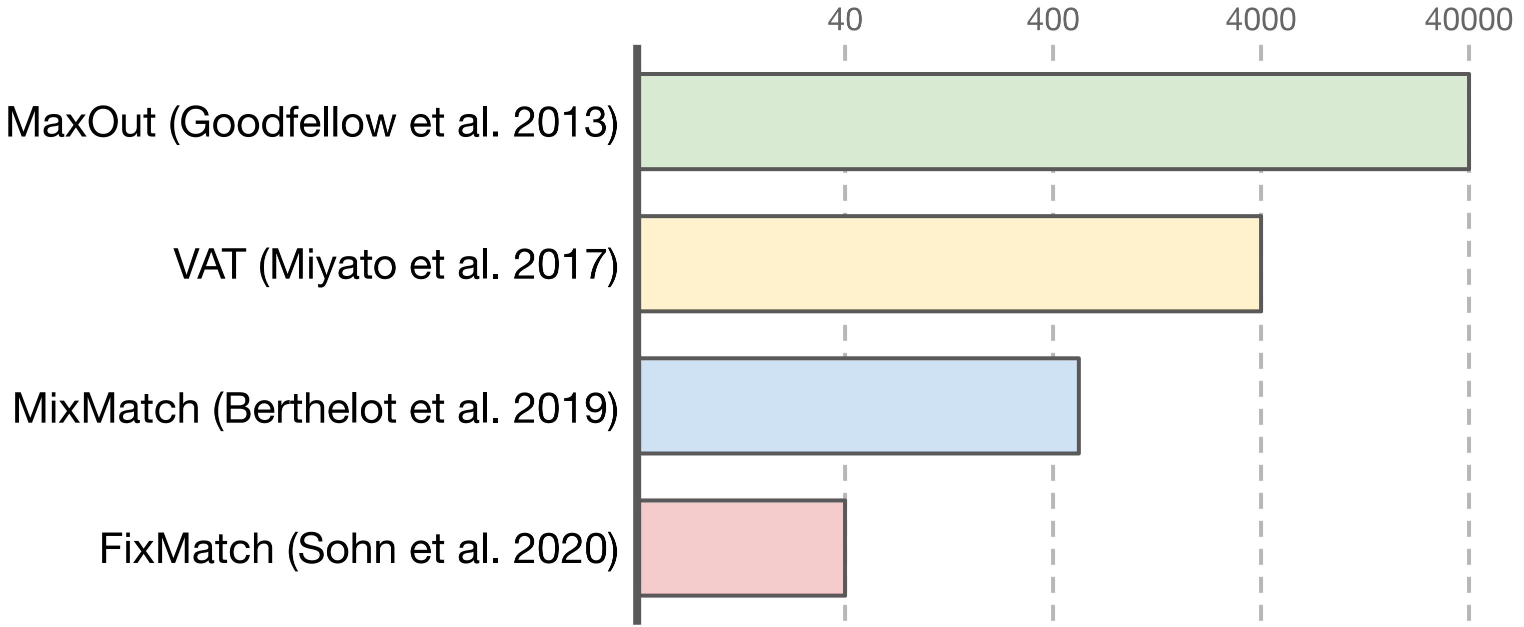
Explicit and Implicit Entropy Minimization in Proxy-Label-Based Semi-Supervised Learning

Colin Raffel

CVPR Workshop on Learning with Limited and Imperfect Data



Number of labels required to reach 90% accuracy on CIFAR-10

$$\mathbb{E}_{x,y} - y \log p_\theta(y|x)$$

$$\mathbb{E}_x - \hat{p}_\theta(y|x) \log p_\theta(y|x)$$

$$\mathbb{E}_x - \hat{p}_\theta(y|x) \log p_\theta(y|x)$$

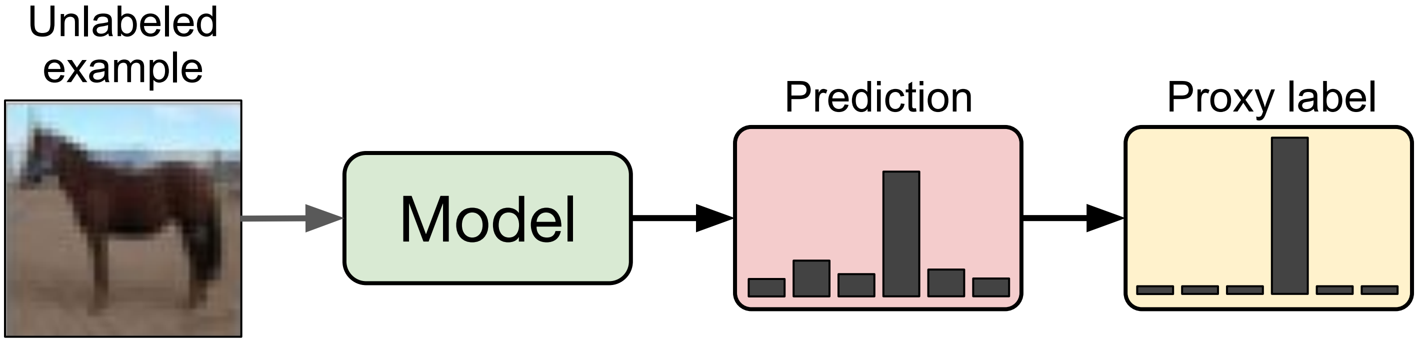
"Proxy label"

$$\mathbb{E}_x -\underbrace{\hat{p}_\theta(y|x)}_{\text{“Pseudo-label”}} \log p_\theta(y|x)$$

$$\mathbb{E}_x \, -\hat{p}_\theta(y|x) \log p_\theta(y|x)$$

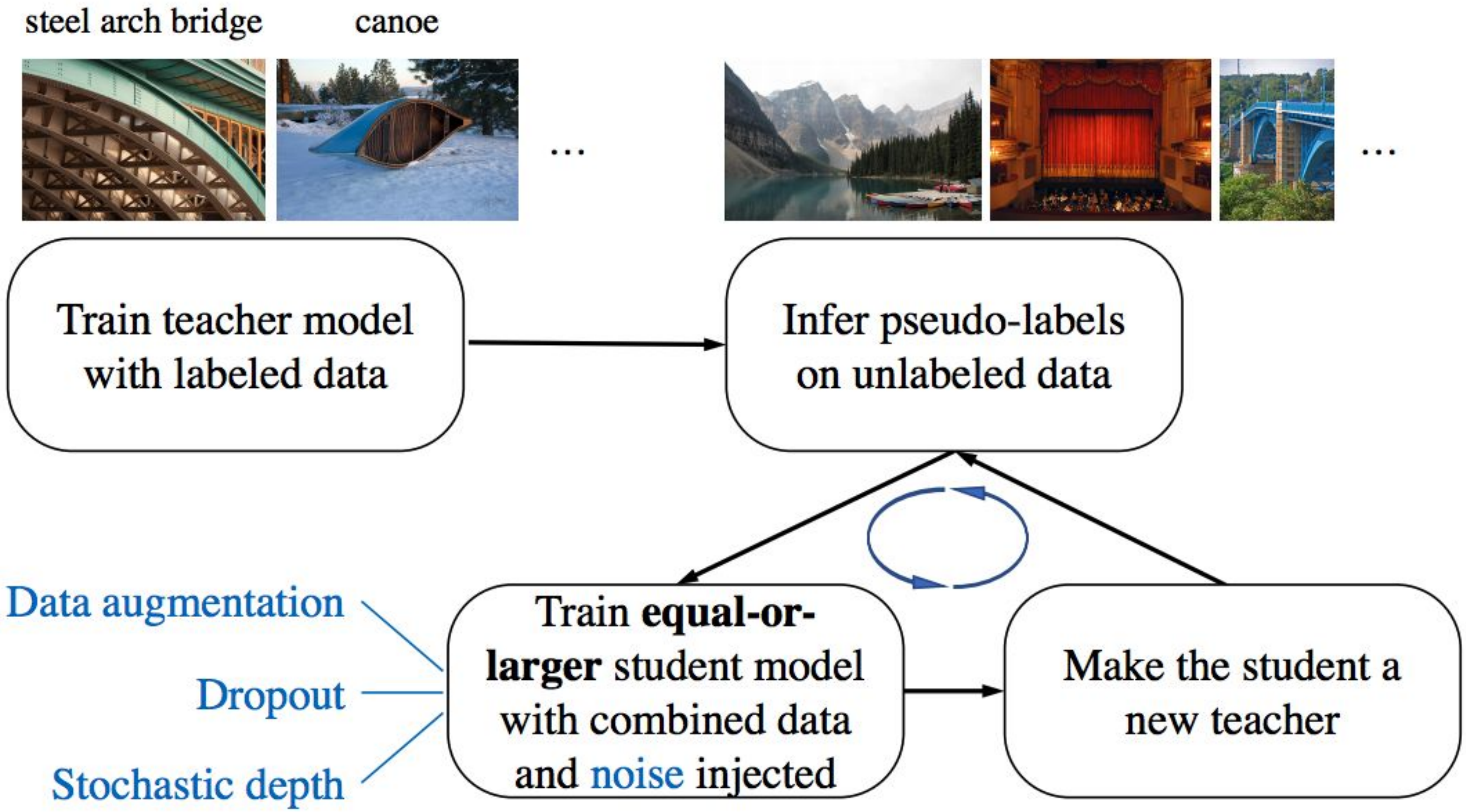
“Label guess”

Self-training



$$\mathbb{E}_x - \hat{p}_\theta(y|x) \log p_\theta(y|x)$$

$$\hat{p}_\theta(y|x) = \arg\max_y [p_\theta(y|x)]$$



Self-training with Noisy Student improves ImageNet classification, Xie et al. 2019

Probability of Error of Some Adaptive Pattern-Recognition Machines

H. J. SCUDDER, III, MEMBER, IEEE

We will make the untaught machine from the same basic configuration as the taught machine and use the output of the machine $\hat{\theta}_n$ to iterate the estimate, instead of teaching the machine with the correct observation θ_n each time.

$$\mathbb{E}_x - \hat{p}_\theta(y|x) \log p_\theta(y|x)$$

$$\hat{p}_\theta(y|x) = \arg\max_y [p_\theta(y|x)]$$

$$\mathbb{E}_x -\hat{p}_\theta(y|x) \log p_\theta(y|x)$$

$$\hat{p}_\theta(y|x) = \cancel{\arg\max_y}[p_\theta(y|x)]$$

$$\mathbb{E}_x - \hat{p}_\theta(y|x) \log p_\theta(y|x)$$

$$\hat{p}_\theta(y|x) = \cancel{\arg\max_y}[p_\theta(y|x)]$$

$$\hat{p}_\theta(y|x) = p_\theta(y|x)$$

$$\mathbb{E}_x - \hat{p}_\theta(y|x) \log p_\theta(y|x)$$

$$\hat{p}_\theta(y|x) = \cancel{\arg\max_y}[p_\theta(y|x)]$$

$$\hat{p}_\theta(y|x) = p_\theta(y|x)$$

$$\mathbb{E}_x - p_\theta(y|x) \log p_\theta(y|x)$$

$$\mathbb{E}_x -\hat{p}_\theta(y|x) \log p_\theta(y|x)$$

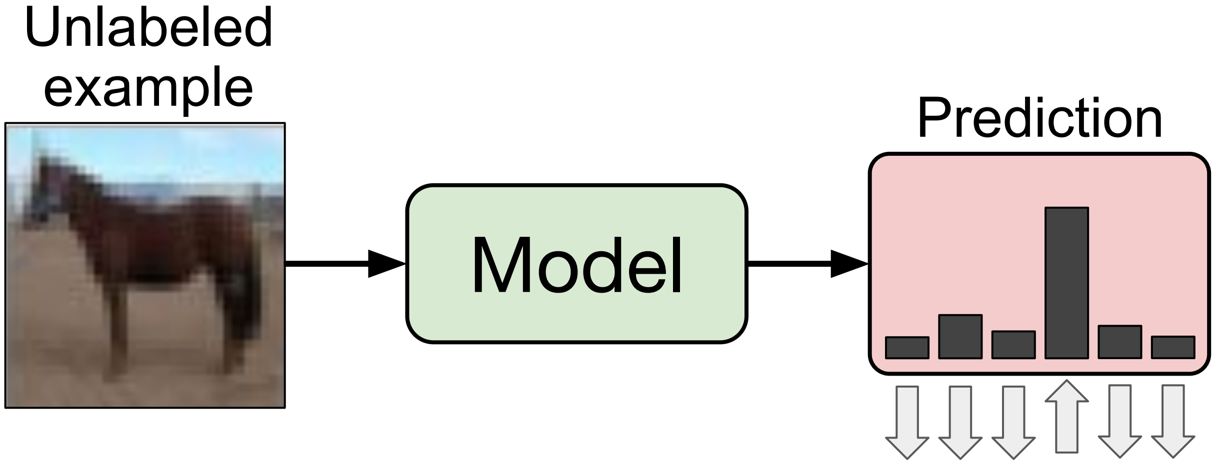
$$\hat{p}_\theta(y|x) = \cancel{\arg\max_y}[p_\theta(y|x)]$$

$$\hat{p}_\theta(y|x) = p_\theta(y|x)$$

$$\mathbb{E}_x -p_\theta(y|x) \log p_\theta(y|x)$$

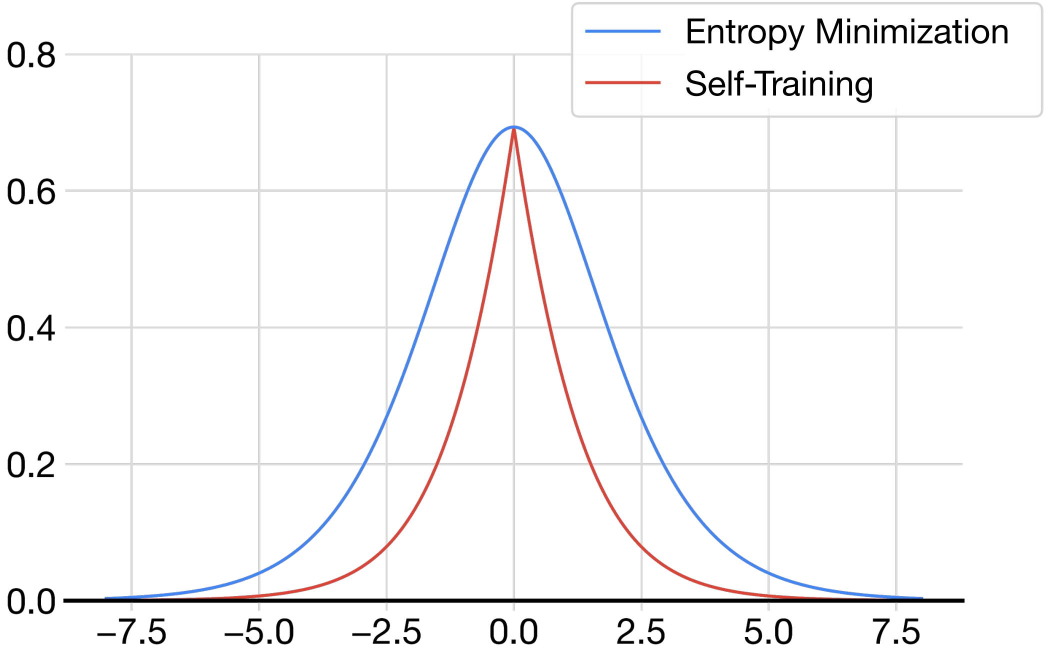
Entropy!

Entropy Minimization



$$\mathbb{E}_x - \hat{p}_\theta(y|x) \log p_\theta(y|x)$$

$$\hat{p}_\theta(y|x) = p_\theta(y|x)$$


Entropy Minimization
Self-Training
0.8
0.6
0.4
0.2
0.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5

$$
\begin{aligned}
\mathcal{I}(c\,;\mathbf{x}) &= \iint dc\, d\mathbf{x}\, p(c,\mathbf{x}) \log \frac{p(c,\mathbf{x})}{p(c)p(\mathbf{x})} & (4)\\
&= \int d\mathbf{x}\, p(\mathbf{x}) \int dc\, p(c|\mathbf{x}) \log \frac{p(c|\mathbf{x})}{p(c)} & (5)\\
&= \int d\mathbf{x}\, p(\mathbf{x}) \int dc\, p(c|\mathbf{x}) \log \frac{p(c|\mathbf{x})}{\int d\mathbf{x}\, p(\mathbf{x}) p(c|\mathbf{x})} & (6)
\end{aligned}
$$

The elements of this expression are separately recognizable:

$\int d\mathbf{x}\, p(\mathbf{x})(\cdot)$ is equivalent to an average over a training set $\frac{1}{N_{ts}} \sum_{ts}(\cdot)$;

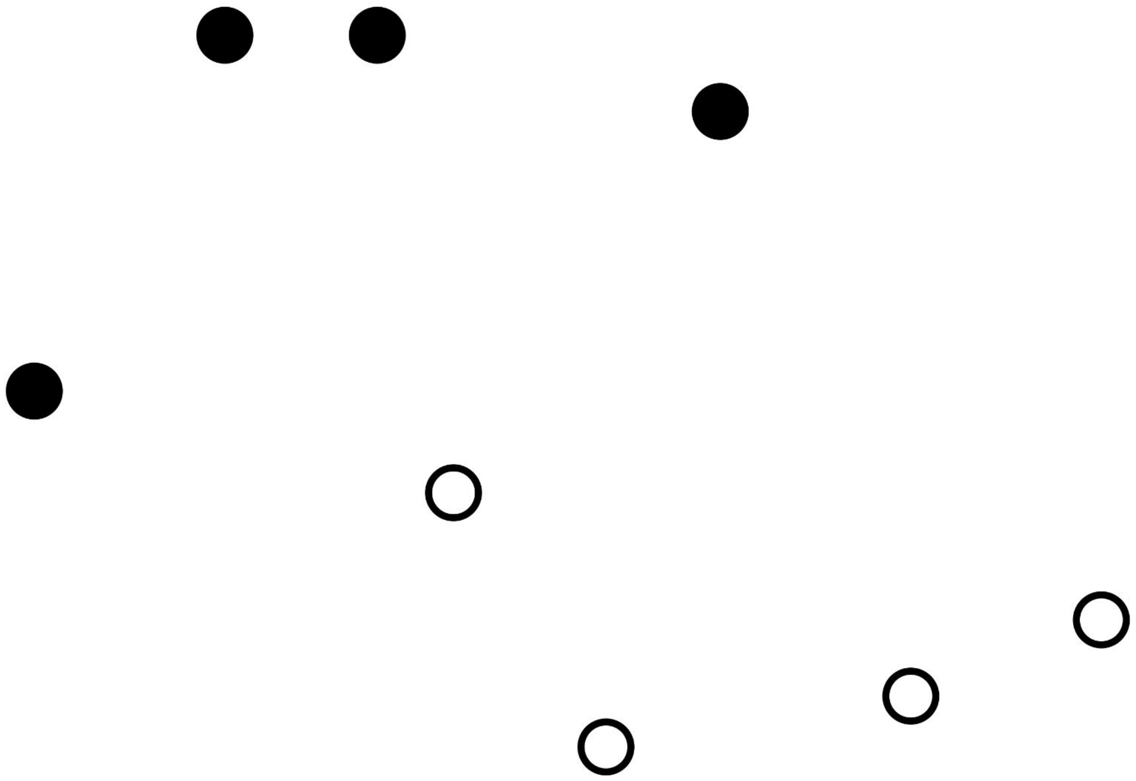
$p(c|\mathbf{x})$ is simply the network output y_c;

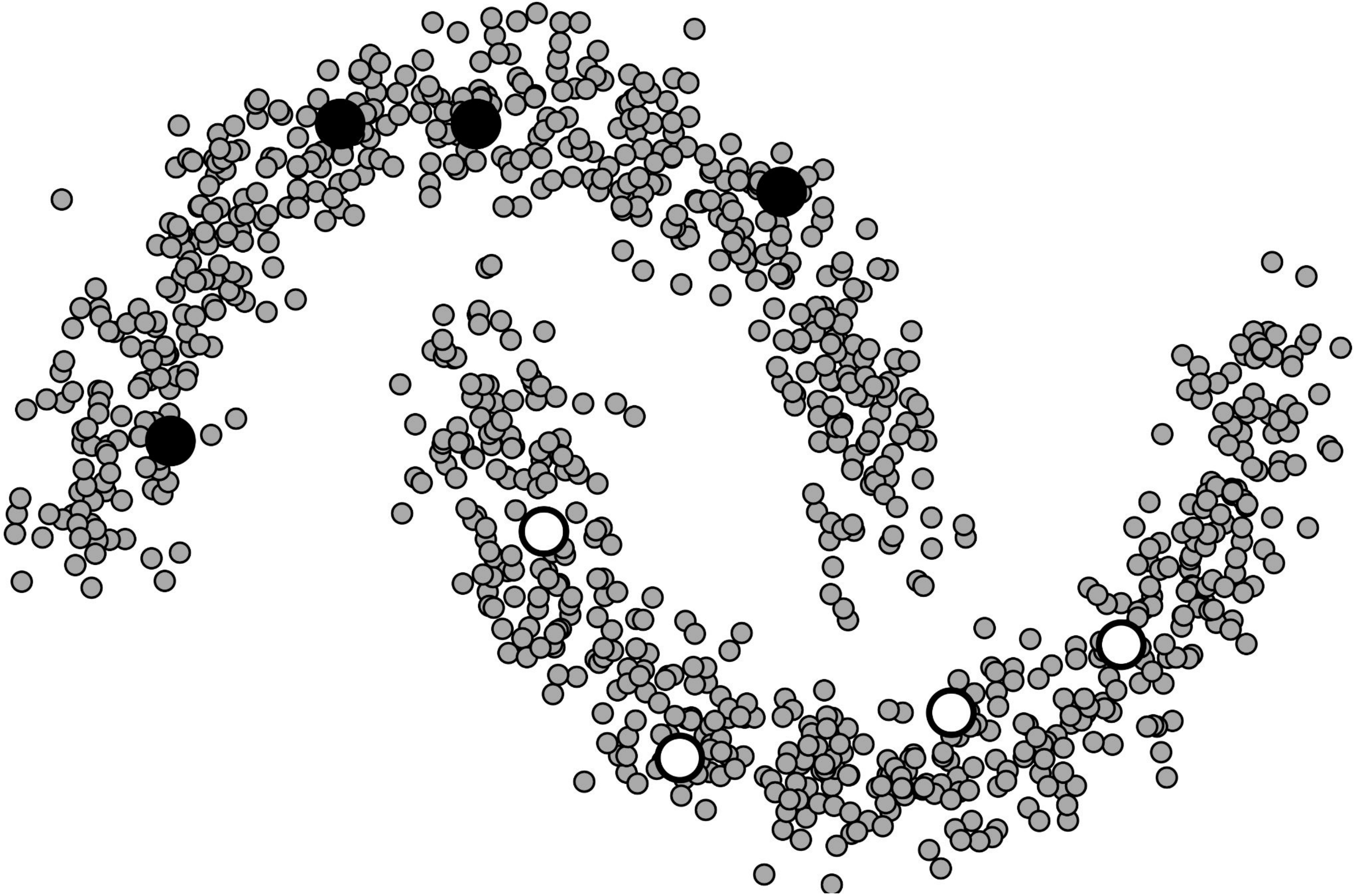
$\int dc\,(\cdot)$ is a sum over the class labels and corresponding network outputs.

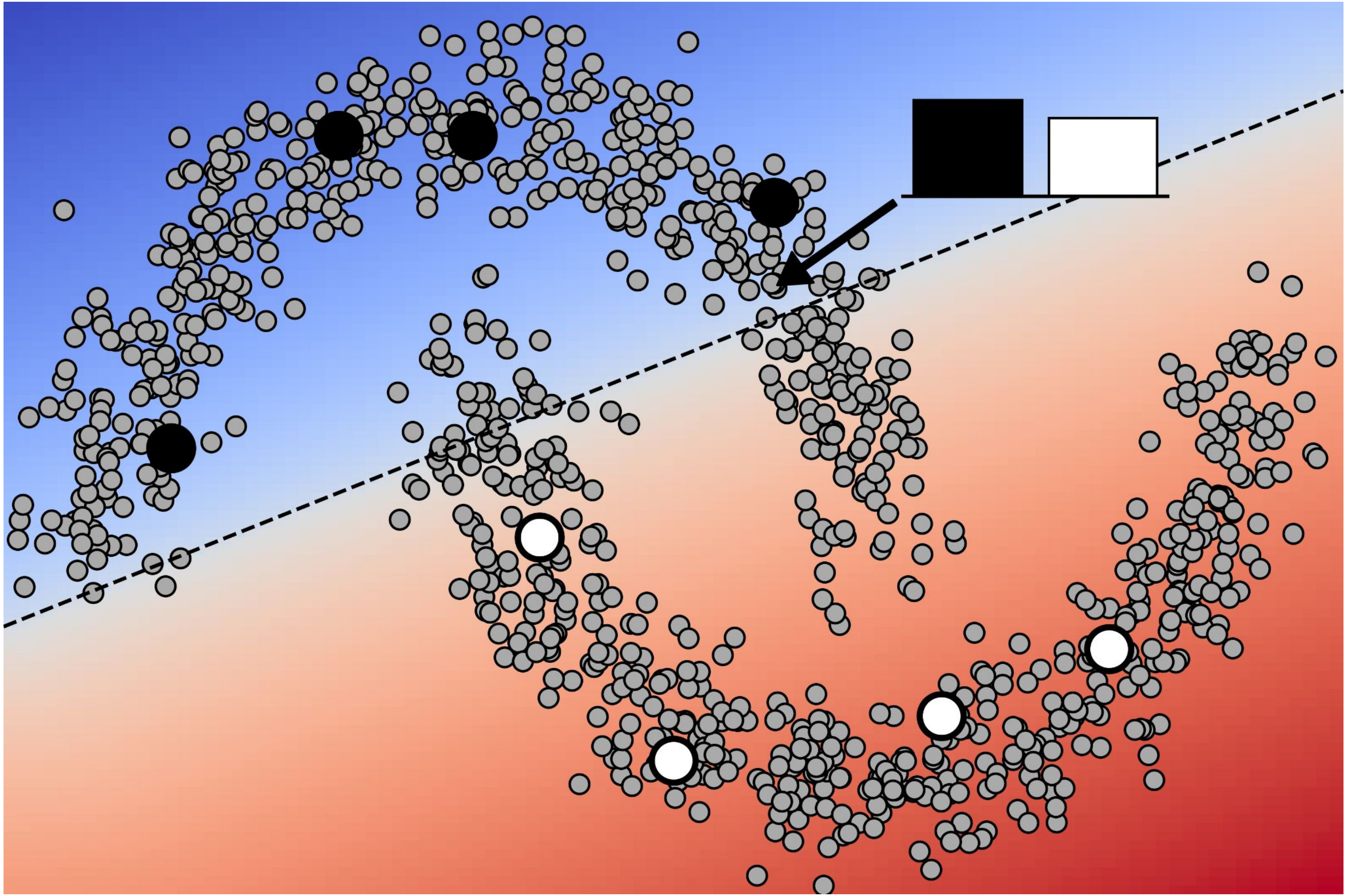
Hence:

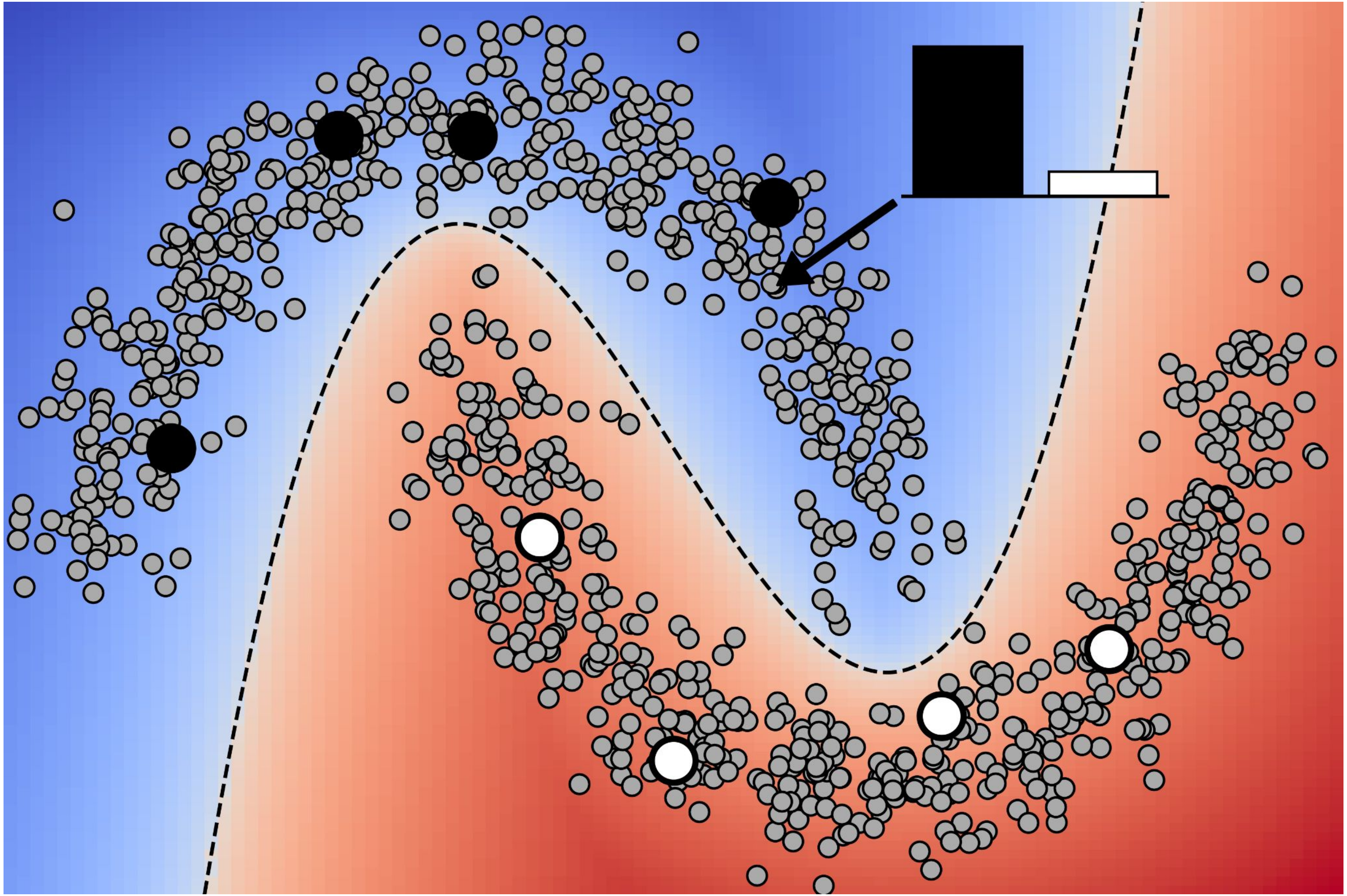
$$
\begin{aligned}
\mathcal{I}(c\,;\mathbf{x}) &= \frac{1}{N_{ts}} \sum_{ts} \sum_{i=1}^{N_c} y_i \log \frac{y_i}{\overline{y}_i} & (7)\\
&= -\sum_{i=1}^{N_c} \overline{y}_i \log \overline{y}_i + \frac{1}{N_{ts}} \sum_{ts} \sum_{i=1}^{N_c} y_i \log y_i & (8)\\
&= \mathcal{H}(\overline{\mathbf{y}}) - \overline{\mathcal{H}(\mathbf{y})} & (9)
\end{aligned}
$$

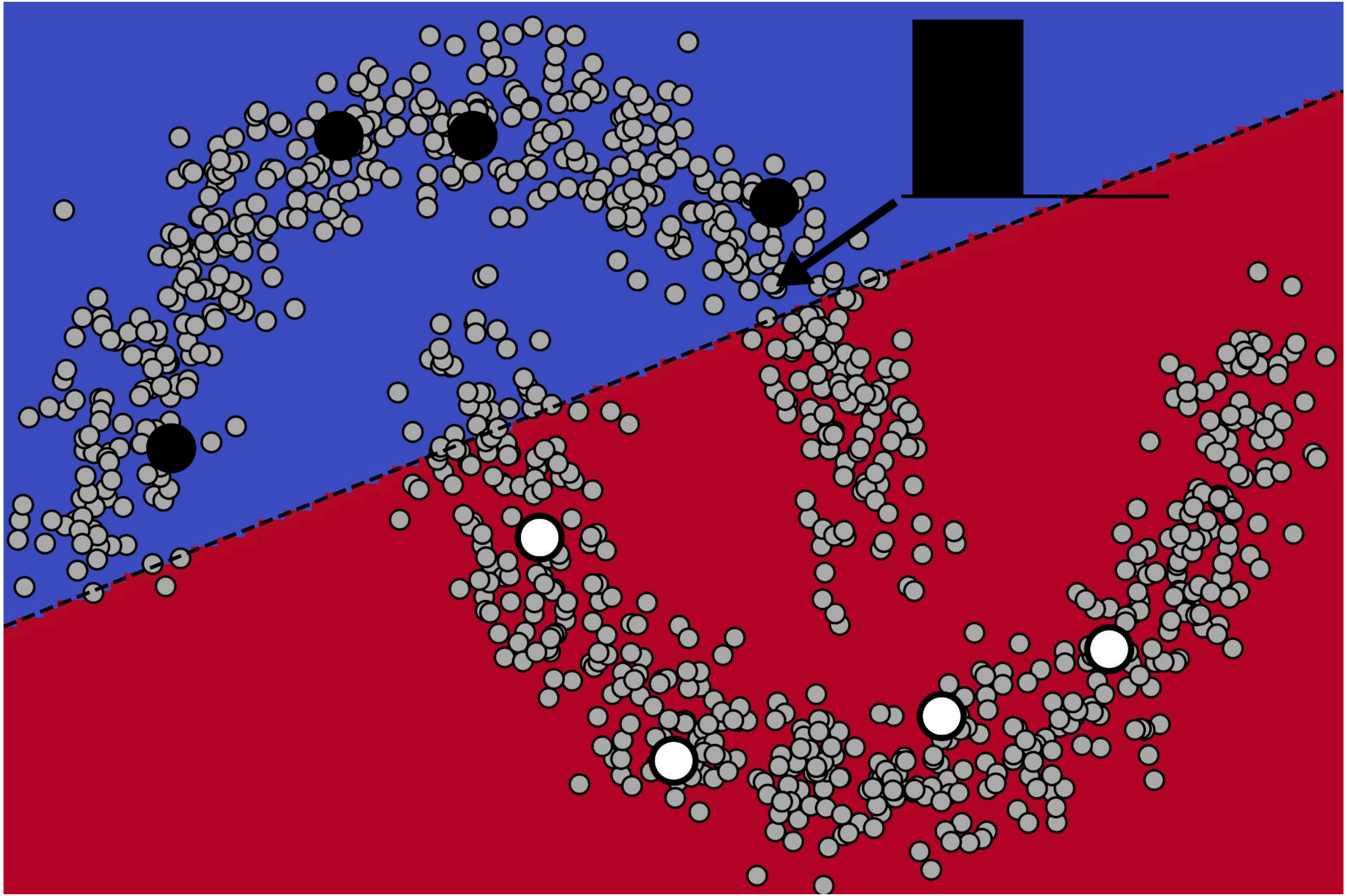
Unsupervised Classifiers, Mutual Information and Phantom Targets, Bridle et al. 1991

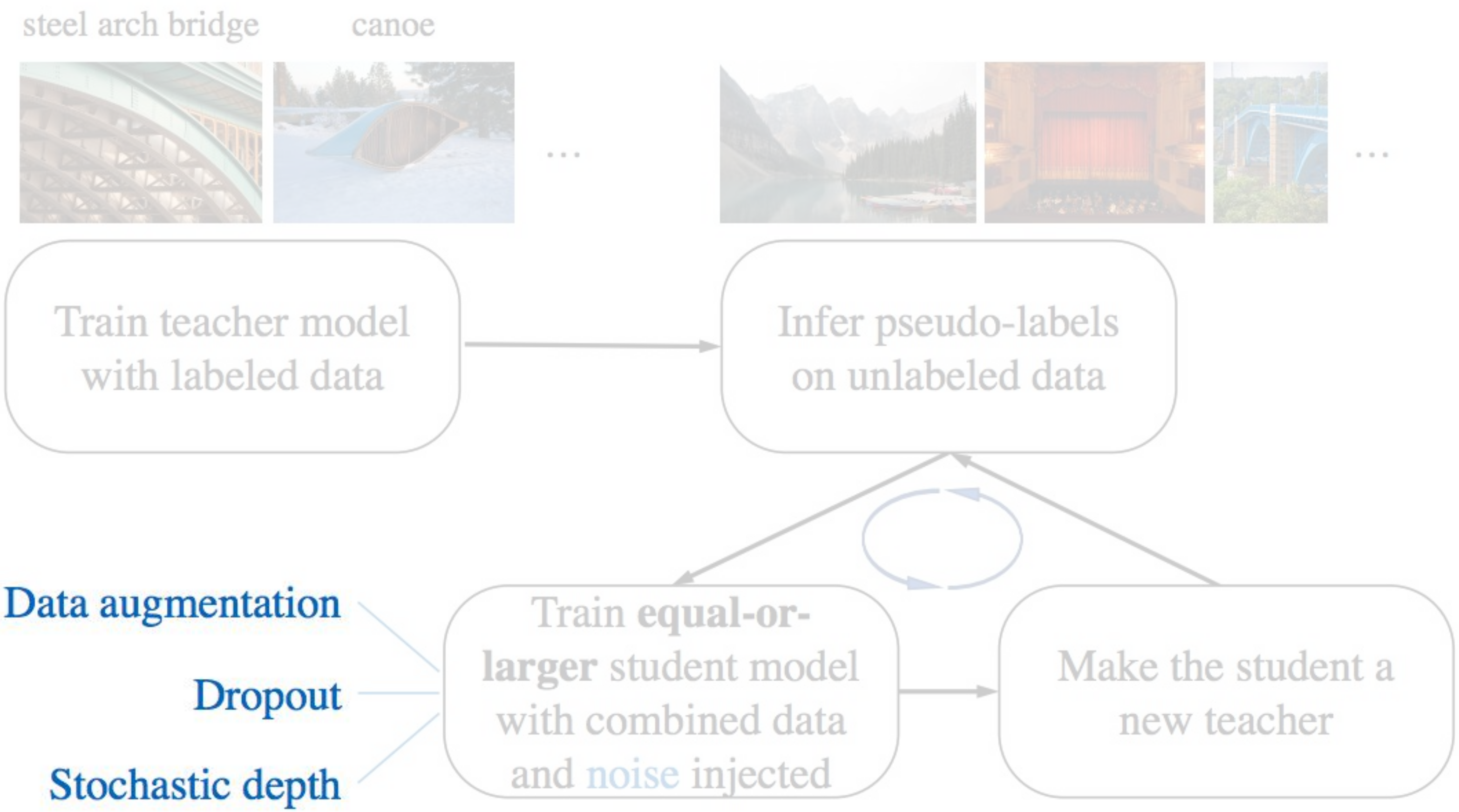









[redacted]



Self-training with Noisy Student improves ImageNet classification, Xie et al. 2019

Pseudo-Labeling and Confirmation Bias in Deep Semi-Supervised Learning

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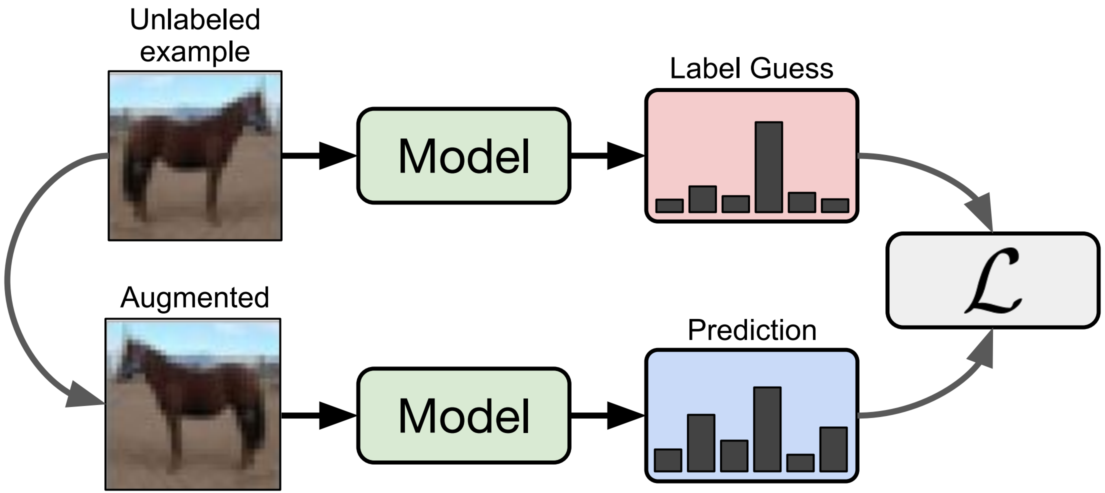
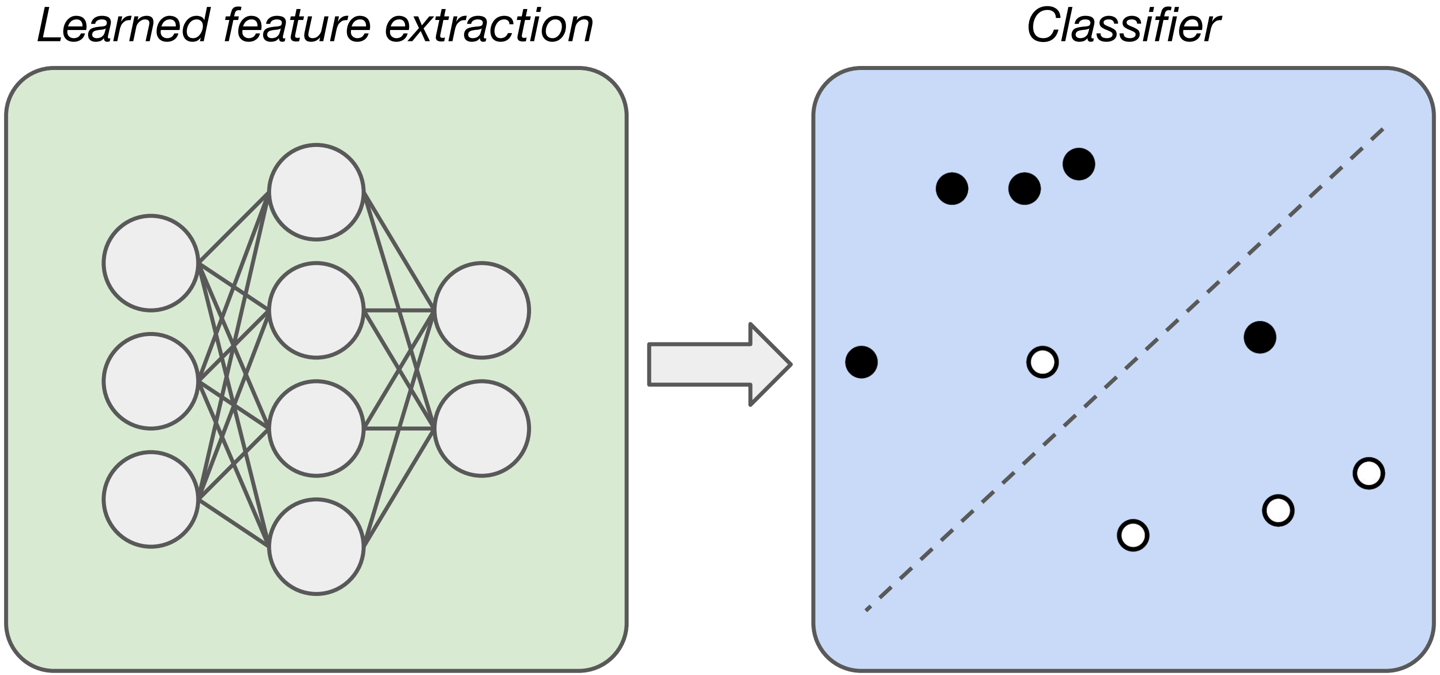
Experiments show that this naive pseudo-labeling is limited by confirmation bias as prediction errors are fit by the network. To deal with this issue, we propose to use mixup augmentation [25] as an effective regularization that helps calibrate deep neural networks [26] and, therefore, alleviates confirmation bias.

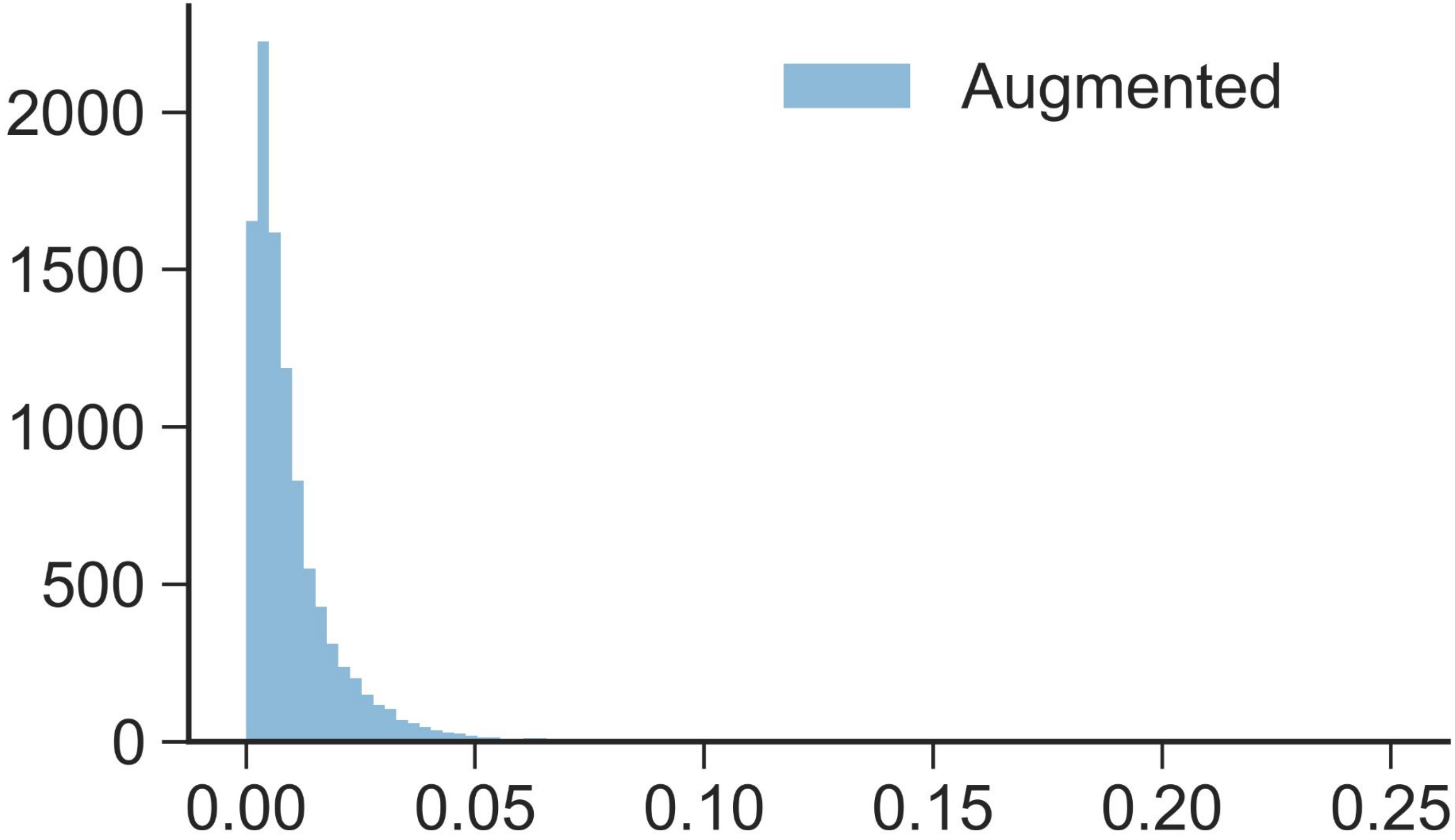
Consistency Regularization

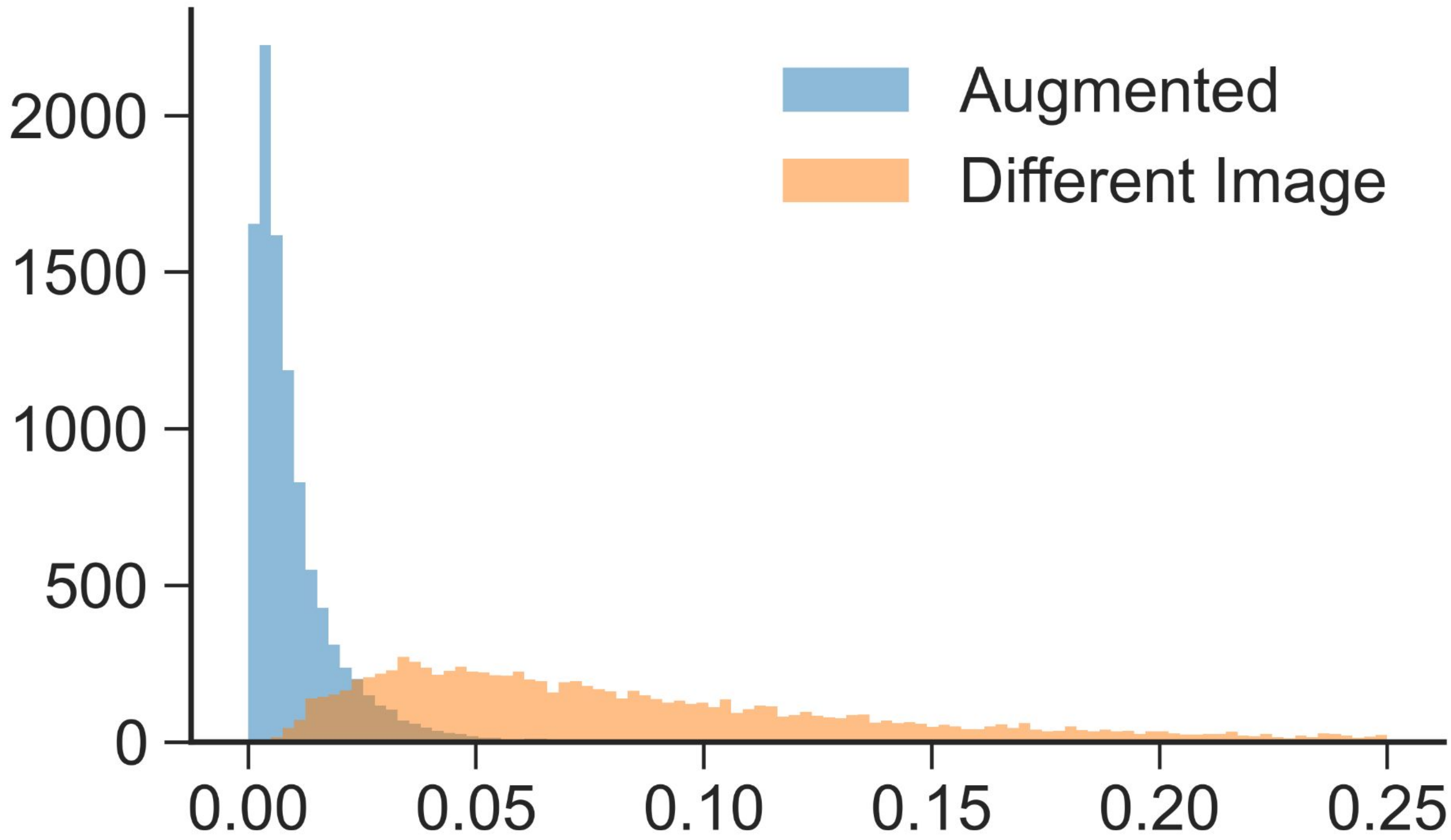


$$\mathbb{E}_x - \hat{p}_\theta(y|x) \log p_\theta(y|x)$$

$$\hat{p}_\theta(y|x) = p_\theta(y|x')$$


Learned feature extraction
Classifier


Augmented
2000
1500
1000
500
0
0.00
0.05
0.10
0.15
0.20
0.25


Augmented
Different Image
2000
1500
1000
500
0
0.00
0.05
0.10
0.15
0.20
0.25

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