Latent Outlier Exposure For Anomaly Detection With Contaminated Data

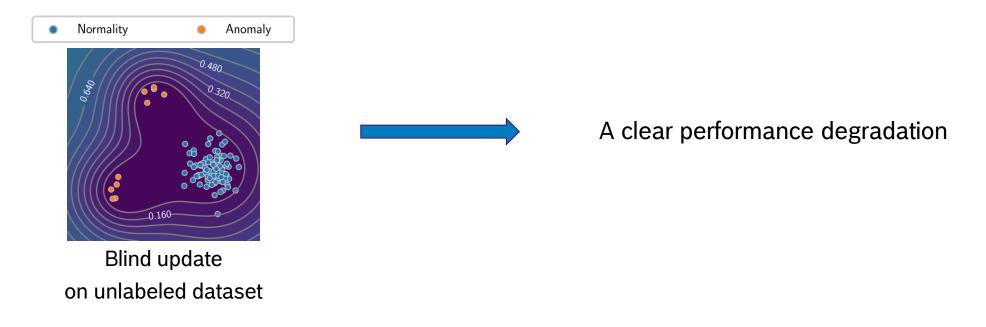
Chen Qiu*1,2, **Aodong Li*3**, Marius Kloft2, Maja Rudolph1, Stephan Mandt3

- 1: Bosch Center for Al
- 2: Technical University Kaiserslautern, Germany
- 3: University of California, Irvine, USA
- * Equal Contribution



Deep Anomaly Detection with Contaminated Data Motivation

- ► A common assumption in unsupervised anomaly detection is that clean training data is available.
- ▶ What if the training data is not clean and already contains some anomalies?
 - ► A dataset of financial transactions could contain unnoticed fraudulent activities



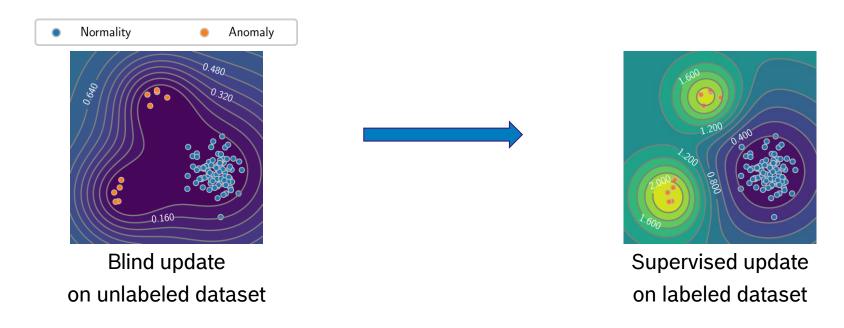




Deep Anomaly Detection with Contaminated Data

Motivation

- ▶ When the contaminated data is well labeled, the model learns the decision boundary very well.
- ▶ Unexploited information is hidden in the contaminated data.







Deep Anomaly Detection with Contaminated Data Contribution & Problem setup

► Our contribution: Latent Outlier Exposure (LOE), a new general strategy for training deep anomaly detection models with contaminated data.

▶ Problem setup: we consider a set of samples x_i that contains many normal samples and a few anomalies.









Proposed loss

 \triangleright Consider a joint loss function with two loss terms (given the binary anomaly label y_i):

$$\mathcal{L}(\theta, \mathbf{y}) = \sum_{i=1}^{N} (1 - y_i) \mathcal{L}_n^{\theta}(\mathbf{x}_i) + y_i \mathcal{L}_a^{\theta}(\mathbf{x}_i).$$

- \blacktriangleright $\mathcal{L}_n^{\theta}(\mathbf{x})$: a normal loss that is designed to be minimized over normal data.
- \blacktriangleright $\mathcal{L}_{a}^{\theta}(\mathbf{x})$: an abnormal loss that is designed to have the opposite effect.
- ▶ E.g., for deep SVDD, $\mathcal{L}_n^{\theta}(\mathbf{x}) = ||f_{\theta}(\mathbf{x}) \mathbf{c}||^2$ and $\mathcal{L}_a^{\theta}(\mathbf{x}) = 1/||f_{\theta}(\mathbf{x}) \mathbf{c}||^2$.





Optimization

- ▶ Problem: the anomaly labels *y* are not observed in practice.
- ► Key idea: infer the anomaly labels during training
- ► Constrained minimization problem:

$$\min_{\theta} \min_{\mathbf{y} \in \mathcal{Y}} \mathcal{L}(\theta, \mathbf{y}) \quad \text{s.t.} \quad \mathcal{Y} = \{\mathbf{y} \in \{0, 1\}^N : \sum_{i=1}^N y_i = \alpha N\}$$

where α is an assumed contamination rate (hyperparameter), and N is the number of samples.







Optimization

Block coordinate update:

- ▶ To update θ , we fix y and minimize $\mathcal{L}(\theta, y)$ over θ .
- ▶ To infer y given θ , we minimize $\mathcal{L}(\theta, y)$ subject to the constraint.
 - ightharpoonup Rank samples according to $S_i^{train} = \mathcal{L}_n^{\theta}(\mathbf{x}_i) \mathcal{L}_a^{\theta}(\mathbf{x}_i)$ and assign 1 to the top α fraction, and 0 to the rest.



Model extension & Anomaly score

► Soft latent outlier exposure:

$$\mathcal{Y}' = \{ \mathbf{y} \in \{0, 0.5\}^N : \sum_{i=1}^N y_i = 0.5\alpha N \}.$$

- ► Avoid being overconfident in assigning labels
- ▶ Treat the identified anomalies as uncertain

► Anomaly score at the test time:

$$S_i^{test} = \mathcal{L}_n^{\theta}(\mathbf{x}_i).$$

 Avoid the overfitting to anomalies encountered during training

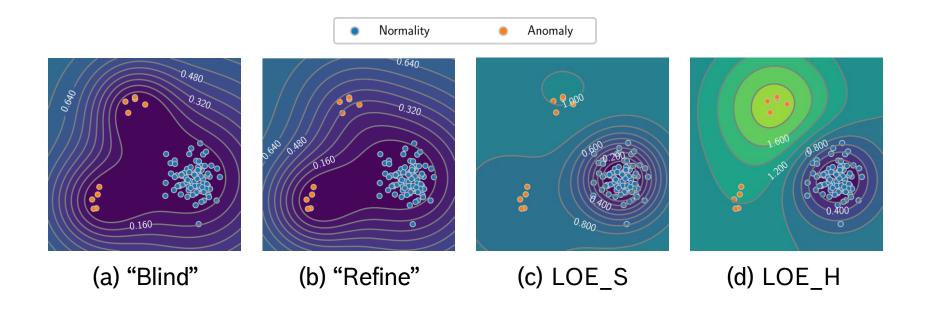






Toy experiment

► Soft LOE and hard LOE learn the boundary of normal and abnormal samples successfully, while the "Blind" and "Refine" baselines do not.





Experiment setup

- ▶ Datasets: image data, video data, and tabular data
- \blacktriangleright Corrupt the training set: we mix a fraction of α_0 abnormal samples into the normal training set.

Image data



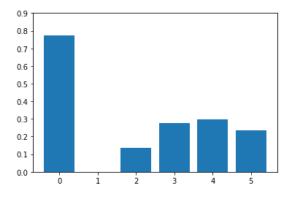


Video data





Tabular data







Quantitative results

► LOE outperforms the baselines on image data, video data, and tabular data when combining with various deep anomaly detection models.

Table 1. AUC (%) with standard deviation for anomaly detection on CIFAR-10 and F-MNIST. For all experiments, we set the contamination ratio as 10%. LOE mitigates the performance drop when NTL and MHRot trained on the contaminated datasets.

		CIFAR-10	F-MNIST
NTL	Blind	91.3±0.1 (-4.4)	85.0±0.2 (-9.7)
	Refine	93.5±0.1 (-2.2)	89.1 ± 0.2 (-5.6)
	LOE_H (ours)	94.9 ± 0.2 (-0.8)	92.9 ± 0.7 (-1.8)
	LOE_S (ours)	94.9 ± 0.1 (-0.8)	92.5 ± 0.1 (-2.2)
MHRot	Blind	84.0±0.5 (-4.2)	88.8±0.1 (-4.9)
	Refine	84.4±0.1 (-3.8)	89.6 ± 0.2 (-4.1)
	LOE_H (ours)	86.4±0.5 (-1.8)	91.4 ± 0.2 (-2.3)
	LOE_S (ours)	86.3±0.2 (-1.9)	91.2 ± 0.4 (-2.5)

Table 4. AUC (%) for different contamination ratios for a video frame anomaly detection benchmark proposed in (Pang et al., 2020). LOE_S (proposed) achieves state-of-the-art performance.

Method	Contamination Ratio			
	10%	20%	30%*	
(Tudor Ionescu et al., 2017)	-	-	68.4	
(Liu et al., 2018)	-	-	69.0	
(Del Giorno et al., 2016)	-	-	59.6	
(Sugiyama & Borgwardt, 2013)	55.0	56.0	56.3	
(Pang et al., 2020)	68.0	70.0	71.7	
Blind	85.2±1.0	76.0 ± 2.7	66.6 ± 2.6	
Refine	82.7±1.5	74.9 ± 2.4	69.3 ± 0.7	
LOE_H (ours)	82.3±1.6	59.6 ± 3.8	56.8 ± 9.5	
LOE_S (ours)	86.8±1.2	79.2 ± 1.3	71.5±2.4	

^{*}Default setup in (Pang et al., 2020), corresponding to $\alpha_0 \approx 30\%$.

Table 3. F1-score (%) for anomaly detection on 30 tabular datasets studied in (Anonymous, 2022). We set $\alpha_0 = \alpha = 10\%$ in all experiments. LOE (proposed) outperforms the "Blind" and "Refine" consistently. (See Tables 5 and 6 for more details, including AUCs.)

$ \begin{array}{c c c c c c c c c c c c c c c c c c c $		NTL			ICL				
annthyroid 29.7±3.5 42.7±7.1 47.7±11.4 50.3±4.5 29.1±2.2 38.5±2.1 48.7±7.6 43.0±8.8 arrhythmia 57.6±2.5 59.1±2.1 62.1±2.8 62.7±3.3 53.9±0.7 60.9±2.2 62.4±1.8 63.6±2.1 50.4±1.8 93.1±0.9 95.6±0.4 95.3±0.4 92.6±1.1 93.4±1.0 96.0±0.6 95.7±0.6 cardio 21.8±4.9 45.2±7.9 73.0±7.9 57.8±5.5 50.2±4.5 56.2±3.4 71.1±3.2 62.2±2.7 ecoli 0.0±0.0 88.9±14.1 100.0±0.0 100.0±0.0 17.8±15.1 46.7±25.7 75.6±4.4 75.6±4.4 glass 11.1±7.0 15.6±5.4 17.8±5.4 20.0±8.3 89.4±4.1 11.1±0.0 11.1±7.0 8.9±8.3 ionosphere 89.0±1.5 91.0±2.0 91.0±1.7 91.3±2.2 86.5±1.1 85.9±2.3 85.7±2.8 88.6±0.6 kdd 95.9±0.0 96.0±1.1 98.1±0.4 98.4±0.1 99.3±0.1 99.3±0.1 99.4±0.1 99.5±0.0 99.4±0.0 kddrev 98.4±0.1 98.4±0.2 89.1±1.7 98.6±0.0 99.9±0.5 98.4±0.4 99.8±0.1 99.5±0.0 99.4±0.0 kddrev 98.4±0.1 84.0±2.2 89.1±1.7 98.6±0.0 99.9±0.5 98.4±0.4 98.8±0.1 98.2±0.4 kddrev 98.4±0.1 84.0±2.5 60.0±8.2 60.0±13.3 73.3±22.6 43.3±8.2 60.0±8.2 80.0±12.5 83.3±10.5 mammogra. 5.5±2.8 2.6±1.7 3.3±1.6 13.5±3.8 8.8±1.9 11.4±1.9 34.0±2.0 242.8±17.6 mist tabular 78.6±0.5 80.3±1.1 71.8±1.8 76.3±2.1 72.1±1.0 80.7±0.7 86.0±0.4 79.2±0.9 mulcross 45.5±9.6 58.2±3.5 58.2±6.2 50.1±8.9 70.4±13.4 94.4±6.3 100.0±0.0 99.9±0.1 policitis 0.2±0.3 1.5±0.3 98.8±0.4 100.0±0.0 100.0±0.0 62.2±3.0 100.0±0.0		Blind	Refine	LOE_H (ours)			Refine	LOE_H (ours)	LOE_S (ours)
arrhythmia 57.6±2.5 59.1±2.1 62.1±2.8 62.7±3.3 53.9±0.7 60.9±2.2 62.4±1.8 63.6±2.1 breastw 84.0±1.8 93.1±0.9 95.6±0.4 95.3±0.4 92.6±1.1 93.4±1.0 96.0±0.6 95.7±0.6 cardio 21.8±4.9 45.2±7.9 73.0±7.9 57.8±5.5 50.2±4.5 56.2±3.4 71.1±3.2 62.2±2.7 ecoli 0.0±0.0 88.9±14.1 100.0±0.0 100.0±0.0 17.8±15.1 46.7±25.7 75.6±4.4 75.6±4.4 forest cover 20.4±4.0 56.2±4.9 61.1±34.9 67.6±30.6 9.2±4.5 8.0±3.6 6.8±3.6 11.1±2.1 glass 11.1±7.0 15.6±5.4 17.8±5.4 20.0±8.3 8.9±4.4 11.1±0.0 11.1±2.1 8.9±8.3 ionosphere 89.0±1.5 91.0±2.0 91.0±1.7 91.3±2.2 86.5±1.1 85.9±2.3 85.7±2.8 88.6±0.6 kddrev 98.4±0.1 98.4±0.1 98.4±0.1 99.3±0.1 99.3±0.1 99.4±0.1 99.5±0.0 99.4±0.0 k		37.9±13.4	55.2 ± 15.9	42.8 ± 26.9	59.3 ± 12.0	50.9 ± 1.5	54.3 ± 2.9	53.4 ± 5.2	51.7 ± 2.4
breastw 84.0±1.8 93.1±0.9 95.6±0.4 95.3±0.4 92.6±1.1 93.4±1.0 96.0±0.6 95.7±0.6 cardio 21.8±4.9 45.2±7.9 73.0±7.9 57.8±5.5 50.2±4.5 56.2±3.4 71.1±3.2 62.2±2.7 forest cover 20.4±4.0 56.2±4.9 61.1±34.9 67.6±30.6 9.2±4.5 8.0±3.6 6.8±3.6 11.1±7.0 glass 11.1±7.0 15.6±5.4 17.8±5.4 20.0±8.3 8.9±4.4 11.1±0.0 11.1±7.0 8.9±8.3 ionosphere 89.0±1.5 91.0±2.0 91.0±1.7 91.3±2.2 86.5±1.1 85.9±2.3 85.7±2.8 88.6±0.6 kddrev 98.4±0.1 98.4±0.2 89.1±1.7 98.6±0.0 97.9±0.5 98.4±0.4 98.8±0.1 99.2±0.0 lympho 53.3±12.5 60.0±8.2 60.0±13.3 73.3±22.6 43.0±2.5 51.2±3.7 54.4±5.6 47.2±4.9 lympho 53.3±12.5 60.0±8.2 60.0±13.3 73.3±22.6 43.3±8.2 60.0±8.2 80.0±12.5 83.3±10.5	annthyroid	29.7 ± 3.5	42.7 ± 7.1			29.1 ± 2.2	38.5 ± 2.1		43.0 ± 8.8
cardio 21.8±4.9 45.2±7.9 73.0±7.9 57.8±5.5 50.2±4.5 56.2±3.4 71.1±3.2 62.2±2.7 ecoli 0.0±0.0 88.9±14.1 100.0±0.0 100.0±0.0 17.8±15.1 46.7±25.7 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.4 75.6±4.1 75.6±4.4 75.6±4.8 11.1±2.1 86.9±4.0 11.1±2.1 89.8±8.3 10.0±4.0 86.6±0.4 80.8±6.0 91.3±2.2 86.5±1.1 85.9±2.3 85.7±2.8 88.6±0.0 80.1±1.7 98.6±0.0 97.9±0.5 98.4±0.4 98.8±0.1 98.2±0.0 99.	arrhythmia	57.6±2.5	59.1 ± 2.1	62.1 ± 2.8	62.7 ± 3.3	53.9 ± 0.7	60.9 ± 2.2	62.4 ± 1.8	63.6 ± 2.1
ecoli 0.0±0.0 88.9±14.1 100.0±0.0 100.0±0.0 17.8±15.1 46.7±25.7 75.6±4.4 75.6±4.4 forest cover 20.4±4.0 56.2±4.9 61.1±34.9 67.6±30.6 9.2±4.5 8.0±3.6 6.8±3.6 11.1±2.1 glass 11.1±7.0 15.6±5.4 17.8±5.4 20.0±8.3 8.9±4.4 11.1±0.0 11.1±7.0 8.9±8.3 ionosphere 89.0±1.5 91.0±2.0 91.0±1.7 91.3±2.2 86.5±1.1 85.9±2.3 85.7±2.8 88.6±0.6 kdd 95.9±0.0 96.0±1.1 98.1±0.4 98.4±0.1 99.3±0.1 99.4±0.1 99.5±0.0 99.4±0.0 kddrev 98.4±0.1 98.4±0.2 89.1±1.7 98.6±0.0 97.9±0.5 98.4±0.1 98.8±0.1 98.2±0.4 letter 36.4±3.6 44.4±3.1 25.4±10.0 45.6±10.6 43.0±2.5 51.2±3.7 54.4±5.6 47.2±4.9 lympho 53.3±12.5 60.0±8.2 60.0±13.3 73.3±2.6 43.3±8.2 60.0±8.2 80.0±12.5 83.3±10.5 mis	breastw	84.0 ± 1.8	93.1 ± 0.9	95.6 ± 0.4	95.3 ± 0.4	92.6 ± 1.1	93.4 ± 1.0	96.0 ± 0.6	95.7 ± 0.6
forest cover glass 20.4±4.0 56.2±4.9 61.1±34.9 67.6±30.6 9.2±4.5 8.0±3.6 6.8±3.6 11.1±2.1 glass 11.1±7.0 15.6±5.4 17.8±5.4 20.0±8.3 8.9±4.4 11.1±0.0 11.1±7.0 8.9±8.3 ionosphere 89.0±1.5 91.0±2.0 91.0±1.7 91.3±2.2 86.5±1.1 85.9±2.3 85.7±2.8 88.6±0.6 kddrev 98.4±0.1 98.4±0.1 98.4±0.1 99.3±0.1 99.4±0.1 99.5±0.0 99.4±0.0 kddrev 98.4±0.1 98.4±0.2 89.1±1.7 98.6±0.0 97.9±0.5 98.4±0.4 98.8±0.1 98.2±0.4 letter 36.4±3.6 44.4±3.1 25.4±10.0 45.6±10.6 43.0±2.5 51.2±3.7 54.4±5.6 47.2±4.9 lympho 53.3±12.5 60.0±8.2 60.0±3.3 73.3±22.6 43.3±8.2 60.0±8.2 80.0±12.5 83.3±10.5 mist tabular 78.6±0.5 80.3±1.1 71.8±1.8 76.3±2.1 72.1±1.0 80.7±0.7 86.0±0.4 79.2±0.9 musk	cardio	21.8±4.9	45.2 ± 7.9	73.0 ± 7.9	57.8 ± 5.5	50.2 ± 4.5	56.2 ± 3.4	71.1 ± 3.2	62.2 ± 2.7
glass ionosphere 89.0±1.5 91.0±2.0 91.0±1.7 91.3±2.2 86.5±1.1 85.9±2.3 85.7±2.8 88.6±0.6 kdd 95.9±0.0 96.0±1.1 98.1±0.4 98.4±0.1 99.3±0.1 99.4±0.1 99.5±0.0 99.4±0.0 kddrev 98.4±0.1 98.4±0.2 89.1±1.7 98.6±0.0 97.9±0.5 98.4±0.4 98.8±0.1 99.2±0.4 letter 36.4±3.6 44.4±3.1 25.4±10.0 45.6±10.6 43.0±2.5 51.2±3.7 54.4±5.6 47.2±4.9 lympho 53.3±12.5 60.0±8.2 60.0±13.3 73.3±22.6 43.3±8.2 60.0±8.2 80.0±12.5 83.3±10.5 mammogra. 5.5±2.8 2.6±1.7 3.3±1.6 13.5±3.8 8.8±1.9 11.4±1.9 34.0±20.2 42.8±17.6 mist tabular 78.6±0.5 80.3±1.1 71.8±1.8 76.3±2.1 72.1±1.0 80.7±0.7 86.0±0.4 79.2±0.9 mulcross 45.5±9.6 58.2±3.5 58.2±6.2 50.1±8.9 70.4±13.4 94.4±6.3 100.0±0.0 99.9±0.1 mulcross 10.2±0.3 98.8±0.4 100.0±0.0 100.0±0.0 6.2±3.0 100.0±0.0 100.0±0.0 100.0±0.0 optdigits 0.2±0.3 1.5±0.3 41.7±45.9 59.1±48.2 0.8±0.5 1.3±1.1 1.2±1.0 0.9±0.5 pendigits 5.0±2.5 32.6±10.0 79.4±4.7 81.9±4.3 10.3±4.6 30.1±8.5 80.3±6.1 88.6±2.2 pima 60.3±2.6 61.0±1.9 61.3±2.4 61.0±0.9 58.1±2.9 59.3±1.4 63.0±1.0 60.1±1.4 satellite 73.6±0.4 74.1±0.3 74.8±0.4 74.7±0.1 72.7±1.3 72.7±0.6 73.6±0.2 73.2±0.6 satimage 26.8±1.5 86.8±4.0 90.7±1.1 91.0±0.7 7.3±0.6 85.1±1.4 91.3±1.1 91.5±0.9 seismic 11.9±1.8 11.5±1.0 18.1±0.7 17.1±0.6 14.9±1.4 17.3±2.1 23.6±2.8 24.2±1.4 shuttle 97.0±0.3 97.0±0.2 97.1±0.2 97.0±0.2 96.6±0.2 96.7±0.1 96.9±0.1 97.0±0.2 speech 6.9±1.2 8.2±2.1 43.3±5.6 50.8±2.5 0.3±0.7 1.6±1.0 2.0±0.7 0.7±0.8 thyroid 43.4±5.5 55.1±4.2 82.4±2.7 82.4±2.3 45.8±7.3 71.6±2.4 83.2±2.9 74.4±8.0 wbc 25.7±12.3 45.7±15.5 76.2±6.0 69.5±3.8 50.5±5.7 50.5±2.3 61.0±4.7 61.0±1.9	ecoli	0.0 ± 0.0	88.9 ± 14.1	100.0 ± 0.0	100.0 ± 0.0	17.8 ± 15.1	46.7 ± 25.7	75.6 ± 4.4	75.6 ± 4.4
ionosphere kdd 89.0±1.5 91.0±2.0 91.0±1.7 91.3±2.2 86.5±1.1 85.9±2.3 85.7±2.8 88.6±0.6 kdd 95.9±0.0 96.0±1.1 98.1±0.4 98.4±0.1 99.3±0.1 99.4±0.1 99.5±0.0 99.4±0.0 kddrev 98.4±0.1 98.4±0.2 89.1±1.7 98.6±0.0 97.9±0.5 98.4±0.4 98.8±0.1 98.2±0.4 letter 36.4±3.6 44.4±3.1 25.4±10.0 45.6±10.6 43.0±2.5 51.2±3.7 54.4±5.6 47.2±4.9 lympho 53.3±12.5 60.0±8.2 60.0±13.3 73.3±22.6 43.3±8.2 60.0±8.2 80.0±12.5 83.3±10.5 mammogra. 75.5±2.8 2.6±1.7 3.3±1.6 13.5±3.8 8.8±1.9 11.4±1.9 34.0±20.2 42.8±17.6 mustross 45.5±9.6 58.2±3.5 58.2±6.2 50.1±8.9 70.4±13.4 94.4±6.3 100.0±0.0 99.9±0.1 mustross 45.5±9.6 58.2±3.5 58.2±6.2 50.1±8.9 70.4±13.4 94.4±6.3 100.0±0.0 99.9±0.1	forest cover	20.4 ± 4.0	56.2 ± 4.9	61.1 ± 34.9	67.6 ± 30.6	9.2 ± 4.5	8.0 ± 3.6	6.8 ± 3.6	11.1 ± 2.1
kdd 95.9±0.0 96.0±1.1 98.1±0.4 98.4±0.1 99.3±0.1 99.4±0.1 99.5±0.0 99.4±0.0 kddrev 98.4±0.1 98.4±0.2 89.1±1.7 98.6±0.0 97.9±0.5 98.4±0.4 98.8±0.1 98.2±0.4 letter 36.4±3.6 44.4±3.1 25.4±10.0 45.6±10.6 43.0±2.5 51.2±3.7 54.4±5.6 47.2±4.9 lympho 53.3±12.5 60.0±8.2 60.0±13.3 73.3±22.6 43.3±8.2 60.0±8.2 80.0±12.5 83.3±10.5 mammogra. 5.5±2.8 2.6±1.7 3.3±1.6 13.5±3.8 8.8±1.9 11.4±1.9 34.0±20.2 42.8±17.6 mist tabular 78.6±0.5 80.3±1.1 71.8±1.8 76.3±2.1 72.1±1.0 80.7±0.7 86.0±0.4 79.2±0.9 musk 21.0±3.3 98.8±0.4 100.0±0.0 100.0±0.0 6.2±3.0 100.0±0.0 100.0±0.0 99.9±0.1 musk 21.0±3.3 98.8±0.4 100.0±0.0 100.0±0.0 6.2±3.0 100.0±0.0 100.0±0.0 99.9±0.1 mu	glass	11.1±7.0	15.6 ± 5.4	17.8 ± 5.4		8.9 ± 4.4	11.1 ± 0.0	11.1 ± 7.0	8.9 ± 8.3
kddrev 98.4±0.1 98.4±0.2 89.1±1.7 98.6±0.0 97.9±0.5 98.4±0.4 98.8±0.1 98.2±0.4 letter 36.4±3.6 44.4±3.1 25.4±10.0 45.6±10.6 43.0±2.5 51.2±3.7 54.4±5.6 47.2±4.9 lympho 53.3±12.5 60.0±8.2 60.0±13.3 73.3±22.6 43.3±8.2 60.0±8.2 80.0±12.5 83.3±10.5 mammogra. 5.5±2.8 2.6±1.7 3.3±1.6 13.5±3.8 8.8±1.9 11.4±1.9 34.0±20.2 42.8±17.6 mist tabular 78.6±0.5 80.3±1.1 71.8±1.8 76.3±2.1 72.1±1.0 80.7±0.7 86.0±0.4 79.2±0.9 mukross 45.5±9.6 58.2±3.5 58.2±6.2 50.1±8.9 70.4±13.4 94.4±6.3 100.0±0.0 99.9±0.1 mukross 21.0±3.3 98.8±0.4 100.0±0.0 100.0±0.0 6.2±3.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0 100.0±0.0	ionosphere	89.0 ± 1.5	91.0 ± 2.0	91.0 ± 1.7	91.3 ± 2.2		85.9 ± 2.3	85.7 ± 2.8	88.6 ± 0.6
letter 36.4±3.6 44.4±3.1 25.4±10.0 45.6±10.6 43.0±2.5 51.2±3.7 54.4±5.6 47.2±4.9 19mpho 53.3±12.5 60.0±8.2 60.0±13.3 73.3±22.6 43.3±8.2 60.0±8.2 80.0±12.5 83.3±10.5 60.0±8.2 80.0±12.5 83.3±10.5 60.0±8.2 60.0±0.9 60.0±0.0 60.0±0	kdd	95.9 ± 0.0	96.0 ± 1.1	98.1 ± 0.4	98.4 ± 0.1	99.3 ± 0.1	99.4 ± 0.1	99.5 ± 0.0	99.4 ± 0.0
$\begin{array}{llllllllllllllllllllllllllllllllllll$	kddrev	98.4 ± 0.1		89.1 ± 1.7	98.6 ± 0.0	97.9 ± 0.5	98.4 ± 0.4	98.8 ± 0.1	98.2 ± 0.4
mammogra. 5.5±2.8 2.6±1.7 3.3±1.6 13.5±3.8 8.8±1.9 11.4±1.9 34.0±20.2 42.8±17.6 mnist tabular 78.6±0.5 80.3±1.1 71.8±1.8 76.3±2.1 72.1±1.0 80.7±0.7 86.0±0.4 79.2±0.9 mulcross 45.5±9.6 58.2±3.5 58.2±6.2 50.1±8.9 70.4±13.4 94.4±6.3 100.0±0.0 99.9±0.1 musk 21.0±3.3 98.8±0.4 100.0±0.0 100.0±0.0 6.2±3.0 100.0±0.0 <t< td=""><td>letter</td><td>36.4 ± 3.6</td><td>44.4 ± 3.1</td><td>25.4 ± 10.0</td><td>45.6 ± 10.6</td><td></td><td>51.2 ± 3.7</td><td>54.4 ± 5.6</td><td>47.2 ± 4.9</td></t<>	letter	36.4 ± 3.6	44.4 ± 3.1	25.4 ± 10.0	45.6 ± 10.6		51.2 ± 3.7	54.4 ± 5.6	47.2 ± 4.9
mnist tabular mulcross 45.5±9.6 58.2±3.5 58.2±6.2 50.1±8.9 70.4±13.4 94.4±6.3 100.0±0.0 99.9±0.1 musk 21.0±3.3 98.8±0.4 100.0±0.0 100.0±0.0 6.2±3.0 100.0±0.0 100.0±0.0 100.0±0.0 optdigits 0.2±0.3 1.5±0.3 41.7±45.9 59.1±48.2 0.8±0.5 1.3±1.1 1.2±1.0 0.9±0.5 pendigits 5.0±2.5 32.6±10.0 79.4±4.7 81.9±4.3 10.3±4.6 30.1±8.5 80.3±6.1 88.6±2.2 pima 60.3±2.6 61.0±1.9 61.3±2.4 61.0±0.9 58.1±2.9 59.3±1.4 63.0±1.0 60.1±1.4 satellite 73.6±0.4 74.1±0.3 74.8±0.4 74.7±0.1 72.7±1.3 72.7±0.6 73.6±0.2 73.2±0.6 satimage 26.8±1.5 86.8±4.0 90.7±1.1 91.0±0.7 7.3±0.6 85.1±1.4 91.3±1.1 91.5±0.9 seismic 11.9±1.8 11.5±1.0 18.1±0.7 17.1±0.6 14.9±1.4 17.3±2.1 23.6±2.8 24.2±1.4 shuttle 97.0±0.3 97.0±0.2 97.1±0.2 97.0±0.2 96.6±0.2 96.7±0.1 96.9±0.1 97.0±0.2 speech 6.9±1.2 8.2±2.1 43.3±5.6 50.8±2.5 0.3±0.7 1.6±1.0 2.0±0.7 0.7±0.8 thyroid 43.4±5.5 55.1±4.2 82.4±2.7 82.4±2.3 45.8±7.3 71.6±2.4 83.2±2.9 80.9±2.5 vertebral 22.0±4.5 21.3±4.5 22.7±11.0 25.3±4.0 8.9±3.1 8.9±4.2 7.8±4.2 10.0±2.7 vowels 36.0±1.8 50.4±8.8 62.8±9.5 48.4±6.6 42.1±9.0 60.4±7.9 81.6±2.9 74.4±8.0 wbc 25.7±12.3 45.7±15.5 76.2±6.0 69.5±3.8 50.5±5.7 50.5±2.3 61.0±4.7 61.0±1.9	lympho	53.3±12.5	60.0 ± 8.2	60.0 ± 13.3	73.3 ± 22.6	43.3 ± 8.2	60.0 ± 8.2	80.0 ± 12.5	83.3 ± 10.5
mulcross 45.5 ± 9.6 58.2 ± 3.5 58.2 ± 6.2 50.1 ± 8.9 70.4 ± 13.4 94.4 ± 6.3 100.0 ± 0.0 99.9 ± 0.1 musk 21.0 ± 3.3 98.8 ± 0.4 100.0 ± 0.0 100.0 ± 0.0 6.2 ± 3.0 100.0 ± 0.0	mammogra.	5.5 ± 2.8	2.6 ± 1.7	3.3 ± 1.6	13.5 ± 3.8	8.8 ± 1.9	11.4 ± 1.9	34.0 ± 20.2	42.8 ± 17.6
musk 21.0 ± 3.3 98.8 ± 0.4 100.0 ± 0.0 100.0 ± 0.0 6.2 ± 3.0 100.0 ± 0.0	mnist tabular							86.0 ± 0.4	
optdigits 0.2 ± 0.3 1.5 ± 0.3 41.7 ± 45.9 59.1 ± 48.2 0.8 ± 0.5 1.3 ± 1.1 1.2 ± 1.0 0.9 ± 0.5 pendigits 5.0 ± 2.5 32.6 ± 10.0 79.4 ± 4.7 81.9 ± 4.3 10.3 ± 4.6 30.1 ± 8.5 80.3 ± 6.1 88.6 ± 2.2 pima 60.3 ± 2.6 61.0 ± 1.9 61.3 ± 2.4 61.0 ± 0.9 58.1 ± 2.9 59.3 ± 1.4 63.0 ± 1.0 60.1 ± 1.4 satellite 73.6 ± 0.4 74.1 ± 0.3 74.8 ± 0.4 74.7 ± 0.1 72.7 ± 1.3 72.7 ± 0.6 73.6 ± 0.2 73.2 ± 0.6 satimage 26.8 ± 1.5 86.8 ± 4.0 90.7 ± 1.1 91.0 ± 0.7 7.3 ± 0.6 85.1 ± 1.4 91.3 ± 1.1 91.5 ± 0.9 seismic 11.9 ± 1.8 11.5 ± 1.0 18.1 ± 0.7 17.1 ± 0.6 14.9 ± 1.4 17.3 ± 2.1 23.6 ± 2.8 24.2 ± 1.4 shuttle 97.0 ± 0.3 97.0 ± 0.2 97.1 ± 0.2 97.0 ± 0.2 96.0 ± 0.2 96.7 ± 0.1 96.9 ± 0.1 97.0 ± 0.2 speech 6.9 ± 1.2 8.2 ± 2.1 43.3 ± 5.6 50.8 ± 2.5 0.3 ± 0.7 <td>mulcross</td> <td>45.5±9.6</td> <td>58.2 ± 3.5</td> <td>58.2 ± 6.2</td> <td>50.1 ± 8.9</td> <td>70.4 ± 13.4</td> <td>94.4 ± 6.3</td> <td>100.0 ± 0.0</td> <td>99.9 ± 0.1</td>	mulcross	45.5±9.6	58.2 ± 3.5	58.2 ± 6.2	50.1 ± 8.9	70.4 ± 13.4	94.4 ± 6.3	100.0 ± 0.0	99.9 ± 0.1
pendigits 5.0 ± 2.5 32.6 ± 10.0 79.4 ± 4.7 81.9 ± 4.3 10.3 ± 4.6 30.1 ± 8.5 80.3 ± 6.1 88.6 ± 2.2 pima 60.3 ± 2.6 61.0 ± 1.9 61.3 ± 2.4 61.0 ± 0.9 58.1 ± 2.9 59.3 ± 1.4 63.0 ± 1.0 60.1 ± 1.4 satellite 73.6 ± 0.4 74.1 ± 0.3 74.8 ± 0.4 74.7 ± 0.1 72.7 ± 1.3 72.7 ± 0.6 73.6 ± 0.2 73.2 ± 0.6 satimage 26.8 ± 1.5 86.8 ± 4.0 90.7 ± 1.1 91.0 ± 0.7 7.3 ± 0.6 85.1 ± 1.4 91.3 ± 1.1 91.5 ± 0.9 seismic 11.9 ± 1.8 11.5 ± 1.0 18.1 ± 0.7 17.1 ± 0.6 14.9 ± 1.4 17.3 ± 2.1 23.6 ± 2.8 24.2 ± 1.4 shuttle 97.0 ± 0.3 97.0 ± 0.2 97.0 ± 0.2 97.0 ± 0.2 96.0 ± 0.1 96.9 ± 0.1 97.0 ± 0.2 speech 6.9 ± 1.2 8.2 ± 2.1 43.3 ± 5.6 50.8 ± 2.5 0.3 ± 0.7 1.6 ± 1.0 2.0 ± 0.7 0.7 ± 0.8 thyroid 43.4 ± 5.5 55.1 ± 4.2 82.4 ± 2.7 82.4 ± 2.3 45.8 ± 7.3 71.6 ± 2.4 83.2 ± 2.9 80.9 ± 2.5 vertebral 22.0 ± 4.5 21.3 ± 4.5 22.7 ± 11.0 25.3 ± 4.0 8.9 ± 3.1 8.9 ± 4.2 7.8 ± 4.2 10.0 ± 2.7 vowels 36.0 ± 1.8 50.4 ± 8.8 62.8 ± 9.5 48.4 ± 6.6 42.1 ± 9.0 60.4 ± 7.9 81.6 ± 2.9 74.4 ± 8.0 wbc 25.7 ± 12.3 45.7 ± 15.5 76.2 ± 6.0 69.5 ± 3.8 50.5 ± 5.7 50.5 ± 2.3 61.0 ± 4.7 61.0 ± 1.9	musk	21.0 ± 3.3	98.8 ± 0.4	100.0 ± 0.0	100.0 ± 0.0	6.2 ± 3.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	optdigits	0.2 ± 0.3	1.5 ± 0.3	41.7 ± 45.9	59.1 ± 48.2	0.8 ± 0.5	1.3 ± 1.1	1.2 ± 1.0	0.9 ± 0.5
satellite 73.6 ± 0.4 74.1 ± 0.3 74.8 ± 0.4 74.7 ± 0.1 72.7 ± 1.3 72.7 ± 0.6 73.6 ± 0.2 73.2 ± 0.6 satimage 26.8 ± 1.5 86.8 ± 4.0 90.7 ± 1.1 91.0 ± 0.7 7.3 ± 0.6 85.1 ± 1.4 91.3 ± 1.1 91.5 ± 0.9 seismic 11.9 ± 1.8 11.5 ± 1.0 18.1 ± 0.7 17.1 ± 0.6 14.9 ± 1.4 17.3 ± 2.1 23.6 ± 2.8 24.2 ± 1.4 shuttle 97.0 ± 0.3 97.0 ± 0.2 97.0 ± 0.2 96.6 ± 0.2 96.7 ± 0.1 96.9 ± 0.1 97.0 ± 0.2 speech 6.9 ± 1.2 8.2 ± 2.1 43.3 ± 5.6 50.8 ± 2.5 0.3 ± 0.7 1.6 ± 1.0 2.0 ± 0.7 0.7 ± 0.8 thyroid 43.4 ± 5.5 55.1 ± 4.2 82.4 ± 2.7 82.4 ± 2.3 45.8 ± 7.3 71.6 ± 2.4 83.2 ± 2.9 80.9 ± 2.5 vertebral 22.0 ± 4.5 21.3 ± 4.5 22.7 ± 11.0 25.3 ± 4.0 8.9 ± 3.1 8.9 ± 4.2 7.8 ± 4.2 10.0 ± 2.7 vowels 36.0 ± 1.8 50.4 ± 8.8 62.8 ± 9.5 48.4 ± 6.6 42.1 ± 9.0 60.4 ± 7.9 81.6 ± 2.9 74.4 ± 8.0 wbc 25.7 ± 12.3 45.7 ± 15.5 76.2 ± 6.0 69.5 ± 3.8 50.5 ± 5.7 50.5 ± 2.3 61.0 ± 4.7 61.0 ± 1.9	pendigits	5.0 ± 2.5	32.6 ± 10.0	79.4 ± 4.7	81.9 ± 4.3	10.3 ± 4.6	30.1 ± 8.5	80.3 ± 6.1	88.6 ± 2.2
satimage 26.8 ± 1.5 86.8 ± 4.0 90.7 ± 1.1 91.0 ± 0.7 7.3 ± 0.6 85.1 ± 1.4 91.3 ± 1.1 91.5 ± 0.9 seismic 11.9 ± 1.8 11.5 ± 1.0 18.1 ± 0.7 17.1 ± 0.6 14.9 ± 1.4 17.3 ± 2.1 23.6 ± 2.8 24.2 ± 1.4 shuttle 97.0 ± 0.3 97.0 ± 0.2 97.0 ± 0.2 96.6 ± 0.2 96.7 ± 0.1 96.9 ± 0.1 97.0 ± 0.2 speech 6.9 ± 1.2 8.2 ± 2.1 43.3 ± 5.6 50.8 ± 2.5 0.3 ± 0.7 1.6 ± 1.0 2.0 ± 0.7 0.7 ± 0.8 thyroid 43.4 ± 5.5 55.1 ± 4.2 82.4 ± 2.7 82.4 ± 2.3 45.8 ± 7.3 71.6 ± 2.4 83.2 ± 2.9 80.9 ± 2.5 vertebral 22.0 ± 4.5 21.3 ± 4.5 22.7 ± 11.0 25.3 ± 4.0 8.9 ± 3.1 8.9 ± 4.2 7.8 ± 4.2 10.0 ± 2.7 vowels 36.0 ± 1.8 50.4 ± 8.8 62.8 ± 9.5 48.4 ± 6.6 42.1 ± 9.0 60.4 ± 7.9 81.6 ± 2.9 74.4 ± 8.0 wbc 25.7 ± 12.3 45.7 ± 15.5 76.2 ± 6.0 69.5 ± 3.8 50.5 ± 2.3 61.0 ± 4.7	pima							63.0 ± 1.0	
seismic 11.9 ± 1.8 11.5 ± 1.0 18.1 ± 0.7 17.1 ± 0.6 14.9 ± 1.4 17.3 ± 2.1 23.6 ± 2.8 24.2 ± 1.4 shuttle 97.0 ± 0.3 97.0 ± 0.2 97.0 ± 0.2 96.6 ± 0.2 96.7 ± 0.1 96.9 ± 0.1 97.0 ± 0.2 speech 6.9 ± 1.2 8.2 ± 2.1 43.3 ± 5.6 50.8 ± 2.5 0.3 ± 0.7 1.6 ± 1.0 2.0 ± 0.7 0.7 ± 0.8 thyroid 43.4 ± 5.5 55.1 ± 4.2 82.4 ± 2.7 82.4 ± 2.3 45.8 ± 7.3 71.6 ± 2.4 83.2 ± 2.9 80.9 ± 2.5 vertebral 22.0 ± 4.5 21.3 ± 4.5 22.7 ± 11.0 25.3 ± 4.0 8.9 ± 3.1 8.9 ± 4.2 7.8 ± 4.2 10.0 ± 2.7 vowels 36.0 ± 1.8 50.4 ± 8.8 62.8 ± 9.5 48.4 ± 6.6 42.1 ± 9.0 60.4 ± 7.9 81.6 ± 2.9 74.4 ± 8.0 wbc 25.7 ± 12.3 45.7 ± 15.5 76.2 ± 6.0 69.5 ± 3.8 50.5 ± 2.3 61.0 ± 4.7 61.0 ± 1.9	satellite				74.7 ± 0.1		72.7 ± 0.6		
shuttle 97.0 ± 0.3 97.0 ± 0.2 97.1 ± 0.2 97.0 ± 0.2 96.0 ± 0.2 96.7 ± 0.1 96.9 ± 0.1 97.0 ± 0.2 speech 6.9 ± 1.2 8.2 ± 2.1 43.3 ± 5.6 50.8 ± 2.5 0.3 ± 0.7 1.6 ± 1.0 2.0 ± 0.7 0.7 ± 0.8 thyroid 43.4 ± 5.5 55.1 ± 4.2 82.4 ± 2.7 82.4 ± 2.3 45.8 ± 7.3 71.6 ± 2.4 83.2 ± 2.9 80.9 ± 2.5 vertebral 22.0 ± 4.5 21.3 ± 4.5 22.7 ± 11.0 25.3 ± 4.0 8.9 ± 3.1 8.9 ± 4.2 7.8 ± 4.2 10.0 ± 2.7 vowels 36.0 ± 1.8 50.4 ± 8.8 62.8 ± 9.5 48.4 ± 6.6 42.1 ± 9.0 60.4 ± 7.9 81.6 ± 2.9 74.4 ± 8.0 wbc 25.7 ± 12.3 45.7 ± 15.5 76.2 ± 6.0 69.5 ± 3.8 50.5 ± 5.7 50.5 ± 2.3 61.0 ± 4.7 61.0 ± 1.9	satimage	26.8 ± 1.5	86.8 ± 4.0		91.0 ± 0.7	7.3 ± 0.6	85.1 ± 1.4	91.3 ± 1.1	91.5 ± 0.9
speech thyroid 6.9 ± 1.2 8.2 ± 2.1 43.3 ± 5.6 50.8 ± 2.5 0.3 ± 0.7 1.6 ± 1.0 2.0 ± 0.7 0.7 ± 0.8 thyroid 43.4 ± 5.5 55.1 ± 4.2 82.4 ± 2.7 82.4 ± 2.3 45.8 ± 7.3 71.6 ± 2.4 83.2 ± 2.9 80.9 ± 2.5 vertebral 22.0 ± 4.5 21.3 ± 4.5 22.7 ± 11.0 25.3 ± 4.0 8.9 ± 3.1 8.9 ± 4.2 7.8 ± 4.2 10.0 ± 2.7 vowels 36.0 ± 1.8 50.4 ± 8.8 62.8 ± 9.5 48.4 ± 6.6 42.1 ± 9.0 60.4 ± 7.9 81.6 ± 2.9 74.4 ± 8.0 wbc 25.7 ± 12.3 45.7 ± 15.5 76.2 ± 6.0 69.5 ± 3.8 50.5 ± 5.7 50.5 ± 2.3 61.0 ± 4.7 61.0 ± 1.9	seismic	11.9 ± 1.8	11.5 ± 1.0	18.1 ± 0.7			17.3 ± 2.1	23.6 ± 2.8	24.2 ± 1.4
thyroid 43.4 ± 5.5 55.1 ± 4.2 82.4 ± 2.7 82.4 ± 2.3 45.8 ± 7.3 71.6 ± 2.4 83.2 ± 2.9 80.9 ± 2.5 vertebral 22.0 ± 4.5 21.3 ± 4.5 22.7 ± 11.0 25.3 ± 4.0 8.9 ± 3.1 8.9 ± 4.2 7.8 ± 4.2 10.0 ± 2.7 vowels 36.0 ± 1.8 50.4 ± 8.8 62.8 ± 9.5 48.4 ± 6.6 42.1 ± 9.0 60.4 ± 7.9 81.6 ± 2.9 74.4 ± 8.0 wbc 25.7 ± 12.3 45.7 ± 15.5 76.2 ± 6.0 69.5 ± 3.8 50.5 ± 5.7 50.5 ± 2.3 61.0 ± 4.7 61.0 ± 1.9	shuttle	97.0 ± 0.3	97.0 ± 0.2	97.1 ± 0.2		96.6 ± 0.2	96.7 ± 0.1	96.9 ± 0.1	97.0 ± 0.2
vertebral vowels wbc 22.0 ± 4.5 21.3 ± 4.5 22.7 ± 11.0 25.3 ± 4.0 8.9 ± 3.1 8.9 ± 4.2 7.8 ± 4.2 10.0 ± 2.7 48.0 ± 3.1 <	speech		8.2 ± 2.1	43.3 ± 5.6	50.8 ± 2.5	0.3 ± 0.7	1.6 ± 1.0	2.0 ± 0.7	0.7 ± 0.8
vowels 36.0 ± 1.8 50.4 ± 8.8 62.8 ± 9.5 48.4 ± 6.6 42.1 ± 9.0 60.4 ± 7.9 81.6 ± 2.9 74.4 ± 8.0 wbc 25.7 ± 12.3 45.7 ± 15.5 76.2 ± 6.0 69.5 ± 3.8 50.5 ± 5.7 50.5 ± 2.3 61.0 ± 4.7 61.0 ± 1.9	thyroid	43.4±5.5		82.4 ± 2.7		45.8 ± 7.3	71.6 ± 2.4	83.2 ± 2.9	80.9 ± 2.5
wbc 25.7 ± 12.3 45.7 ± 15.5 76.2 ± 6.0 69.5 ± 3.8 50.5 ± 5.7 50.5 ± 2.3 61.0 ± 4.7 61.0 ± 1.9	vertebral	22.0 ± 4.5	21.3 ± 4.5	22.7 ± 11.0	25.3 ± 4.0	8.9 ± 3.1	8.9 ± 4.2	7.8 ± 4.2	10.0 ± 2.7
	vowels	36.0 ± 1.8	50.4 ± 8.8	62.8 ± 9.5	48.4 ± 6.6	42.1 ± 9.0	60.4 ± 7.9	81.6 ± 2.9	74.4 ± 8.0
wine $\begin{vmatrix} 24.0 + 18.5 & 66.0 + 12.0 & 90.0 + 0.0 & 92.0 + 4.0 & 4.0 + 4.9 & 10.0 + 8.9 & 98.0 + 4.0 & 100.0 + 0.0 \end{vmatrix}$	wbc	25.7 ± 12.3	45.7 ± 15.5	76.2 ± 6.0	69.5 ± 3.8	50.5±5.7	50.5 ± 2.3	61.0 ± 4.7	61.0 ± 1.9
	wine	24.0±18.5	66.0 ± 12.0	90.0 ± 0.0	92.0 ± 4.0	4.0 ± 4.9	10.0 ± 8.9	98.0 ± 4.0	100.0 ± 0.0

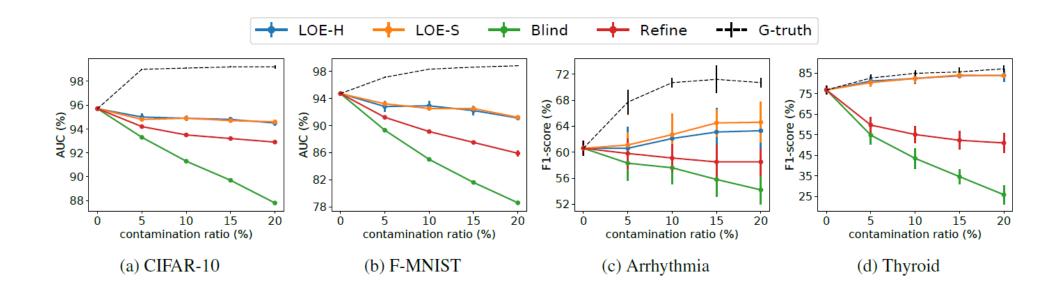






Experiment results on various contamination ratios

▶ LOE shows considerable robustness to different contamination ratios.



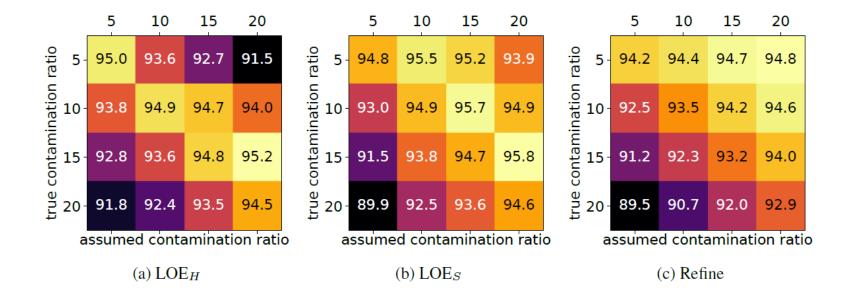






Sensitivity study on the misspecified contamination ratio

► LOE shows considerable robustness against misspecified contamination ratios.







THANK YOU

Paper Link



Code Link



Correspondence: Chen.Qiu@de.bosch.com







