# Revisiting ImprovedGAN with Metric Learning for Semi-Supervised Learning

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### **Supervised Learning**

- successful
- but costly, requires full labels



## **Semi-Supervised Learning**

- partially labeled dataset (practical)
- but challenging



# Generative Adversarial Network (GAN)



noises

#### ImprovedGAN (Semi-Supervised GAN)



# ImprovedGAN Loss

cross entropy on labeled samples



on unlabeled samples

feature matching loss

#### What Help??

# In Metric Learning form

unsupervised discriminator loss

$$L_{u} = \frac{1}{N} \sum_{i=1}^{N} \left[ \log \left( 1 + \frac{1}{\sum_{j=1}^{K} e^{s_{ij}}} \right) + \log \left( 1 + \sum_{j=1}^{K} e^{\widehat{s}_{ij}} \right) \right]$$
  
similarity  $S_{ij} := \mathbf{f}(\mathbf{x}_{i}) \cdot \mathbf{W}_{j}$   
i-th class weight vector  $\mathbf{w}_{j}$   
 $f(\mathbf{x}_{i})$   $\widehat{s}_{ij} := \mathbf{f}(\widehat{\mathbf{x}}_{i}) \cdot \mathbf{w}_{j}$ 

Under Generalized Pair Weighting (GPW),

$$\min_{D} L_u$$
 equivalent to  $\lim_{D} \sum_{i=1}^N \sum_{j=1}^K$ 

$$\min_{D} \sum_{i=1}^{N} \sum_{j=1}^{K} \widehat{\omega}_{ij} \widehat{s}_{ij} - \underbrace{\omega_{ij}}_{\text{coefficient to similarity}} S_{ij}$$

# In Metric Learning form



$$\omega_{ij} = \frac{e^{s_{ij}}}{\sum_k e^{s_{ik}} (1 + \sum_k e^{s_{ik}})}$$

Thus, 
$$\omega_{ij}{}^{(i)}_{\max}\gg\omega_{ij}$$
 (exponentially larger) for  $j^{(i)}_{\max}:=rgmax_{ij}$ 

**Prop 1.** Minimizing  $L_u$  maximizes  $\max_j s_{ij}$  and thus the prediction confidence  $p_{\max}(\mathbf{x}) = \max_y q(y|y < K, \mathbf{x})$  for real  $\mathbf{x}$ .



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# In Metric Learning form



**Prop 2.** If  $\mathbf{f}_i$  and  $\hat{\mathbf{f}}_{i'} = (\hat{\mathbf{x}}_{i'})$  with a generated sample  $\hat{\mathbf{x}}_{i'}$  are sufficiently near to each other, then minimizing  $L_u$  decreases the angle  $\theta_{ij}$  while constraining  $\|\mathbf{f}_i\| \|\mathbf{w}_j\|$  to be fixed.



#### **Class-wise Cluster Separation:**

The above two propositions suggests that the adversarial interaction by  $L_u$  and  $L_g$ induces class-wise cluster separation of the real features  $f_i$ .



# Proposed Method: Intensified ImprovedGAN (I2GAN)

To enhance class-wise cluster separation characteristic:

• Scaling-up

$$L_u \leftarrow \tau L_u \qquad (\tau > 1)$$

- -> higher prediction confidence
- Excessive Sampling on Generated Samples

$$L_g = \|\frac{1}{N} \sum_{i=1}^{N} \mathbf{f}_i - \frac{1}{N'} \sum_{i'=1}^{N'} \widehat{\mathbf{f}}_{i'} \|_1. \qquad N' > N$$

To better satisfy the sufficient condition of Prop 2

## **Results**



### **Results**

# labels	100	200	400
Mean Teacher*	$5.45 \pm 0.14$	$5.21 \pm 0.21$	
LP* (CVPR'19) ICT* (NIPS'19) SWA* (ICLR'19)	$16.93 \pm 0.70$ $15.48 \pm 0.78$ 15.58	13.22 ± 0.29 <b>9.26</b> ± <b>0.09</b> 11.02	$\begin{array}{c} 10.61 \pm 0.28 \\ \textbf{7.29} \pm \textbf{0.02} \\ 9.05 \end{array}$
ALI* TripleGAN* Local-GAN* ImprovedGAN* BadGAN* ImprovedGAN w/ <i>M</i> Inv.* ImprovedGAN w/ <i>M</i> Reg.*	$\begin{array}{c} 19.98 \pm 0.89 \\ 81.08 \pm 0.57 \\ 17.44 \pm 0.25 \\ 21.83 \pm 2.01 \\ 22.42 \pm 0.17 \\ 19.52 \pm 1.5 \\ 16.37 \pm 0.42 \end{array}$	$19.09 \pm 0.44$ $18.21 \pm 0.37$ - $19.61 \pm 2.09$ $18.64 \pm 0.08$ - $15.25 \pm 0.35$	$\begin{array}{c} 17.99 \pm 1.62 \\ 16.99 \pm 0.36 \\ 14.23 \pm 0.27 \\ 18.63 \pm 2.32 \\ 14.41 \pm 0.30 \\ 16.20 \pm 1.6 \\ 14.34 \pm 0.17 \end{array}$
ImprovedGAN I2GAN e-I2GAN	$16.80 \pm 0.54$ <b>14.29</b> $\pm$ <b>0.22</b> 14.93 $\pm$ 0.25	$15.64 \pm 0.12$ $13.80 \pm 0.20$ $13.77 \pm 0.07$	$14.86 \pm 0.26$ $12.63 \pm 0.17$ $13.29 \pm 0.35$

Table: The SSL performance in error rates (%) on CIFAR-10

## **Results**

#### Table: The SSL performance in error rates (%) on SVHN

		# of labeled images for each class	50	100
Table: The SSL performance in error rates (%) on CIFAR-100		Temporal Ensemble*	7.01 ± 0.29	5.73 ± 0.16
# labels	40	SPCTN* Pseudo-Labeling*	-	7.73 ± 0.30 9.94 ± 0.61
Supervise Only	$74.85 \pm 0.55$	Mean Teacher*	$5.45 \pm 0.14$	$5.21 \pm 0.21$
BadGAN*	$61.49 \pm 0.73$	VAT*	-	5.77
ImprovedGAN (our implementation) I2GAN e-I2GAN	$\begin{array}{c} 56.14 \pm 0.64 \\ \textbf{51.31} \pm \textbf{0.32} \\ 52.50 \pm 1.25 \end{array}$	ALI* TripleGAN* LocalGAN* ImprovedGAN* BadGAN*	- 5.33 $\pm$ 0.12 5.48 $\pm$ 0.29 18.44 $\pm$ 4.80 5.79 $\pm$ 0.45	$7.41 \pm 0.65 \\ 5.77 \pm 0.17 \\ 4.73 \pm 0.29 \\ 8.11 \pm 1.3 \\ 4.68 \pm 0.07$
		ImprovedGAN (our implementation) I2GAN e-I2GAN	$\begin{array}{c} 5.79 \pm 0.19 \\ \textbf{5.27} \pm \textbf{0.13} \\ 5.43 \pm 0.13 \end{array}$	$5.60 \pm 0.09$ $5.17 \pm 0.16$ $5.27 \pm 0.10$