal{H}) := \mathbb{E}_p \mathbb{E}_\sigma \left[\sup_{r\in\mathcal{H}} \left|\frac{1}{n}\sum_{i=1}^n \sigma_i r(X_i)\right|\right]$, where $\{\sigma_i\}_{i=1}^n$ are independent uniform sign variables and $\{X_i\}_{i=1}^n \overset{\text{i.i.d.}}{\sim} p$. We omit r^* from the notation of BR_f when there is no ambiguity.

4.1 Estimation Error Bound based on Rademacher Complexity

The following theorem provides an estimation error bound in terms of $\mathcal{R}_n^p$. Here, we state a special case of Theorem 2 in Appendix H such that the *consistent correction function* is $(\cdot)_+$.

Assumption 3. Let $I_r := (b_r, B_r)$. Assume that there exists an empirical risk minimizer $\hat{r} \in \arg\min_{r\in\mathcal{H}} \widehat{\mathrm{nnBR}}_f(r)$ and a population risk minimizer $\bar{r} \in \arg\min_{r\in\mathcal{H}} \mathrm{BR}_f(r)$. Assume $B_\ell := \sup_{t\in I_r}\{\max\{|\ell_1(t)|, |\ell_2(t)|\}\} < \infty$. Also assume ℓ_1 (resp. ℓ_2) is L_{ℓ_1}-Lipschitz (resp. L_{ℓ_2}-Lipschitz) on I_r. Assume also that $\inf_{r\in\mathcal{H}}(\mathbb{E}_{\mathrm{de}} - C\mathbb{E}_{\mathrm{nu}})\ell_1(r(X)) > 0$ holds.

Theorem 1 (Estimation error bound)**.** *Under Assumption 3, for any $\delta \in (0,1)$, with probability at least $1-\delta$, we have* $\mathrm{BR}_f(\hat{r}) - \mathrm{BR}_f(\bar{r}) \le L_{\ell_1}\mathcal{R}_{n_{\mathrm{de}}}^{p_{\mathrm{de}}}(\mathcal{H}) + 8(CL_{\ell_1} + L_{\ell_2})\mathcal{R}_{n_{\mathrm{nu}}}^{p_{\mathrm{nu}}}(\mathcal{H}) + 2\Phi_C^f(n_{\mathrm{nu}}, n_{\mathrm{de}}) + B_\ell\sqrt{8\left(\frac{1}{n_{\mathrm{de}}} + \frac{(1+C)^2}{n_{\mathrm{nu}}}\right)\log\frac{1}{\delta}}$*, where* $\Phi_C^f(n_{\mathrm{nu}}, n_{\mathrm{de}}) := (1+C)B_\ell \exp\left(-\frac{2\alpha^2}{(B_\ell{}^2/n_{\mathrm{de}}) + (C^2 B_\ell{}^2/n_{\mathrm{nu}})}\right)$ *and $\alpha > 0$ is a constant determined in the proof of Lemma 3 in Appendix H.*

In order for the boundedness and Lipschitz continuity in Assumption 3 to hold for the loss functions involving a logarithm (UKL, BKL, PU), a technical assumption $b_r > 0$ is sufficient. We obtain a theoretical guarantee for D3RE from Theorem 1 by additionally imposing Assumption 4 to bound the Rademacher complexities using a previously known result (Golowich et al., 2019, Theorem 1).

Assumption 4 (Neural networks with bounded complexity)**.** Assume that p_{nu} and p_{de} have bounded supports: $\sup_{x\in\mathcal{X}^{\mathrm{de}}} \|x\| < \infty$. Also assume that $\mathcal{H}$ consists of real-valued neural networks of depth L over the domain $\mathcal{X}$, where each parameter matrix W_j has the Frobenius norm at most $B_{W_j} \ge 0$ and with 1-Lipschitz activation functions φ_j that are positive-homogeneous (i.e., φ_j is applied element-wise and $\varphi_j(\alpha t) = \alpha\varphi_j(t)$ for all $\alpha \ge 0$).

Under Assumption 4, Lemma 4 in Appendix I reveals $\mathcal{R}_{n_{\mathrm{nu}}}^{p_{\mathrm{nu}}}(\mathcal{H}) = \mathcal{O}(1/\sqrt{n_{\mathrm{nu}}})$ and $\mathcal{R}_{n_{\mathrm{de}}}^{p_{\mathrm{de}}}(\mathcal{H}) = \mathcal{O}(1/\sqrt{n_{\mathrm{de}}})$. By combining these with Theorem 1, we obtain the following corollary:

Corollary 1 (Estimation error bound for D3RE)**.** *Under Assumptions 3 and 4, for any $\delta \in (0,1)$, we have with probability at least $1-\delta$,*

$$\mathrm{BR}_f(\hat{r}) - \mathrm{BR}_f(\bar{r}) \le \frac{\kappa_1}{\sqrt{n_{\mathrm{de}}}} + \frac{\kappa_2}{\sqrt{n_{\mathrm{nu}}}} + 2\Phi_C^f(n_{\mathrm{nu}}, n_{\mathrm{de}}) + B_\ell\sqrt{8\left(\frac{1}{n_{\mathrm{de}}} + \frac{(1+C)^2}{n_{\mathrm{nu}}}\right)\log\frac{1}{\delta}},$$

where κ_1, κ_2 are constants that depend on C, f, B_p, L, and B_{W_j}.

4.2 Estimation Error Bound for L^2 Distance

Theorem 1 and Corollary 1 can be readily turned into L^2 distance bounds by applying Lemma 1, which can be more convenient for the theoretical analyses for subsequent tasks relying on the density ratio estimator (Cortes et al., 2008). The proof can be found in Appendix J.

Lemma 1 (Estimation error bound in L^2 distance)**.** *Let $\mathcal{H}_2 := \{r : \mathcal{X} \to I_r | \int |r(\boldsymbol{x})|^2 \mathrm{d}\boldsymbol{x} < \infty\}$ and assume the true density ratio r^* is in $\mathcal{H}_2$. If $\inf_{t\in I_r} f''(t) > 0$, then there exists $\mu > 0$ such that*

$$\|\hat{r} - r^*\|_{L^2(p_{\mathrm{de}})}^2 \le \underbrace{\frac{2}{\mu}\left(\mathrm{BR}_f(\hat{r}) - \mathrm{BR}_f(\bar{r})\right)}_{\textit{Theorem 1 or Corollary 1}} + \underbrace{\frac{2}{\mu}\left(\mathrm{BR}_f(\bar{r}) - \mathrm{BR}_f(r^*)\right)}_{\textit{Best approximation error}}.$$

Note that the strong-convexity assumption of Lemma 1 could be exploited to investigate the convergence rate in more detail, via finer-grained proof techniques such as local Rademacher complexity. Nevertheless, the above theoretical guarantee already suffices for the basic justification of D3RE.

5 EXPERIMENT WITH IMAGE DATA

In this section, we experimentally show how the existing estimators fail to estimate the density ratio when using neural networks and that our proposed estimators succeed. To investigate the performances, we consider PU learning. For a binary classification problem with labels $y \in \{-1, +1\}$, we consider training a classifier only from $p(\boldsymbol{x} \mid y = +1)$ and $p(\boldsymbol{x})$ to find a positive data point in test data sampled from $p(\boldsymbol{x})$. The goal is to maximize the *area under the receiver operating characteristic* (AUROC) curve, which is a criterion used for anomaly detection, by estimating the density ratio $r^*(\boldsymbol{x}) = p(\boldsymbol{x} \mid y = +1)/p(\boldsymbol{x})$. We construct the positive and negative dataset from `CIFAR-10`[1](Krizhevsky, 2009) dataset with 10 classes. The positive dataset comprises 'airplane', 'automobile', 'ship', and 'truck'; the negative dataset comprises 'bird', 'cat', 'deer', 'dog', 'frog', and 'horse'. We use $1,000$ positive data sampled from $p(\boldsymbol{x} \mid y = +1)$ and $1,000$ unlabeled data sampled from $p(\boldsymbol{x})$ to train the models. Then, we calculate the AUROCs using $10,000$ test data sampled from $p(\boldsymbol{x})$. In this case, it is desirable to set $C < \frac{1}{2}$ because $\frac{p(\boldsymbol{x}|y=+1)}{0.5p(\boldsymbol{x}|y=+1)+0.5p(\boldsymbol{x}|y=-1)} = \frac{1}{0.5+0.5\frac{p(\boldsymbol{x}|y=-1)}{p(\boldsymbol{x}|y=+1)}}$. For demonstrative purposes, we use the CNN architecture from the PyTorch tutorial (Paszke et al., 2019). Details of the network structure are shown in Appendix D.2. The model is trained using Adam without weight decay and the parameters $(\beta_1, \beta_2, \epsilon)$ in Kingma & Ba (2015) are fixed at the default of PyTorch, namely $(0.9, 0.999, 10^{-8})$.

5.1 COMPARISON WITH NAIVE ESTIMATORS

First, we compare two of the proposed estimators, $\widehat{\mathrm{nnBR}}_{\mathrm{PU}}$ (nnBR-PU) and $\widehat{\mathrm{nnBR}}_{\mathrm{LSIF}}$ (nnBR-LSIF), with the existing estimators, $\widehat{\mathrm{BR}}_{\mathrm{PU}}$ (PU-NN) and $\widehat{\mathrm{BR}}_{\mathrm{LSIF}}$ (uLSIF-NN). We use the logistic loss for PULogLoss. Additionally, we conduct an experiment with uLSIF-NN using a naively capped model $\tilde{r}(\boldsymbol{x}) = \min\{r(\boldsymbol{x}), 1/C\}$ (Bounded uLSIF). We fix the hyperparameter C at $1/3$. We report the results for two learning rates, 1×10^{-4} and 1×10^{-5}. We conducted 10 trials, and calculated the average AUROCs. We also compute $\hat{\mathbb{E}}_{\mathrm{de}}[\hat{r}(X)]$, which should be close to 1 if we successfully estimate the density ratio, because $\int (p(x|y = +1)/p(\boldsymbol{x}))p(\boldsymbol{x})dx = 1$. The results are in Figure 2. In all cases, the proposed estimators outperform the other methods. In contract, the unstable behaviors of PU-NN and LISF-NN are caused by the train-loss hacking (also see (Kiryo et al., 2017) Appendix F.1). The experiment also demonstrates that the naive capping fails to prevent the train-loss hacking (Bounded uLSIF) and leads to a suboptimal behavior. A naive capping is insufficient because an unreasonable model such that $r(\boldsymbol{x}_i^{\mathrm{de}}) = 0$ and $r(\boldsymbol{x}_i^{\mathrm{nu}}) = 1/C$ still can be a minimizer by making one part of the empirical BR divergence largely negative, e.g., as $\frac{1}{2}\hat{\mathbb{E}}_{\mathrm{de}}\left[r^2(X)\right] - \frac{C}{2}\hat{\mathbb{E}}_{\mathrm{nu}}\left[r^2(X)\right] = 0 - \frac{1}{2C}$.

5.2 EMPIRICAL SENSITIVITY ANALYSIS ON THE UPPER BOUNDS OF THE DENSITY RATIO

Next, we investigate the sensitivity of D3RE to the hyperparameter C. We use nnBR-LSIF and nnBR-PU as in Section 5.1, but vary the hyperparameter C in $\{1/5, 1/2, 2/3\}$. The other settings remain unchanged from the previous section. These results are shown in Figure 4 in Appendix F.1. For $\overline{R} = 2.0$, the estimator show a better performance when $1/C$ is close to 2.0.

5.3 COMPARISON WITH VARIOUS ESTIMATORS USING NNBR DIVERGENCE

Finally, we examine the performances of nnBR-LSIF, nnBR-PU, nnBR-UKL, and nnBR-BKL. The learning rate was 1×10^{-3}, and the other settings were identical to those in the previous experiments. These results are shown in Figure 4 in Appendix F.1. Although nnBR-UKL and nnBR-BKL show better performance in earlier epochs, nnBR-LSIF and nnBR-PU appear more stable.

[1]See `https://www.cs.toronto.edu/~kriz/cifar.html`.

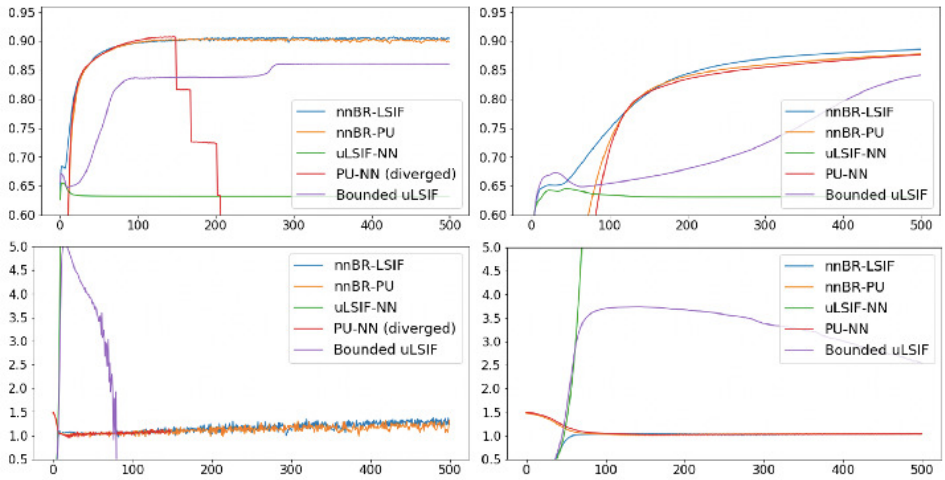

Figure 2: Experimental results of Section 5.1. The horizontal axis is epoch, and the vertical axis is AUROC. The learning rates of the left and right graphs are 1×10^{-4} and 1×10^{-5}, respectively. The upper graphs show the AUROCs and the lower graphs show $\hat{\mathbb{E}}_{\mathrm{de}}[\hat{r}(X)]$, which will approach 1 when we successfully estimate the density ratio.

6 Applications

As applications of D3RE, we introduce *inlier-based outlier detection* and *covariate shift adaptation* with experiments using benchmark datasets. Moreover, we introduce other applications in Appendix G. In addition to `CIFAR-10`, we use `MNIST`[2] (LeCun et al., 1998), `fashion-MNIST` (`FMNIST`)[3] (Xiao et al., 2017), and a document dataset of Amazon[4] (Blitzer et al., 2007).

6.1 Inlier-based Outlier Detection

Hido et al. (2008; 2011) applied the direct DRE for inlier-based outlier detection: finding outliers in a test set based on a training set consisting only of inliers by using the ratio of training and test data densities as an outlier score. Nam & Sugiyama (2015) and Abe & Sugiyama (2019) proposed using neural networks with DRE for this problem. In relation to the experimental setting of Section 5, the problem setting can be seen as a transductive variant of PU learning (Kato et al., 2019).

Experiments: We follow the setting proposed by Golan & El-Yaniv (2018) using `MNIST`, `CIFAR-10`, and `FMNIST`. There are ten classes in each dataset; we use one class as the inlier class and all other classes as the outliers. For example, in the case of `CIFAR-10`, there are $5,000$ train data per class. On the other hand, there are $1,000$ test data for each class, which consist of $1,000$ inlier samples and $9,000$ outlier samples. The AUROC is used as a metric to evaluate whether an outlier class can be detected in the test data. We compare the proposed methods with benchmark methods of deep semi-supervised anomaly detection (DeepSAD) (Ruff et al., 2020) and geometric transformations (GT) (Golan & El-Yaniv, 2018). The details of each method are shown in Appendix E. To compare the methods fairly, we use the same architectures of neural networks from Golan & El-Yaniv (2018) and Ruff et al. (2020), LeNet and Wide Resnet, for D3RE. The details of the structures are shown in Appendix D. A part of the experimental results with `CIFAR-10` and `FMNIST` are shown in Table 2 due to the limitation of the space. The full results are shown in Table 4 in Appendix F.2. The proposed methods result in better AUROCs than the existing methods. The largest performance gain is seen in the CIFAR-10: the mean AUROC is improved by 0.157 on average between the uLSIF-NN and nnBR-LSIF. Although GT and DeepSAD are designed for a different problem, to the best of our knowledge, these are the only applicable neural-network-based methods which are not based on DRE.

[2] `MNIST` has 10 classes from 0 to 9. See `http://yann.lecun.com/exdb/mnist/`.
[3] `FMNIST` has 10 classes. See `https://github.com/zalandoresearch/fashion-mnist`.
[4] `http://john.blitzer.com/software.html`

Table 2: Average AUROC curve (Mean) with the standard deviation (SD) over 5 trials of anomaly detection methods. For all datasets, each model was trained on a single class and tested against all other classes. The best figure is in bold.

CIFAR-10 Network	uLSIF-NN LeNet		nnBR-LSIF LeNet		nnBR-PU LeNet		nnBR-LSIF WRN		nnBR-PU WRN		Deep SAD LeNet		GT WRN	
Inlier Class	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
plane	0.745	0.056	0.934	0.002	**0.943**	0.001	0.925	0.004	0.923	0.001	0.627	0.066	0.697	0.009
car	0.758	0.078	0.957	0.002	**0.968**	0.001	0.965	0.002	0.960	0.001	0.606	0.018	0.962	0.003
bird	0.768	0.012	0.850	0.007	**0.878**	0.004	0.844	0.004	0.858	0.004	0.404	0.006	0.752	0.002
cat	0.745	0.037	0.820	0.003	**0.856**	0.002	0.810	0.009	0.841	0.002	0.517	0.018	0.727	0.014
deer	0.758	0.036	0.886	0.004	**0.909**	0.002	0.864	0.008	0.872	0.002	0.704	0.052	0.863	0.014

FMNIST Network	uLSIF-NN LeNet		nnBR-LSIF LeNet		nnBR-PU LeNet		nnBR-LSIF WRN		nnBR-PU WRN		Deep SAD LeNet		GT WRN	
Inlier Class	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
T-shirt/top	0.960	0.005	0.981	0.001	**0.985**	0.000	0.984	0.001	0.982	0.000	0.558	0.031	0.890	0.007
Trouser	0.961	0.010	0.998	0.000	**1.000**	0.000	0.998	0.000	0.998	0.000	0.758	0.022	0.974	0.004
Pullover	0.944	0.012	0.976	0.001	0.980	0.001	**0.983**	0.002	0.972	0.001	0.617	0.046	0.902	0.005
Dress	0.973	0.006	0.986	0.001	**0.992**	0.000	0.991	0.001	0.986	0.000	0.525	0.038	0.843	0.014
Coat	0.958	0.006	0.978	0.001	**0.983**	0.000	0.981	0.002	0.974	0.000	0.627	0.029	0.885	0.003

Table 3: Average PD (Mean) with standard deviation (SD) over 10 trials with different seeds per method. The best performing method in terms of the mean PD is specified by bold face.

Domains (Train → Test)	book → dvd		book → elec		book → kitchen		dvd → elec		dvd → kitchen		elec → kitchen	
DRE method	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
w/o IW	0.126	0.008	0.174	0.010	0.166	0.009	0.162	0.006	0.146	0.010	0.074	0.005
Kernel uLSIF	0.122	0.009	0.162	0.009	0.159	0.007	0.153	0.006	0.142	0.007	0.068	0.005
Kernel KLIEP	0.130	0.010	0.164	0.009	0.161	0.007	0.154	0.006	0.143	0.006	0.070	0.005
uLSIF-NN	0.126	0.008	0.174	0.010	0.166	0.009	0.162	0.006	0.146	0.010	0.074	0.005
PU-NN	0.126	0.008	0.174	0.010	0.166	0.009	0.162	0.006	0.146	0.010	0.074	0.005
nnBR-LSIF	0.120	0.008	**0.160**	0.008	0.157	0.008	**0.148**	0.006	**0.138**	0.007	**0.066**	0.005
nnBR-PU	**0.119**	0.008	**0.160**	0.008	**0.156**	0.007	**0.148**	0.005	**0.138**	0.007	**0.066**	0.005

6.2 Covariate Shift Adaptation by Importance Weighting

We consider training a model using input distribution different from the test input distribution, which is called *covariate shift*, (Bickel et al., 2009). To solve this problem, the density ratio has been used via importance weighting (IW) (Shimodaira, 2000; Yamada et al., 2010; Reddi et al., 2015).

Experiments: We use the Amazon review dataset for multi-domain sentiment analysis (Blitzer et al., 2007). This data consists of text reviews from four different product domains: book, electronics (elec), dvd, and kitchen. Following Chen et al. (2012) and Menon & Ong (2016), we transform the text data using TF-IDF to map them into the instance space $\mathcal{X} = \mathbb{R}^{10000}$ (Salton & McGill, 1986). Each review is endowed with four labels indicating the positivity of the review, and our goal is to conduct regression for these labels. To achieve this goal, we perform kernel ridge regression with the polynomial kernel. We compare regression without IW (w/o IW) with regression using the density ratio estimated by PU-NN, uLSIF-NN, nnBR-LSIF, nnBR-PU, uLSIF with Gaussian kernels (Kernel uLSIF), and KLIEP with Gaussian kernels (Kernel KLIEP). We conduct experiments on $2,000$ samples from one domain, and test $2,000$ samples. Following Menon & Ong (2016), we reduce the dimension into 100 dimensions by principal component analysis when using Kernel uLSIF, Kernel KLEIP, and regressions. Following Menon & Ong (2016) and Cortes & Mohri (2011), the mean and standard deviation of the pairwise disagreement (PD), $1 - \mathrm{AUROC}$, is reported. A part of results is in Table 3. The full results are in Appendix F.3. The methods with D3RE show preferable performance, but the improvement is not significant compared with the image data. We consider this is owing to the difficulty of the covariate shift problem in this dataset.

7 Conclusion

We proposed a non-negative correction to the empirical BR divergence for DRE. By using the prior knowledge of the upper bound of the density ratio, we can prevent the train-loss hacking when using flexible models. In our theoretical analysis, we showed the generalization bound of the algorithm.

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A DETAILS OF EXISTING METHODS FOR DRE

In this section, we overview examples of DRE methods in the framework of the density ratio matching under BR divergence.

Least Squares Importance Fitting (LSIF): LSIF minimizes the squared error between a density ratio model r and the true density ratio r^* defined as follows (Kanamori et al., 2009):

$$R_{\mathrm{LSIF}}(r) = \mathbb{E}_{\mathrm{de}}[(r(X) - r^*(X))^2] = \mathbb{E}_{\mathrm{de}}[(r^*(X))^2] - 2\mathbb{E}_{\mathrm{nu}}[r(X)] + \mathbb{E}_{\mathrm{de}}[(r(X))^2].$$

In the *unconstrained LSIF* (uLSIF) (Kanamori et al., 2009), we ignore the first term in the above equation and estimate the density ratio by the following minimization problem:

$$\hat{r} = \underset{r \in \mathcal{H}}{\arg\min} \left[\frac{1}{2}\hat{\mathbb{E}}_{\mathrm{de}}[(r(X))^2] - \hat{\mathbb{E}}_{\mathrm{nu}}[r(X)] + \mathcal{R}(r) \right], \tag{4}$$

where $\mathcal{R}$ is a regularization term. This empirical risk minimization is equal to minimizing the empirical BR divergence defined in (3) with $f(t) = (t-1)^2/2$.

Unnormalized Kullback–Leibler (UKL) Divergence and KL Importance Estimation Procedure (KLIEP): The KL importance estimation procedure (KLIEP) is derived from the unnormalized Kullback–Leibler (UKL) divergence objective (Sugiyama et al., 2011b), which uses $f(t) = t\log(t) - t$. Ignoring the terms which are irrelevant for the optimization, we obtain the unnormalized Kullback–Leibler (UKL) divergence objective (Sugiyama et al., 2011b) as

$$\mathrm{BR}_{\mathrm{UKL}}(r) = \mathbb{E}_{\mathrm{de}}\left[r(X)\right] - \mathbb{E}_{\mathrm{nu}}\left[\log\left(r(\boldsymbol{x})\right)\right].$$

KLIEP further imposes a constraint that the ratio model $r(\boldsymbol{x})$ is non-negative for all $\boldsymbol{x}$ and is normalized as

$$\hat{\mathbb{E}}_{\mathrm{de}}\left[r(X)\right] = 1.$$

Then, following is the optimization criterion of KLIEP (Sugiyama et al., 2008):

$$\begin{aligned} &\max_{r} \hat{\mathbb{E}}_{\mathrm{nu}}\left[\log\left(r(\boldsymbol{x})\right)\right] \\ &\text{s.t. } \hat{\mathbb{E}}_{\mathrm{de}}\left[r(X)\right] = 1 \text{ and } r(\boldsymbol{x}) \geq 0 \text{ for all } \boldsymbol{x}. \end{aligned}$$

Logistic Regression: By using $f(t) = \log(t) - (1+t)\log(1+t)$, we obtain the following BR divergence called the binary Kullback–Leibler (BKL) divergence:

$$\mathrm{BR}_{\mathrm{BKL}}(r) = -\mathbb{E}_{\mathrm{de}}\left[\log\left(\frac{1}{1+r(X)}\right)\right] - \mathbb{E}_{\mathrm{nu}}\left[\log\left(\frac{r(X)}{1+r(\boldsymbol{x})}\right)\right].$$

This BR divergence is derived from a formulation based on the logistic regression (Hastie et al., 2001; Sugiyama et al., 2011b).

PU Learning with the Log Loss: Consider a binary classification problem and let $\boldsymbol{x}$ and $y \in \{\pm 1\}$ be the feature and the label of a sample, respectively. In PU learning, the goal is to train a classifier only using positive data sampled from $p(\boldsymbol{x} \mid y = +1)$, and unlabeled data sampled from $p(\boldsymbol{x})$ in binary classification (Elkan & Noto, 2008). More precisely, this problem setting of PU learning is called the *case-control scenario* (Elkan & Noto, 2008; Niu et al., 2016). Let $\mathcal{G}$ be the set of measurable functions from $\mathcal{X}$ to $[\epsilon, 1-\epsilon]$, where $\epsilon \in (0, 1/2)$ is a small positive value. For a loss function $\ell : \mathbb{R} \times \{\pm 1\} \to \mathbb{R}^+$, du Plessis et al. (2015) showed that the classification risk of $g \in \mathcal{G}$ in the PU problem setting can be expressed as

$$R_{\mathrm{PU}}(g) = \pi \int \Big(\ell(g(X), +1) - \ell(g(X), -1)\Big) p(\boldsymbol{x} \mid y = +1) d\boldsymbol{x} + \int \ell(g(X), -1)] p(\boldsymbol{x}) d\boldsymbol{x}. \tag{5}$$

According to Kato et al. (2019), we can derive the following risk for DRE from the risk for PU learning (5) as follows:

$$\mathrm{BR}_{\mathrm{PU}}(g) = \frac{1}{\overline{R}}\mathbb{E}_{\mathrm{nu}}\left[-\log\left(g(X)\right) + \log\left(1 - g(X)\right)\right] - \mathbb{E}_{\mathrm{de}}\left[\log\left(1 - g(X)\right)\right],$$

and Kato et al. (2019) showed that $g^* = \arg\min_{g \in \mathcal{G}} \mathrm{BR}_{\mathrm{PU}}(g)$ satisfies the following:

Proposition 1. It holds almost everywhere that

$$g^*(\boldsymbol{x}) = \begin{cases} 1-\varepsilon & (\boldsymbol{x} \notin D_2), \\ C\frac{p_{\mathrm{nu}}(\boldsymbol{x})}{p_{\mathrm{de}}(\boldsymbol{x})} & (\boldsymbol{x} \in D_1 \cap D_2), \\ \varepsilon & (\boldsymbol{x} \notin D_1), \end{cases}$$

where $C = \frac{1}{R}$, $D_1 = \{\boldsymbol{x} \mid Cp_{\mathrm{nu}}(\boldsymbol{x}) \geq \epsilon p_{\mathrm{de}}(\boldsymbol{x})\}$, and $D_2 = \{\boldsymbol{x} | Cp_{\mathrm{nu}}(\boldsymbol{x}) \leq (1-\epsilon)p_{\mathrm{de}}(\boldsymbol{x})\}$.

Using this result, we define the empirical version of $\mathrm{BR}_{\mathrm{PU}}(g)$ as follows:

$$\widehat{\mathrm{BR}}_{\mathrm{PU}}(r^* \| r) := C\mathbb{E}_{\mathrm{nu}}\left[-\log\left(r(\boldsymbol{x}_i)\right) + \log\left(1 - r(\boldsymbol{x}_j)\right)\right] - \mathbb{E}_{\mathrm{de}}\left[\log\left(1 - r(\boldsymbol{x}_i)\right)\right].$$

Remark 2 (DRE and PU learning)**.** Menon & Ong (2016) showed that minimizing a proper CPE loss is equivalent to minimizing a BR divergence to the true density ratio, and demonstrated the viability of using existing losses from one problem for the other for CPE and DRE. Kato et al. (2019) pointed out the relation between the PU learning and density ratio estimation and leveraged it to solve a sample selection bias problem in PU learning. In this paper, we introduced the BR divergence with $f(t) = \log(1 - Ct) + Ct(\log(Ct) - \log(1 - Ct))$, inspired by the objective function of PU learning with the log loss. In the terminology of Menon & Ong (2016), this f results in a DRE objective without a *link function*. In other words, it yields a direct DRE method.

B Examples of $\tilde{f}$

Here, we show the examples of $\tilde{f}$ such that $\partial f(t) = C\big(\partial f(t)t - f(t)\big) + \tilde{f}(t)$, where $\tilde{f}(t)$ is bounded from above, and $\partial f(t)t - f(t) + A$ is non-negative.

First, we consider $f(t) = (t-1)^2/2$, which results in the LSIF objective. Because $\partial f(t) = t - 1$, we have

$$\begin{aligned} &t - 1 = C\big((t-1)t - (t-1)^2/2\big) + \tilde{f}(t) \\ &\Leftrightarrow \tilde{f}(t) = -C\big((t-1)t - (t-1)^2/2\big) + t - 1 = -\frac{C}{2}t^2 + \frac{C}{2} + t - 1. \end{aligned}$$

The function is a concave quadratic function, therefore it is upper bounded. Note that uLSIF satisfies the Assumption 2 with $A = \frac{1}{2}$ since $\partial f(t)t + f(t) + \frac{1}{2} = \frac{1}{2}t^2$, and Assumption 3 automatically holds. Also note that the term A is irrelevant to the optimization.

Second, we consider $f(t) = t\log(t) - t$, which results in the UKL or KLIEP objective. Because $\partial f(t) = \log(t)$, we have

$$\begin{aligned} &\log(t) = C\big(\log(t)t - t\log(t) + t\big) + \tilde{f}(t) \\ &\Leftrightarrow \tilde{f}(t) = -tC + \log(t). \end{aligned}$$

We can easily confirm that the function is upper bounded by taking the derivative and finding that $t = 1/C$ gives the maximum. Note that UKL satisfies the Assumption 2 with $A = 0$ since $\partial f(t)t - f(t) = t\log(t) - t\log(t) + t = t$, and Assumption 3 automatically holds.

Third, we consider $f(t) = t\log(t) - (1+t)\log(1+t)$, which is used for DRE based on LR or BKL. Because $\partial f(t) = \log(t) - \log(1+t)$, we have

$$\begin{aligned} &\log(t) - \log(1+t) = C\big((\log(t) - \log(1+t))t - t\log(t) + (1+t)\log(1+t)\big) + \tilde{f}(t) \\ &\Leftrightarrow \tilde{f}(t) = -C\big(\log(1+t)\big) + \log(t) - \log(1+t) = \log\left(\frac{C}{1+t}\right) + \log\left(\frac{t}{1+t}\right). \end{aligned}$$

We can easily confirm that the function is upper bounded as the terms involving t always add up to be negative. Note that BKL satisfies the Assumption 2 with $A = 0$ since $\partial f(t)t - f(t) = (\log(t) - \log(1+t))t - t\log(t) + (1+t)\log(1+t) = \log(1+t)$, and Assumption 3 automatically holds.

Fourth, we consider the $f(t)$ in DRE based on PULog. In this case, we can obtain the same risk functional introduced in Kiryo et al. (2017). Note that PULog satisfies the Assumption 2 with $A = 0$ since $\partial f(t)t - f(t) = -\log(1-t)$ with $t < 1$, and Assumption 3 automatically holds.

Algorithm 1 D3RE

Input: Training data $\{\boldsymbol{x}_i^{\mathrm{nu}}\}_{i=1}^{n_{\mathrm{nu}}}$ and $\{\boldsymbol{x}_i^{\mathrm{de}}\}_{i=1}^{n_{\mathrm{de}}}$, the algorithm for stochastic optimization such as Adam (Kingma & Ba, 2015), the learning rate γ, the regularization coefficient λ.
Output: A density ratio estimator $\hat{r}$.
while No stopping criterion has been met: **do**
  Create N mini-batches $\{(\{\boldsymbol{x}_i^{\mathrm{nu}}\}_{i=1}^{n_{\mathrm{nu},j}}, \{\boldsymbol{x}_i^{\mathrm{de}}\}_{i=1}^{n_{\mathrm{de},j}})\}_{j=1}^{N}$.
  for $i = 1$ to N **do**
    if $\hat{\mathbb{E}}_{\mathrm{de}}\big[\ell_1(r(X))\big] - C\hat{\mathbb{E}}_{\mathrm{nu}}\big[\ell_1(r(X))\big] \geq 0$: **then**
      Gradient decent: set gradient $\nabla_r\big\{\hat{\mathbb{E}}_{\mathrm{nu}}^j\big[\ell_2(r(X))\big] + \hat{\mathbb{E}}_{\mathrm{de}}^j\big[\ell_1(r(X))\big] - C\hat{\mathbb{E}}_{\mathrm{nu}}^j\big[\ell_1(r(X))\big] + \lambda\mathcal{R}(r)\big\}$.
    else
      Gradient ascent: set gradient $\nabla_r\big\{-\hat{\mathbb{E}}_{\mathrm{de}}^j\big[\ell_1(r(X))\big] + C\hat{\mathbb{E}}_{\mathrm{nu}}^j\big[\ell_1(r(X))\big] + \lambda\mathcal{R}(r)\big\}$.
    end if
    Update r with the gradient and the learning rate γ.
  end for
end while

C IMPLEMENTATION

The algorithm for D3RE is described in Algorithm 1. For training with a large amount of data, we adopt the *stochastic optimization* by splitting the dataset into mini-batches. In stochastic optimization, we separate the samples into N mini-batches as $(\{\boldsymbol{x}_i^{\mathrm{nu}}\}_{i=1}^{n_{\mathrm{nu},j}}, \{\boldsymbol{x}_i^{\mathrm{de}}\}_{i=1}^{n_{\mathrm{de},j}})$ $(j = 1, \ldots, N$, where $n_{\mathrm{nu},j}$ and $n_{\mathrm{de},j}$ are the sample sizes in each mini-batch. Then, we consider taking sample average in each mini-batch. Let $\hat{\mathbb{E}}_{\mathrm{nu}}^j$ and $\hat{\mathbb{E}}_{\mathrm{de}}^j$ be sample averages over $\{\boldsymbol{x}_i^{\mathrm{nu}}\}_{i=1}^{n_{\mathrm{nu},j}}$ and $\{\boldsymbol{x}_i^{\mathrm{de}}\}_{i=1}^{n_{\mathrm{de},j}}$. In addition, we use regularization such as L1 and L2 penalties, denoted by $\mathcal{R}(r)$. For improving the performance, we heuristically employ *gradient ascent* from Kiryo et al. (2017) when $\hat{\mathbb{E}}_{\mathrm{de}}\big[\ell_1(r(X))\big] - C\hat{\mathbb{E}}_{\mathrm{nu}}\big[\ell_1(r(X))\big]$ becomes less than 0, i.e., update the model in the direction that increases the term. Let us note that our proposed method is agnostic to the optimization procedure, and other methods such as plain gradient descent can be combined with our method. We consider that further theoretical investigation of the optimization procedure is out of scope.

D NETWORK STRUCTURE USED IN SECTIONS 5 AND 6

We explain the structures of neural networks used in the experiments.

D.1 NETWORK STRUCTURE USED IN SECTIONS 5

In Section 5, we used `CIFAR-10` datasets. The model was a convolutional net (Springenberg et al., 2015): $(32 \times 32 \times 3)$-$C(3 \times 6, 3)$-$C(3 \times 16, 3)$-128-84-1, where the input is a 32×32 RGB image, $C(3 \times 6, 3)$ indicates that 3 channels of 3×6 convolutions followed by ReLU is used. This structure has been adopted from the tutorial of Paszke et al. (2019).

D.2 NETWORK STRUCTURE USED IN SECTIONS 6

Inlier-based Outlier Detection: We used the same LeNet-type CNNs proposed in Ruff et al. (2020). In the CNNs, each convolutional module consists of a convolutional layer followed by leaky ReLU activations with leakiness $\alpha = 0.1$ and (2×2)-max-pooling. For MNIST, we employ a CNN with two modules: $(32 \times 32 \times 3)$-$C(3 \times 32, 5)$-$C(32 \times 64, 5)$-$C(64 \times 128, 5)$-1. For `CIFAR-10` we employ the following architecture: $(32 \times 32 \times 1)$-$C(1 \times 8, 5)$-$C(8 \times 4, 5)$-1 with a batch normalization (Ioffe & Szegedy, 2015) after each convolutional layer.

The WRN architecture was proposed in Zagoruyko & Komodakis (2016) and it is also used in Golan & El-Yaniv (2018). This structure improved the performance of image recognition by decreasing the depth and increasing the width of the residual networks (He et al., 2015). We omit the detailed description of the structure here.

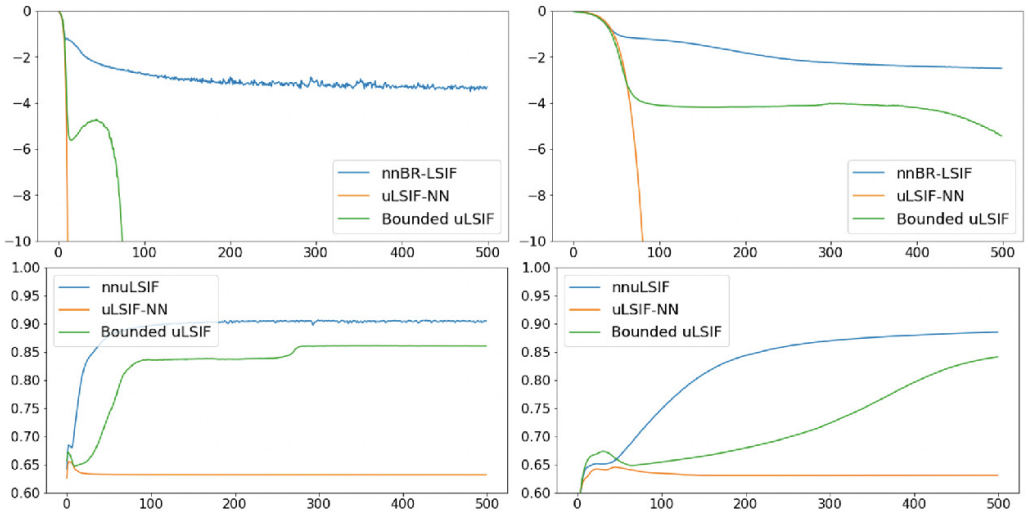

Figure 3: The learning curves of the experiments in Section 5.1. The horizontal axis is epoch. The vertical axes of the top figures indicate the training losses. The vertical axes of the bottom figures show the AURPC for the test data. The bottom figures are identical to the ones displayed in Section 5.1.

Covariate Shift Adaptation: We used the 5-layer perceptron with ReLU activations. The structure is 10000-1000-1000-1000-1000-1.

E EXSTING METHODS FOR ANOMALY DETECTION

This section introduces the existing methods for anomaly detection. DeepSAD is a method for semi-supervised anomaly detection, which tries to take advantage of labeled anomalies (Ruff et al., 2020). GT proposed by Golan & El-Yaniv (2018) trains neural networks based on a self-labeled dataset by performing 72 geometric transformations. The anomaly score based on GT is calculated based on the Dirichlet distribution obtained by maximum likelihood estimation using the softmax output from the trained network.

In the problem setting of the DeepSAD, we have access to a small pool of labeled samples, e.g. a subset verified by some domain expert as being normal or anomalous. In the experimental results shown in Ruff et al. (2020) indicate that, when we can use such samples, the DeepSAD outperforms the other methods. However, in our experimental results, such samples are not assumed to be available, hence the method does not perform well. The problem setting of Ruff et al. (2020) and ours are both termed *semi-supervised learning* in anomaly detection, but the two settings are different.

F DETAILS OF EXPERIMENTS

The details of experiments are shown in this section. The description of the data is as follows:

`MNIST`**:** The `MNIST` database is one of the most popular benchmark datasets for image classification, which consists of 28×28 pixel handwritten digits from 0 to 9 with $60,000$ train samples and $10,000$ test samples (LeCun et al., 1998).

`CIFAR-10`**:** The `CIFAR-10` dataset consists of $60,000$ color images of size 32×32 from 10 classes, each having 6000. There are $50,000$ training images and $10,000$ test images (Krizhevsky et al., 2012).

`fashion-MNIST`**:** The `fashion-MNIST` dataset consists of $70,000$ grayscale images of size 28×28 from 10 classes. There are $60,000$ training images and $10,000$ test images (Xiao et al., 2017).

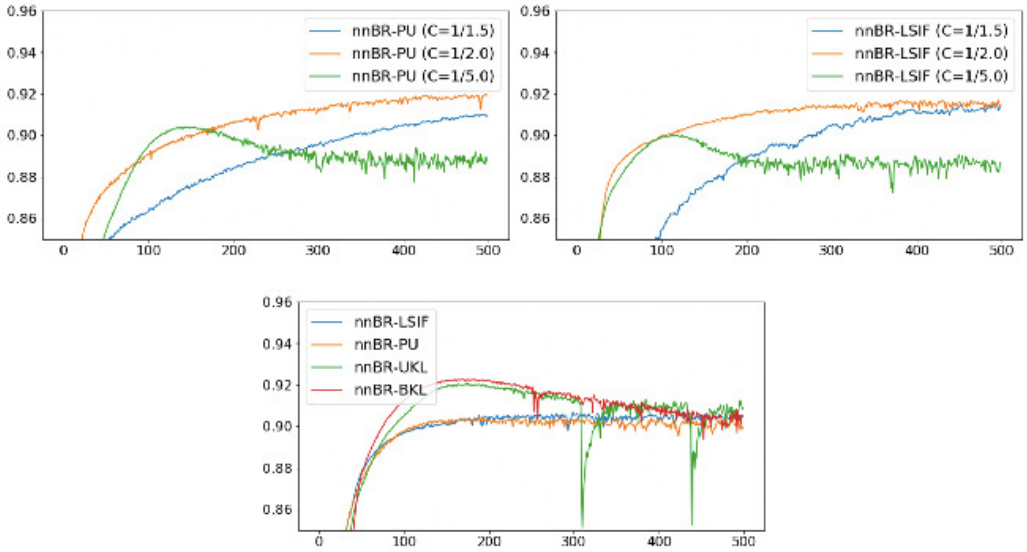

Figure 4: Top figures: the detailed experimental results for Section 5.2. Bottom figure: the detailed experimental results for Section 5.3. The horizontal axis is epoch, and the vertical axis is AUROC.

`Amazon Review Dataset`**:** Blitzer et al. (2007) published the text data of Amazon review. The data originally consists of a rating (0-5 stars) for four different genres of products in the electronic commerce site Amazon.com: books, DVDs, electronics, and kitchen appliances. Blitzer et al. (2007) also released the pre-processed and balanced data of the original data. The pre-processed data consists of text data with four labels 1, 2, 4, and 5. We map the text data into $10,000$ dimensional data by the TF-IDF mapping with that vocabulary size. In the experiment, for the pre-processed data, we solve the regression problem where the text data are the inputs and the ratings 1, 2, 4, and 5 are the outputs. When evaluating the performance, following Menon & Ong (2016), we calculate PD (=1-AUROUC) by regarding 4 and 5 ratings as positive labels and 1 and 2 ratings as negative labels.

F.1 Experiments with Image Data

We show the additional results of Section 5. Figure 3, we show the training loss of LSIF-based methods to demonstrate the train-loss hacking phenomenon caused by the objective function without a lower bound. In Figure 3, even though the training loss of uLSIF-NN and that of bounded uLSIF decrease more rapidly than that of nnBR-LSIF, the test AUROC score (the higher the better) either drops or fails to increase. These graphs are the manifestations of the severe train-loss hacking in DRE without our proposed device. Figure 4 shows the experimental results of Sections 5.2 and 5.3.

F.2 Experiments of Inlier-based Outlier Detection

In Table 4, we show the full results of inlier-based outlier detection. In almost all the cases, D3RE for inlier-based outlier detection outperforms the other methods. As explained in Section E, we consider that DeepSAD does not work well because the method assumes the availability of the labeled anomaly data, which is not available in our problem setting.

Remark 3 (Benchmark Methods)**.** Although GT is outperformed by our proposed method, the problem setting for the comparison is not in favor of GT as it does not assume the access to the test data. Recently proposed methods for semi-supervised anomaly detection by Ruff et al. (2020) did not perform well without using other side information used in Ruff et al. (2020). On the other hand, there is no other competitive methods in this problem setting, to the best of our knowledge.

Table 4: Average area under the ROC curve (Mean) of anomaly detection methods averaged over 5 trials with the standard deviation (SD). For all datasets, each model was trained on the single class, and tested against all other classes. The best performing method in each experiment is in bold. *SD*: Standard deviation.

MNIST	uLSIF-NN		nnBR-LSIF		nnBR-PU		nnBR-LSIF		nnBR-PU		Deep SAD		GT	
Network	LeNet		LeNet		LeNet		WRN		WRN		LeNet		WRN	
Inlier Class	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	0.999	0.000	0.997	0.000	0.999	0.000	**1.000**	0.000	**1.000**	0.000	0.592	0.051	0.963	0.002
1	**1.000**	0.000	0.999	0.000	**1.000**	0.000	**1.000**	0.000	**1.000**	0.000	0.942	0.016	0.517	0.039
2	0.997	0.001	0.994	0.000	0.997	0.001	**1.000**	0.000	**1.000**	0.001	0.447	0.027	0.992	0.001
3	0.997	0.000	0.995	0.001	0.998	0.000	**1.000**	0.000	**1.000**	0.000	0.562	0.035	0.974	0.001
4	0.998	0.000	0.997	0.001	0.999	0.000	**1.000**	0.000	**1.000**	0.000	0.646	0.015	0.989	0.001
5	0.997	0.000	0.996	0.001	0.998	0.000	**1.000**	0.000	**1.000**	0.000	0.502	0.046	0.990	0.001
6	0.997	0.001	0.997	0.001	0.999	0.000	**1.000**	0.000	**1.000**	0.000	0.671	0.027	0.998	0.000
7	0.996	0.001	0.993	0.001	0.998	0.001	**1.000**	0.000	**1.000**	0.001	0.685	0.032	0.927	0.004
8	0.997	0.000	0.994	0.001	0.997	0.000	**0.999**	0.000	**0.999**	0.000	0.654	0.026	0.949	0.002
9	0.993	0.002	0.990	0.002	0.994	0.001	**0.998**	0.001	**0.998**	0.001	0.786	0.021	0.989	0.001

CIFAR-10	uLSIF-NN		nnBR-LSIF		nnBR-PU		nnBR-LSIF		nnBR-PU		Deep SAD		GT	
Network	LeNet		LeNet		LeNet		WRN		WRN		LeNet		WRN	
Inlier Class	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
plane	0.745	0.056	0.934	0.002	**0.943**	0.001	0.925	0.004	0.923	0.001	0.627	0.066	0.697	0.009
car	0.758	0.078	0.957	0.002	**0.968**	0.001	0.965	0.002	0.960	0.001	0.606	0.018	0.962	0.003
bird	0.768	0.012	0.850	0.007	**0.878**	0.004	0.844	0.004	0.858	0.004	0.404	0.006	0.752	0.002
cat	0.745	0.037	0.820	0.003	**0.856**	0.002	0.810	0.009	0.841	0.002	0.517	0.018	0.727	0.014
deer	0.758	0.036	0.886	0.004	**0.909**	0.002	0.864	0.008	0.872	0.002	0.704	0.052	0.863	0.014
dog	0.728	0.103	0.875	0.004	**0.906**	0.002	0.887	0.005	0.896	0.002	0.490	0.025	0.873	0.002
frog	0.750	0.060	0.944	0.003	**0.958**	0.001	0.948	0.004	0.948	0.001	0.744	0.014	0.879	0.008
horse	0.782	0.048	0.928	0.003	0.948	0.002	0.921	0.007	0.927	0.002	0.519	0.015	**0.953**	0.001
ship	0.780	0.048	0.958	0.003	**0.965**	0.001	0.964	0.002	0.957	0.001	0.430	0.062	0.921	0.009
truck	0.708	0.081	0.939	0.003	**0.955**	0.001	0.952	0.003	0.949	0.001	0.393	0.008	0.911	0.003

FMNIST	uLSIF-NN		nnBR-LSIF		nnBR-PU		nnBR-LSIF		nnBR-PU		Deep SAD		GT	
Network	LeNet		LeNet		LeNet		WRN		WRN		LeNet		WRN	
Inlier Class	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
T-shirt/top	0.960	0.005	0.981	0.001	**0.985**	0.000	0.984	0.001	0.982	0.000	0.558	0.031	0.890	0.007
Trouser	0.961	0.010	0.998	0.000	**1.000**	0.000	0.998	0.000	0.998	0.000	0.758	0.022	0.974	0.004
Pullover	0.944	0.012	0.976	0.001	0.980	0.001	**0.983**	0.002	0.972	0.001	0.617	0.046	0.902	0.005
Dress	0.973	0.006	0.986	0.001	**0.992**	0.000	0.991	0.001	0.986	0.000	0.525	0.038	0.843	0.014
Coat	0.958	0.006	0.978	0.001	**0.983**	0.000	0.981	0.002	0.974	0.000	0.627	0.029	0.885	0.003
Sandal	0.968	0.011	0.997	0.001	**0.999**	0.000	**0.999**	0.000	**0.999**	0.000	0.681	0.023	0.949	0.005
Shirt	0.919	0.005	0.952	0.001	**0.958**	0.001	0.944	0.005	0.932	0.001	0.618	0.015	0.842	0.004
Sneaker	0.991	0.001	0.994	0.002	**0.998**	0.000	**0.998**	0.000	**0.998**	0.000	0.802	0.054	0.954	0.006
Bag	0.980	0.005	0.994	0.001	**0.999**	0.000	0.998	0.000	**0.999**	0.000	0.447	0.034	0.973	0.006
Ankle boot	0.992	0.001	0.985	0.015	**0.999**	0.000	0.997	0.000	0.996	0.000	0.583	0.023	0.996	0.000

Table 5: Average PD (Mean) with standard deviation (SD) over 10 trials with different seeds per method. The best performing method in terms of the mean PD is specified by bold face.

Domains (Train → Test)	books → books		dvd → books		dvd → dvd		elec → books		elec → dvd	
DRE method	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
w/o IW	0.093	0.003	0.128	0.008	0.100	0.005	0.212	0.012	0.187	0.008
Kernel uLSIF	0.089	0.002	0.114	0.006	0.094	0.004	0.200	0.009	0.179	0.006
Kernel KLIEP	0.089	0.002	0.116	0.006	0.094	0.004	0.205	0.011	0.184	0.008
uLSIF-NN	0.093	0.003	0.128	0.008	0.100	0.005	0.212	0.012	0.187	0.008
PU-NN	0.093	0.003	0.128	0.008	0.100	0.005	0.212	0.012	0.187	0.008
nnBR-LSIF	**0.086**	0.002	**0.113**	0.005	**0.091**	0.004	**0.199**	0.009	**0.176**	0.005
nnBR-PU	0.090	0.003	**0.113**	0.006	0.096	0.004	**0.199**	0.009	**0.176**	0.006

Domains (Train → Test)	elec → elec		kitchen → books		kitchen → dvd		kitchen → elec		kitchen → kitchen	
DRE method	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
w/o IW	0.079	0.005	0.202	0.013	0.185	0.006	0.073	0.004	0.062	0.002
Kernel uLSIF	0.072	0.003	0.192	0.007	0.178	0.008	0.071	0.003	0.060	0.003
Kernel KLIEP	0.072	0.003	0.195	0.005	0.182	0.007	0.072	0.004	0.060	0.002
uLSIF-NN	0.079	0.005	0.202	0.013	0.185	0.006	0.073	0.004	0.062	0.002
PU-NN	0.079	0.005	0.202	0.013	0.185	0.006	0.073	0.004	0.062	0.002
nnBR-LSIF	**0.071**	0.003	**0.189**	0.008	**0.174**	0.008	**0.068**	0.003	**0.058**	0.003
nnBR-PU	0.074	0.004	0.190	0.008	**0.174**	0.008	**0.068**	0.003	0.062	0.005

F.3 Experiments of Covariate Shift Adaptation

In Table 5, we show the detailed results of experiments of covariate shift adaptation. Even when the training data and the test data follow the same distribution, the covariate shift adaptation based on D3RE improves the mean PD. We consider that this is because the importance weighting emphasizes the loss in the empirical higher-density regions of the test examples.

G Other Applications

In this section, we explain other potential applications of the proposed method.

f-divergence Estimation: f-divergences (Ali & Silvey, 1966; Csiszár, 1967) are the discrepancy measures of probability densities based on the density ratio, hence the proposed method can be used for their estimation. They include the KL divergence (Kullback & Leibler, 1951), the Hellinger distance (Hellinger, 1909), and the Pearson divergence (Pearson, 1900), as examples.

Two-sample Homogeneity Test: The purpose of a homogeneity test is to determine if two or more datasets come from the same distribution (Loevinger, 1948). For two-sample testing, using a semiparametric f-divergence estimator with nonparametric density ratio models has been studied (Keziou., 2003; Keziou & Leoni-Aubin, 2005). Kanamori et al. (2010) and Sugiyama et al. (2011a) employed direct DRE for the nonparametric DRE.

Generative Adversarial Networks: Generative adversarial networks (GANs) are successful deep generative models, which learns to generate new data with the same distribution as the training data Goodfellow et al. (2014). Various GAN methods have been proposed, amongst which Nowozin et al. (2016) proposed *f-GAN*, which minimizes the variational estimate of f-divergence. Uehara et al. (2016) extended the idea of Nowozin et al. (2016) to use BR divergence minimization for DRE. The estimator proposed in this paper also has a potential to improve the method of Uehara et al. (2016).

Off-policy Evaluation with External Validity: In applications such as advertisement design selection, personalized medicine, search engines, and recommendation systems, evaluating and learning a new policy from historical data is a common problem (Beygelzimer & Langford, 2009; Li et al., 2010; Athey & Wager, 2017). To accomplish this goal, *off-policy evaluation* (OPE) evaluates a new policy by estimating the expected reward of the new policy (Dudík et al., 2011; Wang et al., 2017; Narita et al., 2019; Bibaut et al., 2019; Kallus & Uehara, 2019; Oberst & Sontag, 2019). Recently, Kato et al. (2020) proposed using covariate shift adaptation to solve the *external validity*

problem in OPE, i.e., the case that the distribution of covariates is the same between the historical and evaluation data (Cole & Stuart, 2010; Pearl & Bareinboim, 2014).

Change Point Detection: The methods for *change-point detection* try to detect abrupt changes in time-series data (Basseville & Nikiforov, 1993; Gustafsson, 2000; Brodsky & Darkhovsky, 1993). There are two types of problem settings in change-point detection, namely the real-time detection (Adams, 2007; Garnett et al., 2009; Paquet, 2007) and the retrospective detection (Basseville & Nikiforov, 1993; Yamanishi & Takeuchi, 2002). In retrospective detection, which requires longer reaction periods, Liu et al. (2012) proposed using techniques of direct DRE. Whereas the existing methods rely on linear-in-parameter models, our proposed method enables us to employ more complex models for change point detection.

Similarity-based Sentiment Analysis: Kato (2019) used the density ratio estimated from PU learning for sentiment analysis of text data based on similarity.

H ESTIMATION ERROR BOUND

The estimation error bound can be proved by building upon the proof techniques in Kiryo et al. (2017); Lu et al. (2020).

Notations for the Theoretical Analysis: We denote the set of real values by $\mathbb{R}$ and that of positive integers by $\mathbb{N}$. Let $\mathcal{X} \subset \mathbb{R}^d$. Let $p_{\mathrm{nu}}(x)$ and $p_{\mathrm{de}}(x)$ be probability density functions over $\mathcal{X}$, and assume that the density ratio $r^*(x) := \frac{p_{\mathrm{nu}}(x)}{p_{\mathrm{de}}(x)}$ is existent and bounded: $\overline{R} := \|r^*\|_\infty < \infty$. Assume $0 < C < \frac{1}{\overline{R}}$. Since $\overline{R} \geq 1$ (because $1 = \int p_{\mathrm{de}}(x) r^*(x) dx \leq 1 \cdot \|r^*\|_\infty$), we have $C \in (0, 1]$ and hence $p_{\mathrm{mod}} := p_{\mathrm{de}} - C p_{\mathrm{nu}} > 0$.

Problem Setup: Let the hypothesis class of density ratio be $\mathcal{H} \subset \{r : \mathbb{R}^D \to (b_r, B_r) =: I_r\}$, where $0 \leq b_r < \overline{R} < B_r$. Let $f : I_r \to \mathbb{R}$ be a twice continuously-differentiable convex function with a bounded derivative. Define $\tilde{f}$ by $\partial f(t) = C(\partial f(t) t - f(t)) + \tilde{f}(t)$, where ∂f is the derivative of f continuously extended to 0 and B_r. Recall the definitions $\ell_1(t) := \partial f(t) t - f(t) + A$, $\ell_2(t) := -\tilde{f}(t)$, and

$$
\begin{aligned}
\mathrm{BR}_f(r) &:= \mathbb{E}_{\mathrm{de}}\left[\partial f(r(X)) r(X) - f(r(X)) + A\right] - \mathbb{E}_{\mathrm{nu}}\left[\partial f(r(X))\right] \\
&= \mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}}\left[\partial f(r(X)) r(X) - f(r(X)) + A\right] - \mathbb{E}_{\mathrm{nu}}\left[\tilde{f}(r(X))\right] \\
&= \mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X)) + \mathbb{E}_{\mathrm{nu}} \ell_2(r(X)) \\
&\left(= (\mathbb{E}_{\mathrm{de}} - C\mathbb{E}_{\mathrm{nu}}) \ell_1(r(X)) + \mathbb{E}_{\mathrm{nu}} \ell_2(r(X))\right), \\
\widehat{\mathrm{nnBR}}_f(r) &:= \rho\left(\hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))\right) + \hat{\mathbb{E}}_{\mathrm{nu}} \ell_2(r(X)) \\
&\left(= \rho((\hat{\mathbb{E}}_{\mathrm{de}} - C\hat{\mathbb{E}}_{\mathrm{nu}}) \ell_1(r(X)) + \hat{\mathbb{E}}_{\mathrm{nu}} \ell_2(r(X))\right),
\end{aligned}
$$

where we denoted $\hat{\mathbb{E}}_{\mathrm{mod}} = \hat{\mathbb{E}}_{\mathrm{de}} - C\hat{\mathbb{E}}_{\mathrm{nu}}$ and ρ is a consistent correction function with Lipschitz constant L_ρ (Definition 1).

Remark 4. The true density ratio r^* minimizes BR_f.

Definition 1 (Consistent correction function Lu et al. (2020))**.** A function $f : \mathbb{R} \to \mathbb{R}$ is called a consistent correction function if it is Lipschitz continuous, non-negative and $f(x) = x$ for all $x \geq 0$.

Definition 2 (Rademacher complexity)**.** Given $n \in \mathbb{N}$ and a distribution p, define the Rademacher complexity $\mathcal{R}_n^p(\mathcal{H})$ of a function class $\mathcal{H}$ as

$$
\mathcal{R}_n^p(\mathcal{H}) := \mathbb{E}_p \mathbb{E}_\sigma \left[\sup_{r \in \mathcal{H}} \left| \frac{1}{n} \sum_{i=1}^n \sigma_i r(X_i) \right|\right],
$$

where $\{\sigma_i\}_{i=1}^n$ are Rademacher variables (i.e., independent variables following the uniform distribution over $\{-1, +1\}$) and $\{X_i\}_{i=1}^n \overset{\text{i.i.d.}}{\sim} p$.

The theorem in the paper is a special case of the following theorem with $\rho(\cdot) := \max\{0, \cdot\}$ (in which case $L_\rho = 1$).

Theorem 2 (Estimation error bound)**.** *Assume that $B_\ell := \sup_{t \in I_r}\{\max\{|\ell_1(t)|, |\ell_2(t)|\}\} < \infty$. Assume ℓ_1 is L_{ℓ_1}-Lipschitz and ℓ_2 is L_{ℓ_2}-Lipschitz. Assume that there exists an empirical risk minimizer $\hat{r} \in \arg\min_{r \in \mathcal{H}} \widehat{\mathrm{nnBR}}_f(r)$ and a population risk minimizer $\bar{r} \in \arg\min_{r \in \mathcal{H}} \mathrm{BR}_f(r)$. Also assume $\inf_{r \in \mathcal{H}} \mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X)) > 0$ and that $(\rho - \mathrm{Id})$ is $(L_{\rho-\mathrm{Id}})$-Lipschitz. Then for any $\delta \in (0, 1)$, with probability at least $1 - \delta$, we have*

$$\mathrm{BR}_f(\hat{r}) - \mathrm{BR}_f(\bar{r}) \leq 8L_\rho L_{\ell_1}\mathcal{R}^{p_{\mathrm{de}}}_{n_{\mathrm{de}}}(\mathcal{H}) + 8(L_\rho C L_{\ell_1} + L_{\ell_2})\mathcal{R}^{p_{\mathrm{nu}}}_{n_{\mathrm{nu}}}(\mathcal{H}) + 2\Phi_{(C,f,\rho)}(n_{\mathrm{nu}}, n_{\mathrm{de}}) + B_\ell\sqrt{8\left(\frac{L_\rho^2}{n_{\mathrm{de}}} + \frac{(1 + L_\rho C)^2}{n_{\mathrm{nu}}}\right)\log\frac{1}{\delta}},$$

where $\Phi_{(C,f,\rho)}(n_{\mathrm{nu}}, n_{\mathrm{de}})$ is defined as in Lemma 3.

Proof. Since $\hat{r}$ minimizes $\widehat{\mathrm{nnBR}}_f$, we have

$$\begin{aligned}
\mathrm{BR}_f(\hat{r}) - \mathrm{BR}_f(\bar{r}) &= \mathrm{BR}_f(\hat{r}) - \widehat{\mathrm{nnBR}}_f(\hat{r}) + \widehat{\mathrm{nnBR}}_f(\hat{r}) - \mathrm{BR}_f(\bar{r}) \\
&\leq \mathrm{BR}_f(\hat{r}) - \widehat{\mathrm{nnBR}}_f(\hat{r}) + \widehat{\mathrm{nnBR}}_f(\bar{r}) - \mathrm{BR}_f(\bar{r}) \\
&\leq 2\sup_{r \in \mathcal{H}} |\widehat{\mathrm{nnBR}}_f(r) - \mathrm{BR}_f(r)| \\
&\leq \underbrace{2\sup_{r \in \mathcal{H}} |\widehat{\mathrm{nnBR}}_f(r) - \mathbb{E}\widehat{\mathrm{nnBR}}_f(r)|}_{\text{Maximal deviation}} + \underbrace{2\sup_{r \in \mathcal{H}} |\mathbb{E}\widehat{\mathrm{nnBR}}_f(r) - \mathrm{BR}_f(r)|}_{\text{Bias}}.
\end{aligned}$$

We apply McDiarmid's inequality McDiarmid (1989); Mohri et al. (2018) to the maximal deviation term. The absolute value of the difference caused by altering one data point in the maximal deviation term is bounded from above by $2B_\ell\frac{L_\rho}{n_{\mathrm{de}}}$ if the altered point is a sample from p_{de} and $2B_\ell\frac{1+L_\rho C}{n_{\mathrm{nu}}}$ if it is from p_{nu}. Therefore, McDiarmid's inequality implies, with probability at least $1 - \delta$, that we have

$$\begin{aligned}
&\sup_{r \in \mathcal{H}} |\widehat{\mathrm{nnBR}}_f(r) - \mathbb{E}\widehat{\mathrm{nnBR}}_f(r)| \\
&\leq \underbrace{\mathbb{E}\left[\sup_{r \in \mathcal{H}} |\widehat{\mathrm{nnBR}}_f(r) - \mathbb{E}\widehat{\mathrm{nnBR}}_f(r)|\right]}_{\text{Expected maximal deviation}} + B_\ell\sqrt{2\left(\frac{L_\rho^2}{n_{\mathrm{de}}} + \frac{(1 + L_\rho C)^2}{n_{\mathrm{nu}}}\right)\log\frac{1}{\delta}}.
\end{aligned}$$

Applying Lemma 2 to the expected maximal deviation term and Lemma 3 to the bias term, we obtain the assertion. □

The following lemma generalizes the symmetrization lemmas proved in Kiryo et al. (2017) and Lu et al. (2020).

Lemma 2 (Symmetrization under Lipschitz-continuous modification)**.** *Let $0 \leq a < b$, $J \in \mathbb{N}$, and $\{K_j\}_{j=1}^J \subset \mathbb{N}$. Given i.i.d. samples $\mathcal{D}_{(j,k)} := \{X_i\}_{i=1}^{n_{(j,k)}}$ each from a distribution $p_{(j,k)}$ over $\mathcal{X}$, consider a stochastic process $\hat{S}$ indexed by $\mathcal{F} \subset (a, b)^{\mathcal{X}}$ of the form*

$$\hat{S}(f) = \sum_{j=1}^{J} \rho_j \left(\sum_{k=1}^{K_j} \hat{\mathbb{E}}_{(i,j)}[\ell_{(j,k)}(f(X))]\right),$$

where each ρ_j is a L_{ρ_j}-Lipschitz function on $\mathbb{R}$, $\ell_{(j,k)}$ is a $L_{\ell_{(j,k)}}$-Lipschitz function on (a, b), and $\hat{\mathbb{E}}_{(i,j)}$ denotes the expectation with respect to the empirical measure of $\mathcal{D}_{(j,k)}$. Denote $S(f) := \mathbb{E}\hat{S}(f)$ where $\mathbb{E}$ is the expectation with respect to the product measure of $\{\mathcal{D}_{(j,k)}\}_{(j,k)}$. Here, the index j denotes the grouping of terms due to ρ_j, and k denotes each sample average term. Then we have

$$\mathbb{E}\sup_{f \in \mathcal{F}} |\hat{S}(f) - S(f)| \leq 4\sum_{j=1}^{J}\sum_{k=1}^{K_j} L_{\rho_j} L_{\ell_{(j,k)}} \mathcal{R}_{n_{(j,k)}, p_{(j,k)}}(\mathcal{F}).$$

Proof. First, we consider a continuous extension of $\ell_{(j,k)}$ defined on (a, b) to $[0, b)$. Since the functions in $\mathcal{F}$ take values only in (a, b), this extension can be performed without affecting the values of $\hat{S}(f)$ or $S(f)$. We extend the function by defining the values for $x \in [0, a]$ as $\ell_{(j,k)}(x) := \lim_{x' \downarrow a} \ell_{(j,k)}(x')$, where the right-hand side is guaranteed to exist since $\ell_{(j,k)}$ is Lipschitz continuous hence uniformly continuous. Then, $\ell_{(j,k)}$ remains a L_{ρ_j}-Lipschitz continuous function on $[0, b)$. Now we perform symmetrization (Vapnik, 1998), deal with ρ_j's, and then bound the symmetrized process by Rademacher complexity. Denoting independent copies of $\{X_{(j,k)}\}$ by $\{X_{j,k}^{(\mathrm{gh})}\}_{(j,k)}$ and the corresponding expectations as well as the sample averages with $^{(\mathrm{gh})}$,

$$
\begin{aligned}
&\mathbb{E} \sup_{f \in \mathcal{F}} |\hat{S}(f) - S(f)| \\
&\leq \sum_{j=1}^{J} \mathbb{E} \sup_{f \in \mathcal{F}} |\rho_j(\sum_{k=1}^{K_j} \hat{\mathbb{E}}_{(i,j)} \ell_{(j,k)}(f(X))) - \mathbb{E}^{(\mathrm{gh})} \rho_j(\sum_{k=1}^{K_j} \hat{\mathbb{E}}_{(j,k)}^{(\mathrm{gh})} \ell_{(j,k)}(f(X^{(\mathrm{gh})})))| \\
&\leq \sum_{j=1}^{J} \mathbb{E}\mathbb{E}^{(\mathrm{gh})} \sup_{f \in \mathcal{F}} |\rho_j(\sum_{k=1}^{K_j} \hat{\mathbb{E}}_{(i,j)} \ell_{(j,k)}(f(X))) - \rho_j(\sum_{k=1}^{K_j} \hat{\mathbb{E}}_{(j,k)}^{(\mathrm{gh})} \ell_{(j,k)}(f(X^{(\mathrm{gh})})))| \\
&\leq \sum_{j=1}^{J} L_{\rho_j} \sum_{k=1}^{K_j} \mathbb{E}\mathbb{E}^{(\mathrm{gh})} \sup_{f \in \mathcal{F}} |\hat{\mathbb{E}}_{(i,j)} \ell_{(j,k)}(f(X)) - \hat{\mathbb{E}}_{(j,k)}^{(\mathrm{gh})} \ell_{(j,k)}(f(X^{(\mathrm{gh})}))| \\
&= \sum_{j=1}^{J} L_{\rho_j} \sum_{k=1}^{K_j} \mathbb{E}\mathbb{E}^{(\mathrm{gh})} \sup_{f \in \mathcal{F}} |\hat{\mathbb{E}}_{(i,j)}(\ell_{(j,k)}(f(X)) - \ell_{(j,k)}(0)) - \hat{\mathbb{E}}_{(j,k)}^{(\mathrm{gh})}(\ell_{(j,k)}(f(X^{(\mathrm{gh})})) - \ell_{(j,k)}(0))| \\
&\leq \sum_{j=1}^{J} L_{\rho_j} \sum_{k=1}^{K_j} \left(2\mathcal{R}_{n_{(j,k)}, p_{(j,k)}}(\{\ell_{(j,k)} \circ f - \ell_{(j,k)}(0) : f \in \mathcal{F}\})\right) \\
&\leq \sum_{j=1}^{J} L_{\rho_j} \sum_{k=1}^{K_j} 2 \cdot 2 L_{\ell_{(j,k)}} \mathcal{R}_{n_{(j,k)}, p_{(j,k)}}(\mathcal{F}),
\end{aligned}
$$

where we applied Talagrand's contraction lemma for two-sided Rademacher complexity (Ledoux & Talagrand, 1991; Bartlett & Mendelson, 2001) with respect to $(t \mapsto \ell_{(j,k)}(t) - \ell_{(j,k)}(0))$ in the last inequality. □

Lemma 3 (Bias due to risk correction)**.** *Assume* $\inf_{r \in \mathcal{H}} \mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X)) > 0$ *and that* $(\rho - \mathrm{Id})$ *is* $(L_{\rho - \mathrm{Id}})$*-Lipschitz on* $\mathbb{R}$*. There exists* $\alpha > 0$ *such that*

$$
\begin{aligned}
\sup_{r \in \mathcal{H}} |\widehat{\mathbb{E}\mathrm{nnBR}}_f(r) - \mathrm{BR}_f(r)| &\leq (1 + C) B_\ell L_{\rho - \mathrm{Id}} \exp\left(-\frac{2\alpha^2}{({B_\ell}^2/n_{\mathrm{de}}) + (C^2 {B_\ell}^2/n_{\mathrm{nu}})}\right) \\
&=: \Phi_{(C,f,\rho)}(n_{\mathrm{nu}}, n_{\mathrm{de}}).
\end{aligned}
$$

Remark 5. Note that we already have $p_{\mathrm{mod}} \geq 0$ and $\ell_1 \geq 0$ and hence $\inf_{r \in \mathcal{H}} \mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X)) \geq 0$. Therefore, the assumption of Lemma 3 is essentially referring to the strict positivity of the infimum. Here, $\mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}}$ and $\mathbb{P}(\cdot)$ denote the expectation and the probability with respect to the joint distribution of the samples included in $\hat{\mathbb{E}}_{\mathrm{mod}}$.

Proof. Fix an arbitrary $r \in \mathcal{H}$. We have

$$
\begin{aligned}
&|\widehat{\mathbb{E}\mathrm{nnBR}}_f(r) - \mathrm{BR}_f(r)| \leq |\mathbb{E}[\widehat{\mathrm{nnBR}}_f(r) - \widehat{\mathrm{BR}}_f(r)]| \\
&= |\mathbb{E}[\rho(\hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))) - \hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))]| \leq \mathbb{E}\left[|\rho(\hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))) - \hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))|\right] \\
&= \mathbb{E}\left[\mathbb{1}\{\rho(\hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))) \neq \hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))\} \cdot |\rho(\hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))) - \hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))|\right] \\
&\leq \mathbb{E}\left[\mathbb{1}\{\rho(\hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))) \neq \hat{\mathbb{E}}_{\mathrm{mod}} \ell_1(r(X))\}\right] \left(\sup_{s : |s| \leq (1+C) B_\ell} |\rho(s) - s|\right)
\end{aligned}
$$

where $\mathbb{1}\{\cdot\}$ denotes the indicator function, and we used $|\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X))| \leq (1+C)B_\ell$. Further, we have

$$\sup_{s:|s|\leq(1+C)B_\ell} |\rho(s) - s| \leq \sup_{s:|s|\leq(1+C)B_\ell} |(\rho - \mathrm{Id})(s) - (\rho - \mathrm{Id})(0)| + |(\rho - \mathrm{Id})(0)|$$
$$\leq \sup_{s:|s|\leq(1+C)B_\ell} L_{\rho-\mathrm{Id}}|s - 0| + 0 \leq (1+C)B_\ell L_{\rho-\mathrm{Id}},$$

where Id denotes the identity function. On the other hand, since $\inf_{r\in\mathcal{H}} \mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X)) > 0$ is assumed, there exists $\alpha > 0$ such that for any $r \in \mathcal{H}$, $\mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X)) > \alpha$. Therefore, denoting the support of a function by $\mathrm{supp}(\cdot)$,

$$\mathbb{E}\left[\mathbb{1}\{\rho(\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X))) \neq \hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X))\}\right] = \mathbb{P}\left(\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X)) \in \mathrm{supp}(\rho - \mathrm{Id})\right)$$
$$\leq \mathbb{P}\left(\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X)) < 0\right) \leq \mathbb{P}\left(\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X)) < \mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X)) - \alpha\right)$$

holds. Now we apply McDiarmid's inequality to the right-most quantity. The absolute difference caused by altering one data point in $\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X))$ is bounded by $\frac{B_\ell}{n_{\mathrm{de}}}$ if the change is in a sample from p_{de} and $\frac{CB_\ell}{n_{\mathrm{nu}}}$ otherwise. Therefore, McDiarmid's inequality implies

$$\mathbb{P}\left(\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X)) < \mathbb{E}\hat{\mathbb{E}}_{\mathrm{mod}}\ell_1(r(X)) - \alpha\right) \leq \exp\left(-\frac{2\alpha^2}{({B_\ell}^2/n_{\mathrm{de}}) + (C^2{B_\ell}^2/n_{\mathrm{nu}})}\right).$$

□

I Rademacher Complexity Bound

The following lemma provides an upper-bound on the Rademacher complexity for multi-layer perceptron models in terms of the Frobenius norms of the parameter matrices. Alternatively, other approaches to bound the Rademacher complexity can be employed. The assertion of the lemma follows immediately from the proof of Theorem 1 of Golowich et al. (2019) after a slight modification to incorporate the absolute value function in the definition of Rademacher complexity.

Lemma 4 (Rademacher complexity bound (Golowich et al., 2019, Theorem 1))**.** *Assume the distribution p has a bounded support: $B_p := \sup_{x\in\mathrm{supp}(p)} \|x\| < \infty$. Let $\mathcal{H}$ be the class of real-valued networks of depth L over the domain $\mathcal{X}$, where each parameter matrix W_j has Frobenius norm at most $B_{W_j} \geq 0$, and with 1-Lipschitz activation functions φ_j which are positive-homogeneous (i.e., φ_j is applied element-wise and $\varphi_j(\alpha t) = \alpha\varphi_j(t)$ for all $\alpha \geq 0$). Then*

$$\mathcal{R}_n^p(\mathcal{H}) \leq \frac{B_p\left(\sqrt{2\log(2)L} + 1\right)\prod_{j=1}^L B_{W_j}}{\sqrt{n}}.$$

Proof. The assertion immediately follows once we modify the beginning of the proof of Theorem 1 by introducing the absolute value function inside the supremum of the Rademacher complexity as

$$\mathbb{E}_\sigma\left[\sup_{r\in\mathcal{H}}\left|\sum_{i=1}^n \sigma_i r(x_i)\right|\right] \leq \frac{1}{\lambda}\log\mathbb{E}_\sigma \sup_{r\in\mathcal{H}} \exp\left(\lambda\left|\sum_{i=1} \sigma_i r(x_i)\right|\right).$$

for $\lambda > 0$. The rest of the proof is identical to that of Theorem 1 of Golowich et al. (2019). □

J Strong convexity and L^2 error bound

An estimation error bound in terms of BR_f can be converted to that of an L^2 distance when the true density ratio and the density ratio model are square-integrable and f is strongly convex.

Lemma 5 (L^2 distance bound)**.** *Let $\mathcal{H} := \{r : \mathcal{X} \to (b_r, B_r) =: I_r | \int |r(x)|^2 \mathrm{d}\boldsymbol{x} < \infty\}$ and assume $r^* \in \mathcal{H}$. If $\inf_{t\in I_r} f''(t) > 0$, then there exists $\mu > 0$ such that for all $r \in \mathcal{H}$,*

$$\|r - r^*\|_{L^2(p_{\mathrm{de}})}^2 \leq \frac{2}{\mu}\left(\mathrm{BR}_f(r) - \mathrm{BR}_f(r^*)\right)$$

holds.

Proof. Since $\mu := \inf_{t \in I_r} f''(t) > 0$, the function f is μ-strongly convex. By the definition of strong convexity,

$$\begin{aligned}
&\mathrm{BR}_f(r) - \mathrm{BR}_f(r^*) = (\mathrm{BR}_f(r) - \mathbb{E}_{\mathrm{de}} f(r^*(X))) - \underbrace{(\mathrm{BR}_f(r^*) + \mathbb{E}_{\mathrm{de}} f(r^*(X)))}_{=0} \\
&= \mathbb{E}_{\mathrm{de}} \left[f(r^*(X)) - f(r(X)) + \partial f(r(X))(r^*(X) - r(X)) \right] \\
&\geq \mathbb{E}_{\mathrm{de}} \left[\frac{\mu}{2} (r^*(X) - r(X))^2 \right] = \frac{\mu}{2} \|r^* - r\|^2_{L^2(p_{\mathrm{de}})}.
\end{aligned}$$

□

Lemma 6 (ℓ_2 distance bound)**.** *Fix $r \in \mathcal{H}$. Given n samples $\{x_i\}_{i=1}^n$ from p_{de}, with probability at least $1 - \delta$, we have*

$$\frac{1}{n} \sum_{i=1}^{n} (r(x_i) - r^*(x_i))^2 \leq \underbrace{\mathbb{E}\left[(r - r^*)^2(X) \right]}_{= \|r - r^*\|^2_{L^2(p_{\mathrm{de}})}} + (2\overline{R})^2 \sqrt{\frac{\log \frac{1}{\delta}}{2n}}.$$

Proof. The assertion follows from McDiarmid's inequality after noting that altering one sample results in an absolute change bounded by $\frac{1}{n}(2\overline{R})^2$. □