Histogram-based Outlier Score (HBOS): A fast Unsupervised Anomaly Detection

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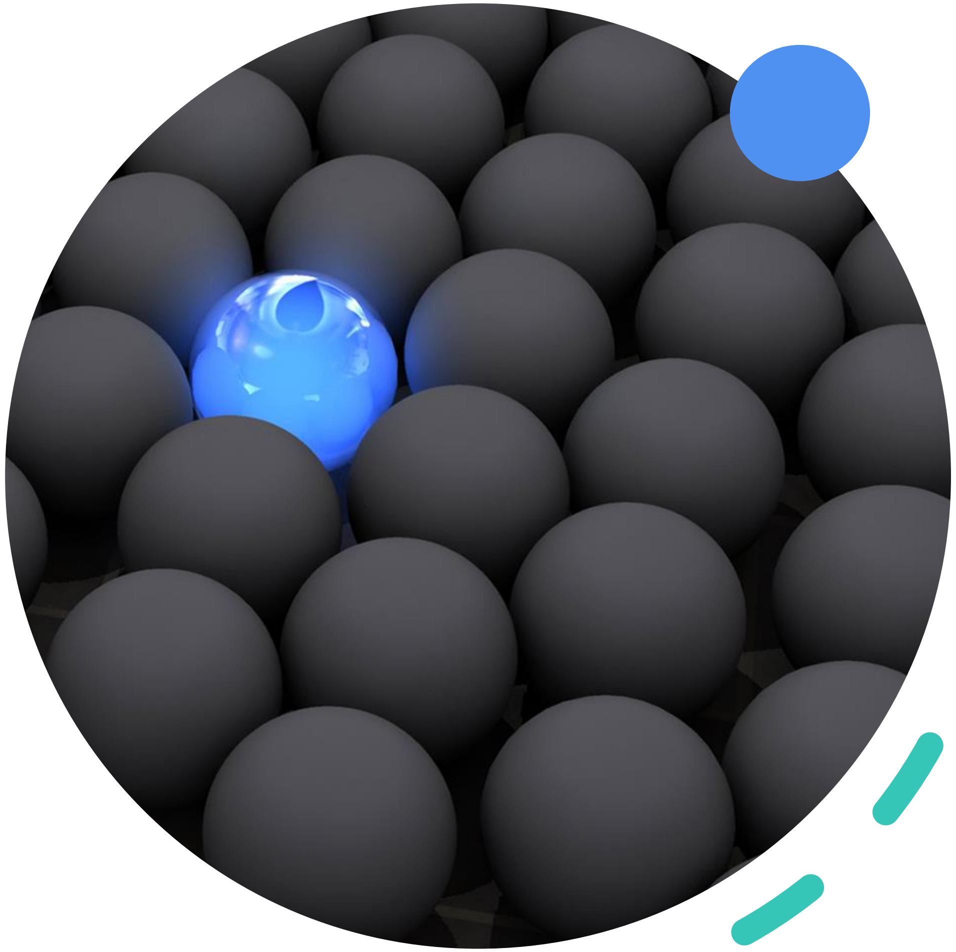
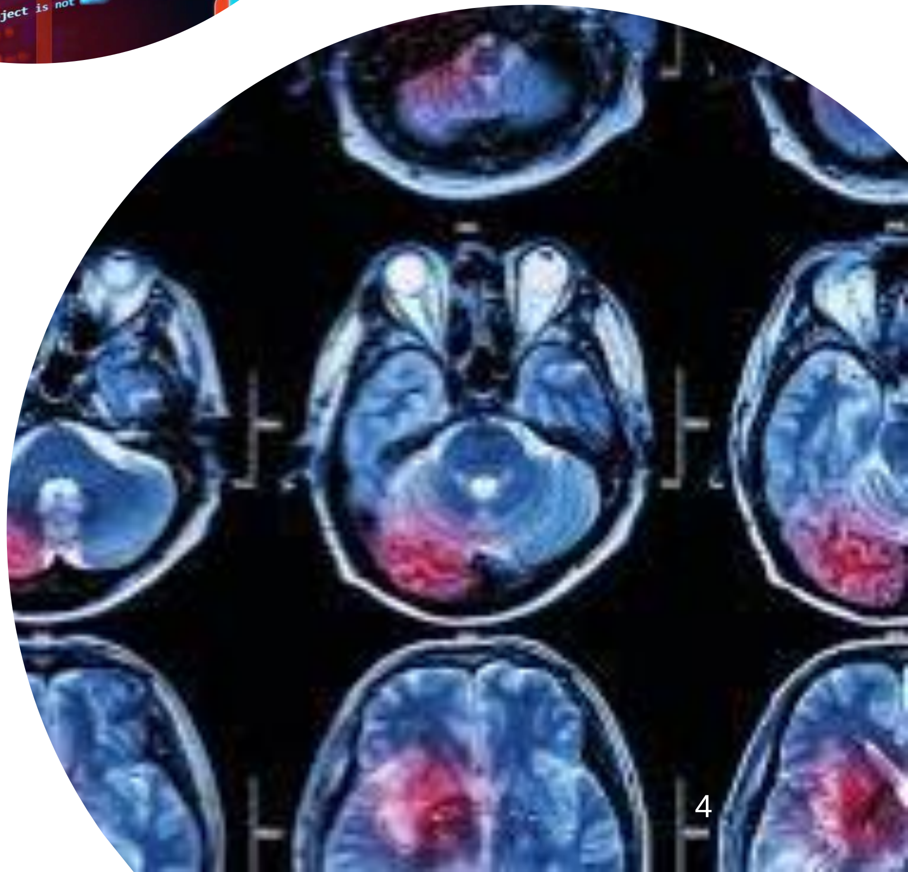
Introduction

Anomaly detection is the process of identifying data points that deviate from the expected patterns or behaviors of a given system or dataset. Anomalies are often referred to as outliers, novelties, or anomalies, and they can be caused by a variety of factors such as errors, fraud, unusual events, or changes in underlying trends.



Motivations

- The motivation behind anomaly detection is to detect unusual or suspicious events or behaviors that may indicate a potential problem or threat. It is an important task in many domains:
- finance - detect fraudulent transactions or identify abnormal trading behavior.
- Healthcare - identify rare diseases or unusual patient symptoms.
- Cybersecurity - detect network intrusions or identify unusual patterns of activity.
- industrial automation - can help identify equipment malfunctions or anomalies in manufacturing processes.



The Problem

Finding an effective solution for identifying anomalies in various datasets keepint

- Hige Precision in Anomaly detection
- Supporting unsupervised data
- Fast run time and low complexity

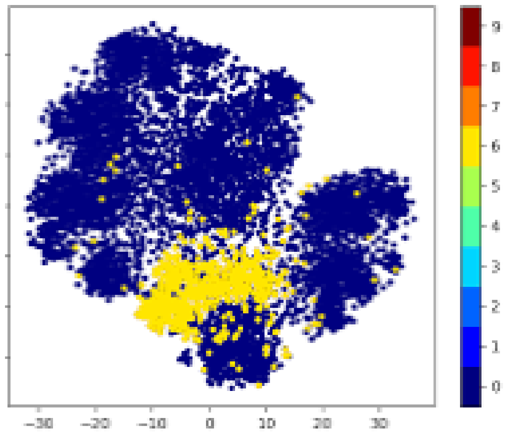
Histogram-based Outlier Score (HBOS)

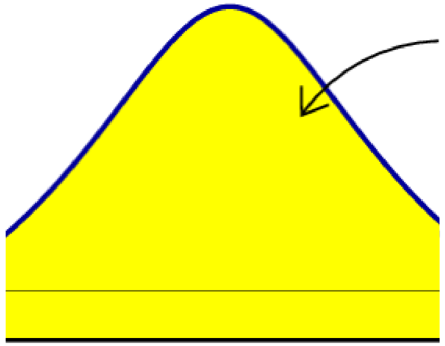
Markus Goldstein and Andreas Dengel

HBOS

- There are 3 main approaches to deal with anomaly detection problem:
  - distance-based algorithms like: KNN and Local Outlier Factor (LOF).
  - Clustering based algorithms like CBLOF and LDCOF are using k-means as a clustering algorithm.
  - Statistical methods: parametric and non-parametric models like GMM and kernel-density estimators (KDE).

While first 2 has high complexity and sensitivity to outliers, HBOS uses statistical methods





HBOS Calculation

- Bins with density estimation per feature
- Each histogram is normalized, max height=1
- Calculating HBOS using height of each Histogram

$$HBOS(p) = \sum_{i=0}^{d} \log\left(\frac{1}{hist_i(p)}\right)$$

- Linear computation time

HBOS Performance

HBOS outperforms or get close to best in half of the above datasets compared to all other algorithms

Alg.	b-cancer	pen-global	pen-local	letter	speech	satellite	thyroid	shuttle	aloi	kdd99
k-NN	<0.1	<0.1	2.4	0.3	5.7	2.0	2.6	106	166	538
k^{th}-NN	<0.1	<0.1	2.4	0.3	5.8	2.0	2.6	105	165	538
LOF	<0.1	<0.1	2.4	0.3	5.8	2.0	2.7	105	165	538
LOF-UB	<0.1	<0.1	2.6	0.3	5.9	2.1	2.8	107	167	539
COF	<0.1	0.1	2.8	0.5	9.0	2.5	3.1	107	169	539
INFLO	<0.1	<0.1	2.4	0.3	5.8	2.0	2.6	105	165	538
LoOP	<0.1	<0.1	2.5	0.3	5.8	2.0	2.6	105	165	538
LOCI	18	240	—	2572	25740	—	—	—	—	—
aLOCI	0.5	1.8	90	12.7	9.5	56	30	73	1137	298
CBLOF/LDCOF 10	<0.1	0.1	1.5	0.6	24.8	4.0	1.0	6.9	39.1	5.01
CBLOF/LDCOF 50	0.1	0.2	3.7	5.9	24.7	5.2	4.4	10.3	74.6	16.14
CMGOS-Red 10	0.5	0.2	1.7	1.1	82	4.6	1.2	7.0	40	5.15
CMGOS-Red 50	0.1	0.5	4.3	1.7	49	8.2	4.6	10.6	77	16.25
CMGOS-Reg 10	0.4	0.2	1.7	1.1	83	4.6	1.3	7.0	40	5.19
CMGOS-Reg 50	0.1	0.5	4.3	1.7	49	8.1	5.4	10.6	77	16.29
CMGOS-MCD 10	159	211	863	759	—	3821	1967	354	3003	491
CMGOS-MCD 50	735	519	1045	1441	—	4041	4159	1525	10933	8745
HBOS	<0.1	<0.1	<0.1	<0.1	0.5	<0.1	<0.1	<0.1	0.4	0.06
rPCA	<0.1	<0.1	0.2	<0.1	9.2	0.1	<0.1	0.3	1.5	21.8
oc-SVM	0.3	0.5	31	8.5	807	28	26	19639	59531	5480
η-oc-SVM	0.3	0.4	70	8.2	745	24	27	19087	58559	3310

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Real Time

Alg.	b-cancer	pen-global	pen-local	letter	speech	satellite	thyroid	shuttle	aloi	kdd99
k-NN	0.9791 ±0.0010	**0.9872** ±0.0055	0.9837 ±0.0018	0.8719 ±0.0176	0.4966 ±0.0101	**0.9701** ±0.0007	0.5956 ±0.0125	0.9424 ±0.0069	0.6502 ±0.0191	0.9747 ±0.0045
k^{th}-NN	0.9807 ±0.0008	0.9778 ±0.0142	0.9757 ±0.0069	0.8268 ±0.0228	0.4784 ±0.0007	0.9681 ±0.0015	0.5748 ±0.0128	0.9434 ±0.0101	0.6177 ±0.0189	**0.9796** ±0.0035
LOF	**0.9816** ±0.0024	0.8495 ±0.0679	**0.9877** ±0.0016	0.8673 ±0.0271	0.5038 ±0.0215	0.8147 ±0.1126	0.6470 ±0.0192	0.5127 ±0.0129	0.7563 ±0.0135	0.5964 ±0.0284
LOF-UB	0.9805 ±0.0020	0.8541 ±0.0777	0.9876 ±0.0013	0.9019 ±0.0030	0.5233 ±0.0134	0.8425 ±0.0839	0.6663 ±0.0103	0.5182 ±0.0124	0.7713 ±0.0045	0.5774 ±0.0159
COF	0.9518 ±0.0054	0.8695 ±0.1261	0.9513 ±0.0134	0.8336 ±0.0228	0.5218 ±0.0287	0.7491 ±0.0952	0.6505 ±0.0154	0.5257 ±0.0086	0.7857 ±0.0118	0.5548 ±0.0236
INFLO	0.9642 ±0.0171	0.7887 ±0.0540	0.9817 ±0.0024	0.8632 ±0.0250	0.5017 ±0.0191	0.8272 ±0.0761	0.6542 ±0.0158	0.4930 ±0.0175	0.7684 ±0.0142	0.5524 ±0.0222
LoOP	0.9725 ±0.0123	0.7684 ±0.0994	0.9851 ±0.0068	**0.9068** ±0.0078	**0.5347** ±0.0343	0.7681 ±0.0433	**0.6893** ±0.0149	0.5049 ±0.0035	**0.7899** ±0.0093	0.5749 ±0.0275
LOCI	0.9787	0.8877	—	0.7880	0.4979	—	—	—	—	—
aLOCI	0.8105 ±0.0883	0.6889 ±0.0345	0.8011 ±0.0615	0.6208 ±0.0220	0.4992 ±0.0348	0.8324 ±0.0372	0.6174 ±0.0221	**0.9474** ±0.0379	0.5855 ±0.0143	0.6552 ±0.0458

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Alg.	b-cancer	pen-global	pen-local	letter	speech	satellite	thyroid	shuttle	aloi	kdd99
CBLOF	0.2983 ±0.1492	0.3190 ±0.1155	0.6995 ±0.1407	0.6792 ±0.0386	0.5021 ±0.0680	0.5539 ±0.0692	0.5825 ±0.0384	0.9037 ±0.1263	0.5393 ±0.0154	0.6589 ±0.2098
uCBLOF	**0.9496** ±0.0390	**0.8721** ±0.0511	0.9555 ±0.0109	0.8192 ±0.0231	0.4692 ±0.0029	**0.9627** ±0.0038	0.5469 ±0.0212	**0.9716** ±0.0324	0.5575 ±0.0061	**0.9964** ±0.0016
LDCOF	0.7645 ±0.1653	0.5948 ±0.0825	0.9593 ±0.0145	0.8107 ±0.0244	0.4366 ±0.0099	0.9522 ±0.0325	0.5703 ±0.0232	0.8076 ±0.1814	0.5726 ±0.0146	0.9873 ±0.0034
CMGOS-Red	0.9140 ±0.0815	0.5693 ±0.1000	**0.9727** ±0.0141	0.7711 ±0.0614	0.5077 ±0.0158	0.9054 ±0.0233	0.4395 ±0.0402	0.5425 ±0.2446	0.5852 ±0.0161	0.7265 ±0.1027
CMGOS-Reg	0.8992 ±0.0643	0.6994 ±0.0681	0.9449 ±0.0510	**0.8902** ±0.0200	**0.5081** ±0.0161	0.9056 ±0.0233	0.6587 ±0.0268	0.5679 ±0.2402	**0.5855** ±0.0161	0.9797 ±0.0080
CMGOS-MCD	0.9196 ±0.0830	0.6265 ±0.0969	0.9038 ±0.0511	0.7848 ±0.0485	—	0.9120 ±0.0520	**0.8014** ±0.0436	0.6903 ±0.1670	0.5547 ±0.0160	0.9696 ±0.0416
Best NN	**0.9816** ±0.0024	**0.9872** ±0.0055	**0.9877** ±0.0016	**0.9068** ±0.0078	**0.5347** ±0.0343	**0.9701** ±0.0007	0.6893 ±0.0149	0.9474 ±0.0379	**0.7899** ±0.0093	0.9796 ±0.0035

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Alg.	b-cancer	pen-global	pen-local	letter	speech	satellite	thyroid	shuttle	aloi	kdd99
HBOS	**0.9827** ±0.0016	0.7477 ±0.0206	0.6798 ±0.0249	0.6216 ±0.0073	0.4708 ±0.0030	0.9135 ±0.0047	**0.9150** ±0.0123	**0.9925** ±0.0039	0.4757 ±0.0010	**0.9990** ±0.0007
rPCA	0.9664 ±0.0000	0.9375 ±0.0001	0.7841 ±0.0151	0.8095 ±0.0029	0.5024 ±0.0000	0.9461 ±0.0023	0.6574 ±0.0036	0.9963 ±0.0000	0.5621 ±0.0000	0.7371 ±0.0000
oc-SVM	0.9721 ±0.0102	0.9512 ±0.0436	0.9543 ±0.0130	0.5195 ±0.0382	0.4650 ±0.0021	0.9549 ±0.0021	0.5316 ±0.0152	0.9862 ±0.0002	0.5319 ±0.0021	0.9518 ±0.0050
η-oc-SVM	0.9581 ±0.0311	0.8993 ±0.0387	0.9236 ±0.0140	0.7298 ±0.1365	0.4649 ±0.0026	0.9430 ±0.0058	0.5625 ±0.0088	0.9848 ±0.0019	0.5221 ±0.0025	0.7945 ±0.0000
Best NN	0.9816 ±0.0024	**0.9872** ±0.0055	**0.9877** ±0.0016	**0.9068** ±0.0078	**0.5347** ±0.0343	**0.9701** ±0.0007	0.6893 ±0.0149	0.9474 ±0.0379	**0.7899** ±0.0093	0.9796 ±0.0035
Best Cluster	0.9496 ±0.0390	0.8721 ±0.0511	0.9727 ±0.0141	0.8902 ±0.0200	0.5081 ±0.0161	0.9627 ±0.0038	0.7843 ±0.0437	0.9716 ±0.0324	0.5855 ±0.0161	0.9964 ±0.0016
Best Alg.	HBOS	*k*-NN	LOF	LoOP	LoOP	*k*-NN	HBOS	HBOS	COF	HBOS

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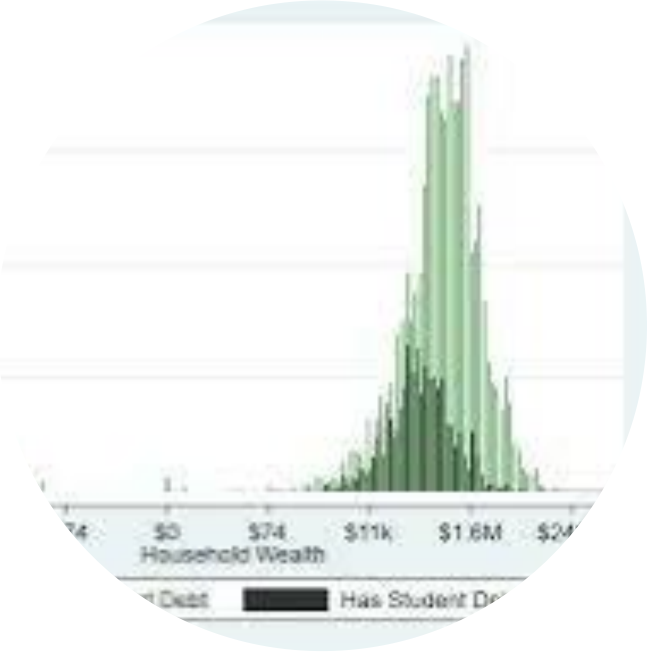
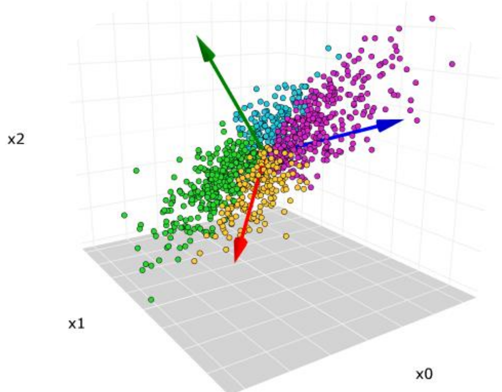
Performance

Suggested Modification

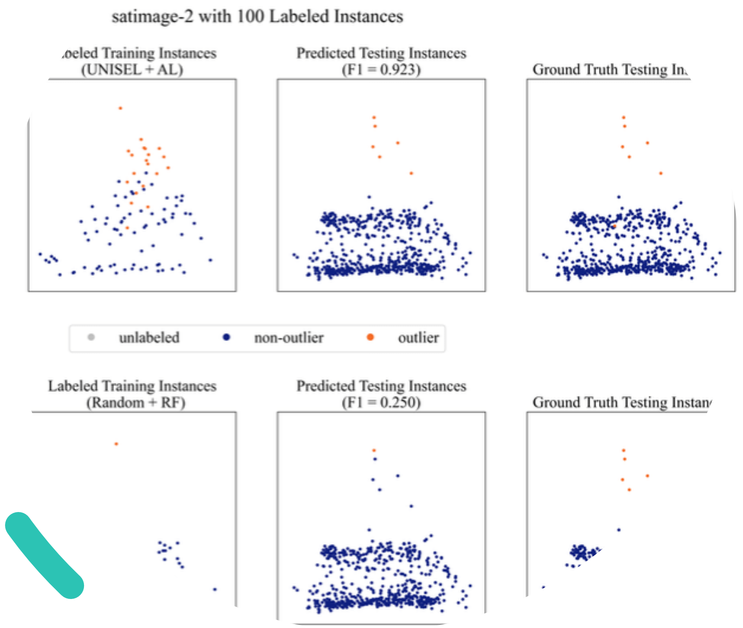
- In order to improve the performance of HBOS while maintaining low complexity, we've tested
  - Running PCA as correlation between features offset result
  - Test softmax on bins
  - Weighting the bins per variance of their features

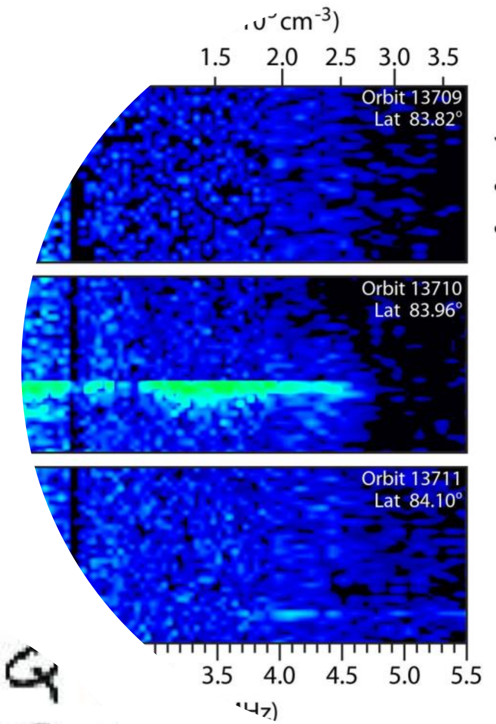




Datasets

- ionosphere - Classification of radar returns from the ionosphere
- letter - For recognizing handwritten forms
- mnist - a large dataset of handwritten digits
- satimage-2 - The original Statlog (Landsat Satellite) dataset





Results

Table 10 Modified HBOS with PCA (M-HBOS) RoC comparison

	Data	#Samples	# Dimensions	Outlier Perc	HBOS	PCA	M-HBOS
0	ionosphere	351	33	35.8974	0.5154	0.8068	0.9601
0	letter	1600	32	6.25	0.5783	0.511	0.804
0	mnist	7603	100	9.2069	0.5775	0.8565	0.7812
0	satimage-2	5803	36	1.2235	0.9864	0.9842	0.9783

Table 11 Modified HBOS with PCA (M-HBOS) Precision comparison

	Data	#Samples	# Dimensions	Outlier Perc	HBOS	PCA	M-HBOS
0	ionosphere	351	33	35.8974	0.3585	0.6226	0.8679
0	letter	1600	32	6.25	0.1	0.1	0.275
0	mnist	7603	100	9.2069	0.1259	0.3741	0.3777
0	satimage-2	5803	36	1.2235	0.7273	0.8485	0.8125

Table 12 Modified HBOS with PCA run time comparison

	Data	#Samples	# Dimensions	Outlier Perc	HBOS	PCA	M-HBOS
0	ionosphere	351	33	35.8974	0.8202	0.0871	0.6102
0	letter	1600	32	6.25	0.0116	0.0114	0.029
0	mnist	7603	100	9.2069	0.0595	0.1433	0.0581
0	satimage-2	5803	36	1.2235	0.02	0.0173	0.0159

Summary

We have presented a suggested improvement to the widely used HBOS algorithm, adding PCA prior the HBOS calculation.

We further implemented the above on 4 commonly used dataset namely ionosphere, letter, mnist and satimage-2 to show significant improvements while maintaining the low complexity.

Thank you

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