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CDMAD: Class-Distribution-Mismatch-Aware Debiasing for Class-Imbalanced Semi-Supervised Learning

Hyuck Lee Heeyoung Kim
Department of Industrial and Systems Engineering, KAIST
Daejeon 34141, Republic of Korea
{dlgur0921, heeyoungkim}@kaist.ac.kr

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Background

Classifiers trained on a class-imbalanced set suffer from being biased toward the majority classes.

Under semi-supervised learning (SSL) settings, the use of biased pseudo-labels for training:

- Classifiers of pseudo-label-based algorithms tend to be further biased.
- The use of biased pseudo-labels also decreases the quality of representations.

The biased problem becomes more serious when the class distributions of the labeled and unlabeled sets differ significantly.

Background

Many class imbalanced SSL (CISSL) algorithms have been proposed.

1. Fan et al. [7], Lee et al. [17], Wei et al. [26] assumed that the class distribution of the unlabeled set is known and the same as that of the labeled set, although the class distribution of the unlabeled set can be unknown in practice. E.g., STL-10 is collected from different periods are likely to have a class distribution mismatch.

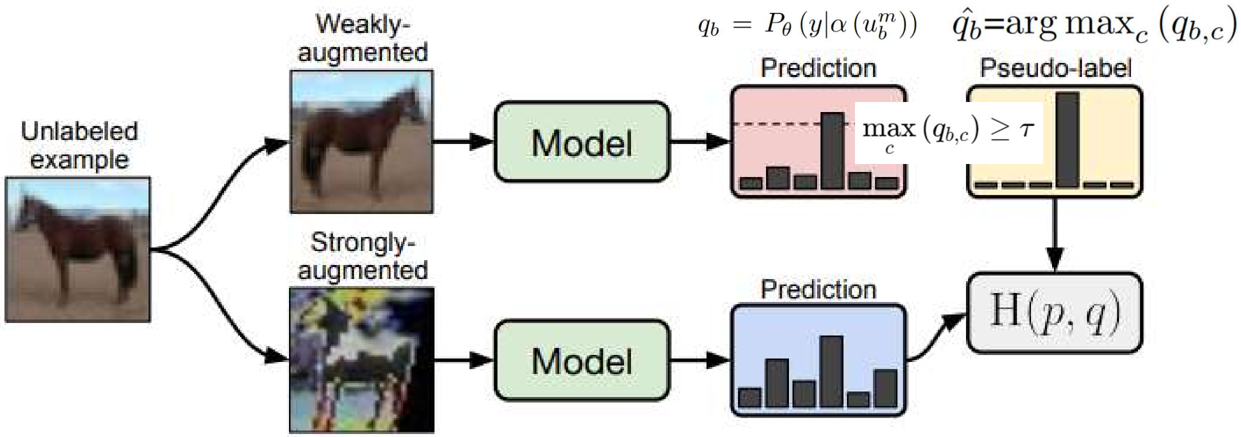
2. Some algorithms after the main training stage,
they additionally used technique (proposed for fully supervised class-imbalanced learning) of Classifier Retraining (cRT) [11] or post-hoc logit-adjustment (LA).

cRT: only the labeled set is used for training the classifier, cannot be learned interactively with (unlabeled) .

LA: not consider the unknown class distribution of the unlabeled set. When the class distribution of the unlabeled set is unknown and differs from that of the labeled set, may not re-balance the classifier.

Background

FixMatch



1) The proposed algorithm does not use hard pseudo-labels because entropy minimization of class predictions may cause the classifier to be biased towards certain classes.
2) The proposed algorithm does not use confidence threshold τ for FixMatch, enabling the utilization of all unlabeled samples.

$$loss_F\left(\mathcal{MX}, \mathcal{MU}, \hat{q}, \tau; \theta\right),$$

Background

ReMixMatch

the class distribution of the labeled set

denotes the moving average of the class probabilities predicted over the last 128 unlabeled minibatches.

distribution alignment $\tilde{q}_b = Normalize\left(q_b \times P_l\left(y\right)/q\left(y\right)\right)$

sharpens

$$\bar{q}_b = Normalize\left(\tilde{q}_b^{\,1/T}\right)$$

$Normalize\left(x\right)_i = x_i / \sum_j x_j$ and $q\left(y\right)$

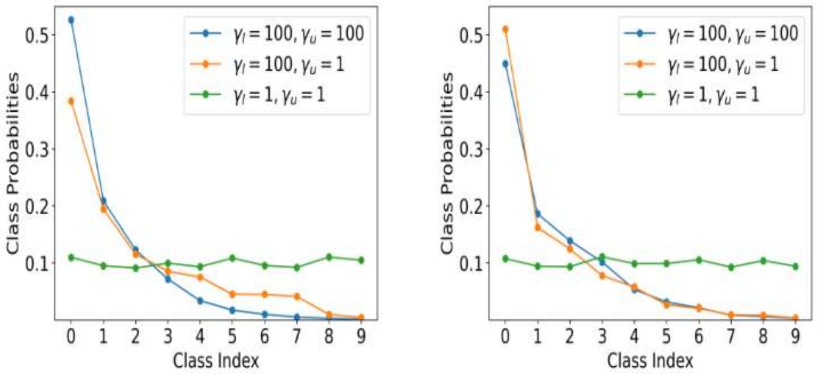
Does not employ the distribution alignment when the class distribution of the unlabeled set is unknown.

Because:

- The labeled and unlabeled sets can potentially have different class distributions.
- This modification helps prevent the generation of low-quality pseudo-labels in situations.

$$loss_R\left(\mathcal{MX}, \mathcal{MU}, \bar{q}; \theta\right),$$

Motivation



(a) FixMatch (b) ReMixMatch

Figure 1. Class probabilities on an image without any patterns.

For an image irrelevant to the learned features, the predicted class probabilities are expected to be uniform across classes.

However, this may not be true when the training set is class imbalanced because the classifier tends to be biased towards the majority classes.

It assume that the solid color image does not have the features learned from the training set.

Then, the class probabilities for the solid color image can be thought of as predicted based solely on the classifier's biased degree towards each class

Method

Refinement of pseudo-labels during training

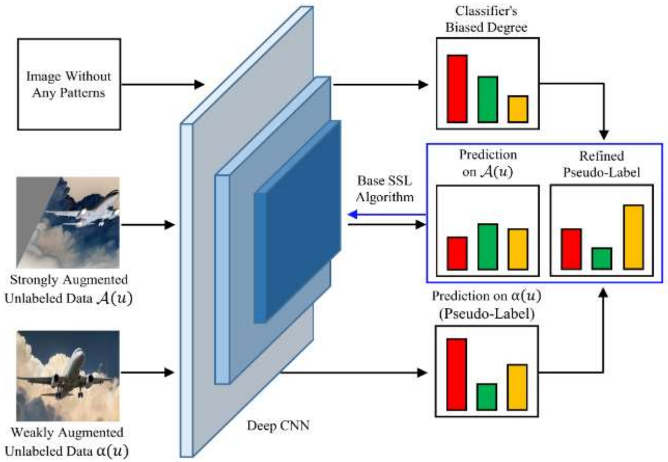


Figure 2. Pseudo-label refinement process using CDMAD.

$$g_\theta^*\left(\alpha\left(u_b^m\right)\right)=g_\theta\left(\alpha\left(u_b^m\right)\right)-g_\theta\left(\mathcal{I}\right),$$

$$q_b^*=\phi\left(g_\theta^*\left(\alpha\left(u_b^m\right)\right)\right).$$

Method

Refinement of biased class predictions during testing

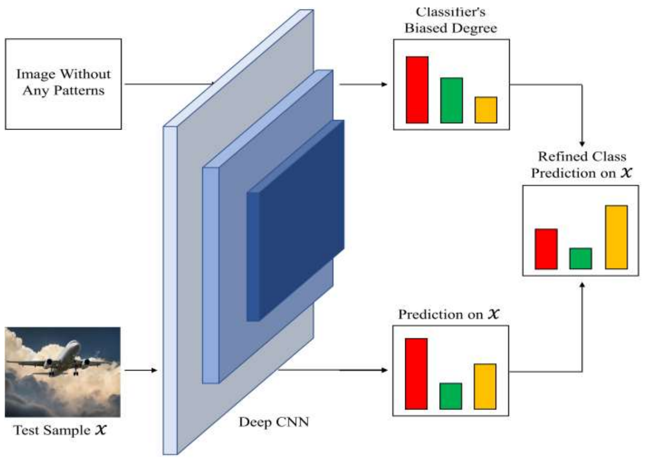


Figure 6. Refinement of biased class predictions on test samples using CDMAD

$$g_\theta^*\left(x_k^{test}\right)=g_\theta\left(x_k^{test}\right)-g_\theta(\mathcal{I}).$$

$$\begin{aligned} f_\theta^*\left(x_k^{test}\right) &= \arg\max_c g_\theta^*\left(x_k^{test}\right)_c \\ &= \arg\max_{y\in[C]} P_\theta\left(y|x_k^{test}\right)/P_\theta(y|\mathcal{I}). \end{aligned}$$

CDMAD as a CISSL extension of post-hoc logitadjustment (LA)

$$g_\theta^*\left(x_k^{test}\right)=g_\theta\left(x_k^{test}\right)-\log\pi.$$

$$g_\theta(\mathcal{I})+constant = \log P_\theta(y|\mathcal{I})$$

proven to be Fisher consistent for minimizing the balanced error rate (BER)

$$\mathrm{BER}\left(f_\theta^*\right)=\frac{1}{C}\sum_{y\in[C]}P_{x|y}\left(y\neq f_\theta^*(x)\right).$$

Experiment

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Table 1. Comparison of bACC/GM on CIFAR-10-LT

CIFAR-10-LT ($\gamma = \gamma_l = \gamma_u$, γ_u is assumed to be known)			
Algorithm	$\gamma = 50$	$\gamma = 100$	$\gamma = 150$
Vanilla	$65.2_{\pm 0.05}$ / $61.1_{\pm 0.09}$	$58.8_{\pm 0.13}$ / $58.2_{\pm 0.11}$	$55.6_{\pm 0.43}$ / $44.0_{\pm 0.98}$
Re-sampling	$64.3_{\pm 0.48}$ / $60.6_{\pm 0.67}$	$55.8_{\pm 0.47}$ / $45.1_{\pm 0.30}$	$52.2_{\pm 0.05}$ / $38.2_{\pm 1.49}$
LDAM-DRW	$68.9_{\pm 0.07}$ / $67.0_{\pm 0.08}$	$62.8_{\pm 0.17}$ / $58.9_{\pm 0.60}$	$57.9_{\pm 0.20}$ / $50.4_{\pm 0.30}$
cRT	$67.8_{\pm 0.13}$ / $66.3_{\pm 0.15}$	$63.2_{\pm 0.45}$ / $59.9_{\pm 0.40}$	$59.3_{\pm 0.10}$ / $54.6_{\pm 0.72}$
FixMatch	$79.2_{\pm 0.33}$ / $77.8_{\pm 0.36}$	$71.5_{\pm 0.72}$ / $66.8_{\pm 1.51}$	$68.4_{\pm 0.15}$ / $59.9_{\pm 0.43}$
/++DARP+cRT	$85.8_{\pm 0.43}$ / $85.6_{\pm 0.56}$	$82.4_{\pm 0.26}$ / $81.8_{\pm 0.17}$	$79.6_{\pm 0.42}$ / $78.9_{\pm 0.35}$
/+CReST+LA	$85.6_{\pm 0.36}$ / $81.9_{\pm 0.45}$	$81.2_{\pm 0.70}$ / $74.5_{\pm 0.99}$	$71.9_{\pm 2.24}$ / $64.4_{\pm 1.75}$
/+ABC	$85.6_{\pm 0.26}$ / $85.2_{\pm 0.29}$	$81.1_{\pm 1.14}$ / $80.3_{\pm 1.29}$	$77.3_{\pm 1.25}$ / $75.6_{\pm 1.65}$
/+CoSSL	$86.8_{\pm 0.30}$ / $86.6_{\pm 0.25}$	$83.2_{\pm 0.49}$ / $82.7_{\pm 0.60}$	$80.3_{\pm 0.55}$ / $79.6_{\pm 0.57}$
/+SAW+LA	$86.2_{\pm 0.15}$ / $83.9_{\pm 0.35}$	$80.7_{\pm 0.15}$ / $77.5_{\pm 0.21}$	$73.7_{\pm 0.06}$ / $71.2_{\pm 0.17}$
/+Adsh	$83.4_{\pm 0.06}$ / -	$76.5_{\pm 0.35}$ / -	$71.5_{\pm 0.30}$ / -
/+DebiasPL	- / -	$80.6_{\pm 0.50}$ / -	- / -
/+UDAL	$86.5_{\pm 0.29}$ / -	$81.4_{\pm 0.39}$ / -	$77.9_{\pm 0.33}$ / -
/+L2AC	- / -	$82.1_{\pm 0.57}$ / $81.5_{\pm 0.64}$	$77.6_{\pm 0.53}$ / $75.8_{\pm 0.71}$
/+CDMAD	**87.3**$_{\pm 0.12}$ / **87.0**$_{\pm 0.15}$	**83.6**$_{\pm 0.46}$ / **83.1**$_{\pm 0.57}$	**80.8**$_{\pm 0.86}$ / **79.9**$_{\pm 1.07}$
ReMixMatch	$81.5_{\pm 0.26}$ / $80.2_{\pm 0.32}$	$73.8_{\pm 0.38}$ / $69.5_{\pm 0.84}$	$69.9_{\pm 0.47}$ / $62.5_{\pm 0.35}$
/+DARP+cRT	$87.3_{\pm 0.61}$ / $87.0_{\pm 0.11}$	$83.5_{\pm 0.07}$ / $83.1_{\pm 0.09}$	$79.7_{\pm 0.54}$ / $78.9_{\pm 0.49}$
/+CReST+LA	$84.2_{\pm 0.11}$ / -	$81.3_{\pm 0.34}$ / -	$79.2_{\pm 0.31}$ / -
/+ABC	$87.9_{\pm 0.47}$ / $87.6_{\pm 0.51}$	$84.5_{\pm 0.32}$ / $84.1_{\pm 0.36}$	$80.5_{\pm 1.18}$ / $79.5_{\pm 1.36}$
/+CoSSL	$87.7_{\pm 0.21}$ / $87.6_{\pm 0.25}$	$84.1_{\pm 0.56}$ / $83.7_{\pm 0.66}$	$81.3_{\pm 0.83}$ / $80.5_{\pm 0.76}$
/+SAW+cRT	$87.6_{\pm 0.21}$ / $87.4_{\pm 0.26}$	$85.4_{\pm 0.32}$ / $83.9_{\pm 0.21}$	$79.9_{\pm 0.15}$ / $79.9_{\pm 0.12}$
/+CDMAD	**88.3**$_{\pm 0.35}$ / **88.1**$_{\pm 0.35}$	**85.5**$_{\pm 0.46}$ / **85.3**$_{\pm 0.44}$	**82.5**$_{\pm 0.23}$ / **82.0**$_{\pm 0.30}$

mitigated class imbalance but did not significantly improve the classification performance compared to the vanilla algorithm

importance of using the unlabeled set

Experiment

Table 2. Comparison of bACC/GM on CIFAR-10-LT and STL-10-LT under $\gamma_l \neq \gamma_u$ (γ_u is assumed to be unknown). ReMixMatch* denotes ReMixMatch with the estimated class distribution of the unlabeled set [12].

	CIFAR-10-LT ($\gamma_l = 100$, γ_u is assumed to be unknown)			STL-10-LT (γ_u =Unknown)	
Algorithm	$\gamma_u = 1$	$\gamma_u = 50$	$\gamma_u = 150$	$\gamma_l = 10$	$\gamma_l = 20$
FixMatch	$68.9_{\pm1.95}$/ $42.8_{\pm8.11}$	$73.9_{\pm0.25}$/ $70.5_{\pm0.52}$	$69.6_{\pm0.60}$/ $62.6_{\pm1.11}$	$72.9_{\pm0.09}$/ $69.6_{\pm0.01}$	$63.4_{\pm0.21}$/ $52.6_{\pm0.09}$
FixMatch+DARP	$85.4_{\pm0.55}$/ $85.0_{\pm0.65}$	$77.3_{\pm0.17}$/ $75.5_{\pm0.21}$	$72.9_{\pm0.24}$/ $69.5_{\pm0.18}$	$77.8_{\pm0.33}$/ $76.5_{\pm0.40}$	$69.9_{\pm1.77}$/ $65.4_{\pm3.07}$
FixMatch+DARP+LA	$86.6_{\pm1.11}$/ $86.2_{\pm1.15}$	$82.3_{\pm0.32}$/ $81.5_{\pm0.29}$	$78.9_{\pm0.23}$/ $77.7_{\pm0.06}$	$78.6_{\pm0.30}$/ $77.4_{\pm0.40}$	$71.9_{\pm0.49}$/ $68.7_{\pm0.51}$
FixMatch+DARP+cRT	$87.0_{\pm0.70}$/ $86.8_{\pm0.67}$	$82.7_{\pm0.21}$/ $82.3_{\pm0.25}$	$80.7_{\pm0.44}$/ $80.2_{\pm0.61}$	$79.3_{\pm0.23}$/ $78.7_{\pm0.21}$	$74.1_{\pm0.61}$/ $73.1_{\pm1.21}$
FixMatch+ABC	$82.7_{\pm0.49}$/ $81.9_{\pm0.68}$	$82.7_{\pm0.64}$/ $82.0_{\pm0.76}$	$78.4_{\pm0.87}$/ $77.2_{\pm1.07}$	$79.1_{\pm0.46}$/ $78.1_{\pm0.57}$	$73.8_{\pm0.15}$/ $72.1_{\pm0.15}$
FixMatch+SAW	$81.2_{\pm0.68}$/ $80.2_{\pm0.91}$	$79.8_{\pm0.25}$/ $79.1_{\pm0.32}$	$74.5_{\pm0.97}$/ $72.5_{\pm1.37}$	-/-	-/-
FixMatch+SAW+LA	$84.5_{\pm0.68}$/ $84.1_{\pm0.78}$	$82.9_{\pm0.38}$/ $82.6_{\pm0.38}$	$79.1_{\pm0.81}$/ $78.6_{\pm0.91}$	-/-	-/-
FixMatch+SAW+cRT	$84.6_{\pm0.23}$/ $84.4_{\pm0.26}$	$81.6_{\pm0.38}$/ $81.3_{\pm0.32}$	$77.6_{\pm0.40}$/ $77.1_{\pm0.41}$	-/-	-/-
FixMatch+CDMAD	**87.5**$_{\pm0.46}$/ **87.1**$_{\pm0.50}$	**85.7**$_{\pm0.36}$/ **85.3**$_{\pm0.38}$	**82.3**$_{\pm0.23}$/ **81.8**$_{\pm0.29}$	**79.9**$_{\pm0.23}$/ **78.9**$_{\pm0.38}$	**75.2**$_{\pm0.40}$/ **73.5**$_{\pm0.31}$
ReMixMatch	$48.3_{\pm0.14}$/ $19.5_{\pm0.85}$	$75.1_{\pm0.43}$/ $71.9_{\pm0.77}$	$72.5_{\pm0.10}$/ $68.2_{\pm0.32}$	$67.8_{\pm0.45}$/ $61.1_{\pm0.92}$	$60.1_{\pm1.18}$/ $44.9_{\pm1.52}$
ReMixMatch*	$85.0_{\pm1.35}$/ $84.3_{\pm1.55}$	$77.0_{\pm0.12}$/ $74.7_{\pm0.04}$	$72.8_{\pm0.10}$/ $68.8_{\pm0.21}$	$76.7_{\pm0.15}$/ $73.9_{\pm0.32}$	$67.7_{\pm0.46}$/ $60.3_{\pm0.76}$
ReMixMatch*+DARP	$86.9_{\pm0.10}$/ $86.4_{\pm0.15}$	$77.4_{\pm0.22}$/ $75.0_{\pm0.25}$	$73.2_{\pm0.11}$/ $69.2_{\pm0.31}$	$79.4_{\pm0.07}$/ $78.2_{\pm0.10}$	$70.9_{\pm0.44}$/ $67.0_{\pm1.62}$
ReMixMatch*+DARP+LA	$81.8_{\pm0.45}$/ $80.9_{\pm0.40}$	$83.9_{\pm0.42}$/ $83.4_{\pm0.45}$	$81.1_{\pm0.20}$/ $80.3_{\pm0.26}$	$80.6_{\pm0.45}$/ $79.6_{\pm0.55}$	$76.8_{\pm0.60}$/ $74.8_{\pm0.68}$
ReMixMatch*+DARP+cRT	$88.7_{\pm0.25}$/ $88.5_{\pm0.25}$	$83.5_{\pm0.53}$/ $83.1_{\pm0.51}$	$80.9_{\pm0.25}$/ $80.3_{\pm0.31}$	$80.9_{\pm0.53}$/ $80.0_{\pm0.46}$	$76.7_{\pm0.50}$/ $74.9_{\pm0.70}$
ReMixMatch+ABC	$76.4_{\pm5.34}$/ $74.8_{\pm6.05}$	$85.2_{\pm0.20}$/ $84.7_{\pm0.25}$	$80.4_{\pm0.40}$/ $80.0_{\pm0.44}$	$76.8_{\pm0.52}$/ $74.8_{\pm0.64}$	$71.2_{\pm1.37}$/ $67.4_{\pm1.89}$
ReMixMatch*+SAW	$87.0_{\pm0.75}$/ $86.4_{\pm0.85}$	$80.6_{\pm1.57}$/ $79.2_{\pm2.19}$	$77.6_{\pm0.76}$/ $76.0_{\pm0.93}$	-/-	-/-
ReMixMatch*+SAW+LA	$74.2_{\pm1.49}$/ $65.1_{\pm2.36}$	$84.8_{\pm1.07}$/ $82.4_{\pm2.32}$	$81.3_{\pm2.42}$/ $80.9_{\pm2.47}$	-/-	-/-
ReMixMatch*+SAW+cRT	$88.8_{\pm0.79}$/ $88.6_{\pm0.83}$	$84.5_{\pm0.78}$/ $83.6_{\pm1.27}$	$82.4_{\pm0.10}$/ $82.0_{\pm0.10}$	-/-	-/-
ReMixMatch+CDMAD	**89.9**$_{\pm0.45}$/ **89.6**$_{\pm0.46}$	**86.9**$_{\pm0.21}$/ **86.7**$_{\pm0.17}$	**83.1**$_{\pm0.46}$/ **82.7**$_{\pm0.50}$	**83.0**$_{\pm0.38}$/ **82.1**$_{\pm0.35}$	**81.9**$_{\pm0.32}$/ **80.9**$_{\pm0.44}$

distribution alignment technique employed in ReMixMatch significantly degraded the quality of pseudo-labels

Experiment

Table 3. Comparison of bACC/GM under $\gamma_l = \gamma_u = 100$ (reversed).

CIFAR-10-LT, $\gamma_l = 100$, $\gamma_u = 100$ (reversed)					
Algorithm	ABC	SAW	SAW+LA	SAW+cRT	**CDMAD**
FixMatch+	69.5/66.8	72.3/68.7	74.1/72.0	75.5/73.9	**77.1/75.4**
ReMixMatch+	63.6/60.5	79.5/78.5	50.2/14.8	80.8/79.9	**81.7/81.0**

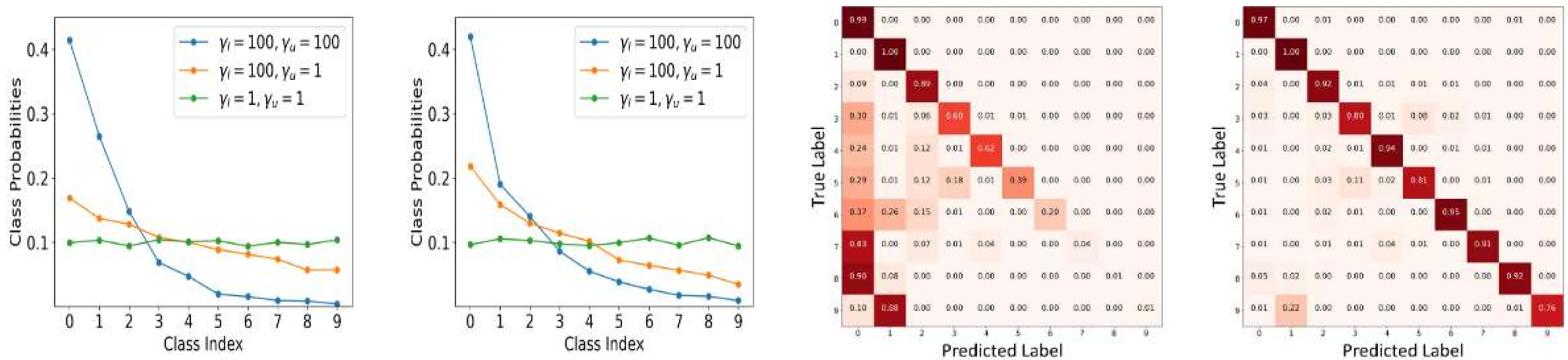
Table 4. Comparison of bACC on CIFAR-100-LT.

CIFAR-100-LT ($\gamma = \gamma_l = \gamma_u$, γ_u is assumed to be known)			
Algorithm	$\gamma = 20$	$\gamma = 50$	$\gamma = 100$
FixMatch	$49.6_{\pm 0.78}$	$42.1_{\pm 0.33}$	$37.6_{\pm 0.48}$
FixMatch+DARP	$50.8_{\pm 0.77}$	$43.1_{\pm 0.54}$	$38.3_{\pm 0.47}$
FixMatch+DARP+cRT	$51.4_{\pm 0.68}$	$44.9_{\pm 0.54}$	$40.4_{\pm 0.78}$
FixMatch+CReST	$51.8_{\pm 0.12}$	$44.9_{\pm 0.50}$	$40.1_{\pm 0.65}$
FixMatch+CReST+LA	$52.9_{\pm 0.07}$	$47.3_{\pm 0.17}$	$42.7_{\pm 0.70}$
FixMatch+ABC	$53.3_{\pm 0.79}$	$46.7_{\pm 0.26}$	$41.2_{\pm 0.06}$
FixMatch+CoSSL	$53.9_{\pm 0.78}$	$47.6_{\pm 0.57}$	$43.0_{\pm 0.61}$
FixMatch+UDAL	-	$48.0_{\pm 0.56}$	$43.7_{\pm 0.41}$
FixMatch+CDMAD	$\mathbf{54.3}_{\pm 0.44}$	$\mathbf{48.8}_{\pm 0.75}$	$\mathbf{44.1}_{\pm 0.29}$
ReMixMatch	$51.6_{\pm 0.43}$	$44.2_{\pm 0.59}$	$39.3_{\pm 0.43}$
ReMixMatch+DARP	$51.9_{\pm 0.35}$	$44.7_{\pm 0.66}$	$39.8_{\pm 0.53}$
ReMixMatch+DARP+cRT	$54.5_{\pm 0.42}$	$48.5_{\pm 0.91}$	$43.7_{\pm 0.81}$
ReMixMatch+CReST	$51.3_{\pm 0.34}$	$45.5_{\pm 0.76}$	$41.0_{\pm 0.78}$
ReMixMatch+CReST+LA	$51.9_{\pm 0.60}$	$46.6_{\pm 1.14}$	$41.7_{\pm 0.69}$
ReMixMatch+ABC	$55.6_{\pm 0.35}$	$47.9_{\pm 0.10}$	$42.2_{\pm 0.12}$
ReMixMatch+CoSSL	$55.8_{\pm 0.62}$	$48.9_{\pm 0.61}$	$44.1_{\pm 0.59}$
ReMixMatch+CDMAD	$\mathbf{57.0}_{\pm 0.32}$	$\mathbf{51.1}_{\pm 0.46}$	$\mathbf{44.9}_{\pm 0.42}$

Table 5. Comparison of bACC on Small-ImageNet-127 (size 32×32 and 64×64, γ_u is assumed to be known)

Small-ImageNet-127 ($\gamma = \gamma_l = \gamma_u$, γ_u is assumed to be known)		
Algorithm	32×32	64×64
FixMatch	29.7	42.3
FixMatch+DARP	30.5	42.5
FixMatch+DARP+cRT	39.7	51.0
FixMatch+CReST	32.5	44.7
FixMatch+CReST+LA	40.9	55.9
FixMatch+ABC	46.9	56.1
FixMatch+CoSSL	43.7	53.8
FixMatch+CDMAD	**48.4**	**59.3**

Experiment



(a) FixMatch+CDMAD (b) ReMixMatch+CDMAD (c) ReMixMatch (d) ReMixMatch+CDMAD

Figure 3. (a) and (b) present the class probabilities predicted on a white image using the proposed algorithm. (c) and (d) present the confusion matrices of the class predictions on test samples.

Based on the above findings, CDMAD can be considered as measuring the classifier's biased degree by implicitly incorporating the class distributions of both labeled and unlabeled sets.

Experiment

Table 8. Ablation study for the proposed algorithm on CIFAR-10-LT under $\gamma_l = 100$ and $\gamma_u = 1$

Ablation study ($\gamma_l = 100, \gamma_u = 1$)	**bACC/GM**		**bACC/GM**
FixMatch+CDMAD	**87.5/87.1**	**ReMixMatch+CDMAD**	**89.9/89.6**
Without CDMAD for refining pseudo-labels	78.2/75.8	Without CDMAD for refining pseudo-labels	72.3/65.9
Without CDMAD for test phase	84.9/84.1	Without CDMAD for test phase	88.2/87.7
With the use of hard pseudo-labels	86.7/86.3	With the use of sharpened pseudo-labels	88.9/88.6
With the use of confidence threshold $\tau = 0.95$	86.8/86.3	With the use of distribution alignment technique	80.4/78.5

Table 9. Experiments with the replacement of $\mathcal{I}$ by other inputs

ReMixMatch+CDMAD	CIFAR-10-LT	
Input	$\gamma_l = \gamma_u = 100$	$\gamma_l = 100, \gamma_u = 1$
Uniform	81.3/ 80.7	85.3/ 84.2
Bernoulli	82.5/ 82.0	83.6/ 82.8
Normal	78.4/ 77.5	84.0/ 83.2
Black	84.8/ 84.5	89.3/ 89.0
Red	84.8/ 84.6	90.1/ 89.9
Green	84.9/ 84.6	89.3/ 88.9
Blue	84.9/ 84.7	90.2/ 89.9
Gray	85.1/ 84.9	89.6/ 89.3
White	85.5/ 85.3	89.9/ 89.6

Table 10. Experiments with replacing $\mathcal{I}$ by non-image input

Algorithm	CIFAR-10-LT	$\gamma_l = \gamma_u = 100$	$\gamma_l = 100, \gamma_u = 1$
FixMatch+CDMAD	White image	83.6/83.1	87.5/87.1
	Non-image	84.0/83.6	87.4/87.0
ReMixMatch+CDMAD	White image	85.5/85.3	89.9/89.6
	Non-image	85.6/85.4	89.8/89.6

outside the range [0, 255]

the classification of images is related to their color.

This may be because the parameters of the distributions (e.g., mean and standard deviation of a normal distribution) used to generate random pixels may be related to specific classes.

Non-image > white > other solid color > distribution

Thank you