

# Detecting Subsequence Anomalies in Time Series



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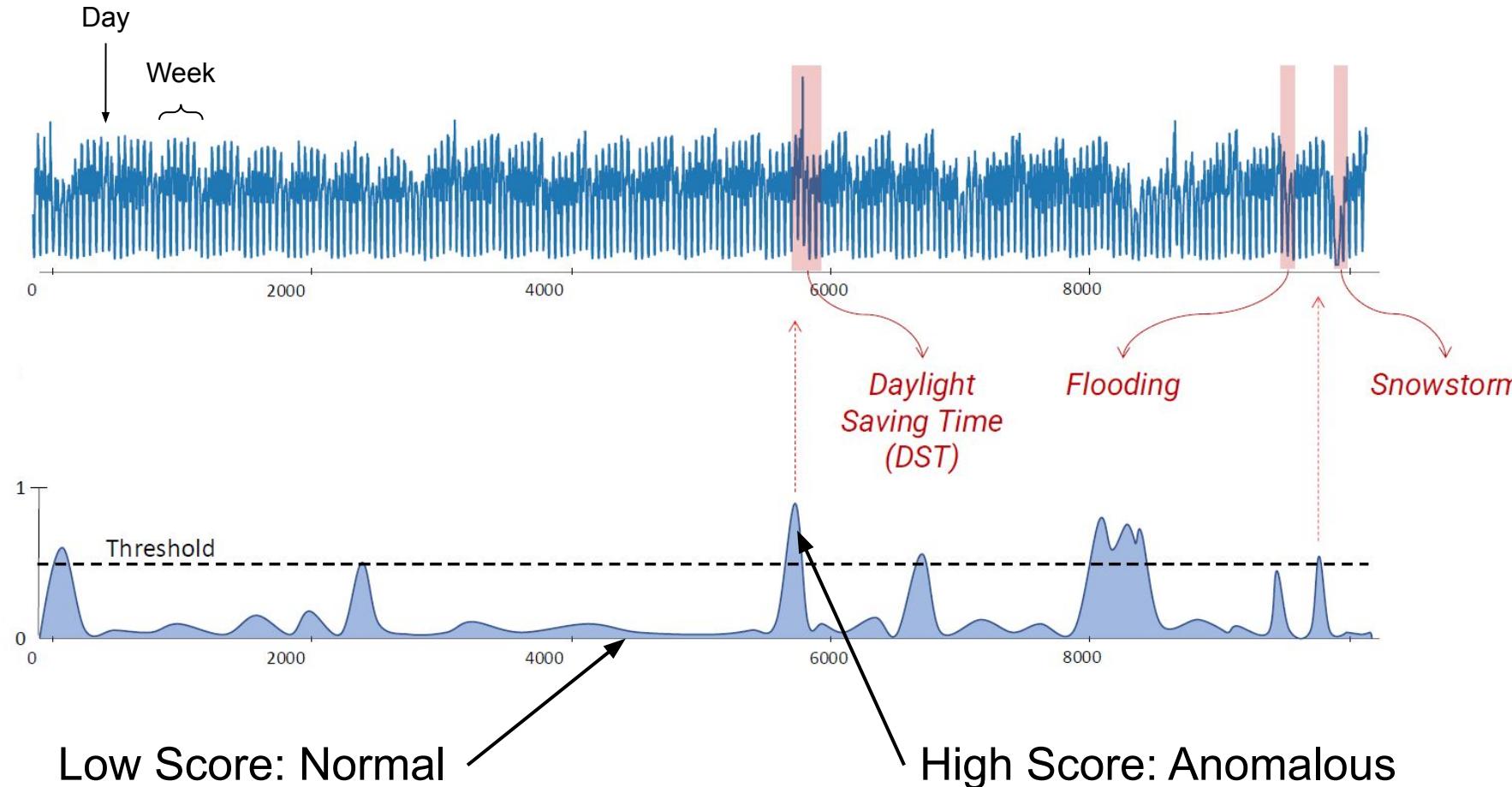
**Phillip Wenig**  
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Big Data Analytics  
Philipp-University of Marburg  
Germany

# Introduction



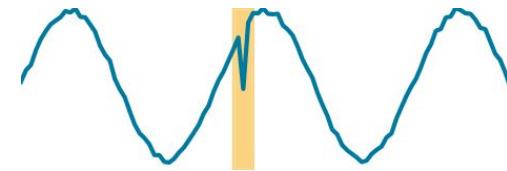
“  
An anomaly is a point or a sequence of points that deviate w.r.t. some measure or model from the regular patterns of the time series.  
”

**For this tutorial:**  
A potentially undesired rare point or rare sequence of points of a given length.

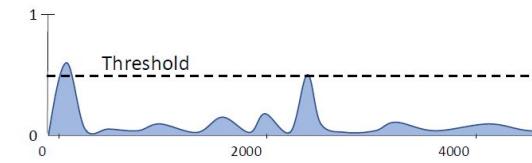
# Outline

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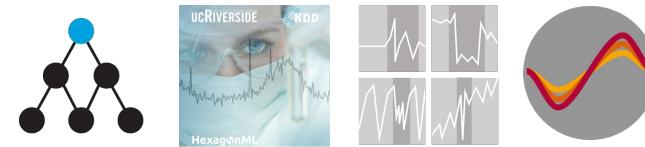
## 1. Time Series Anomalies



## 2. Anomaly Detection Methods



## 3. TSAD Benchmarks & Datasets

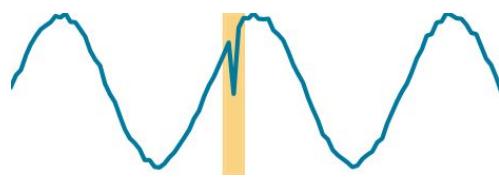


## 4. Outlook

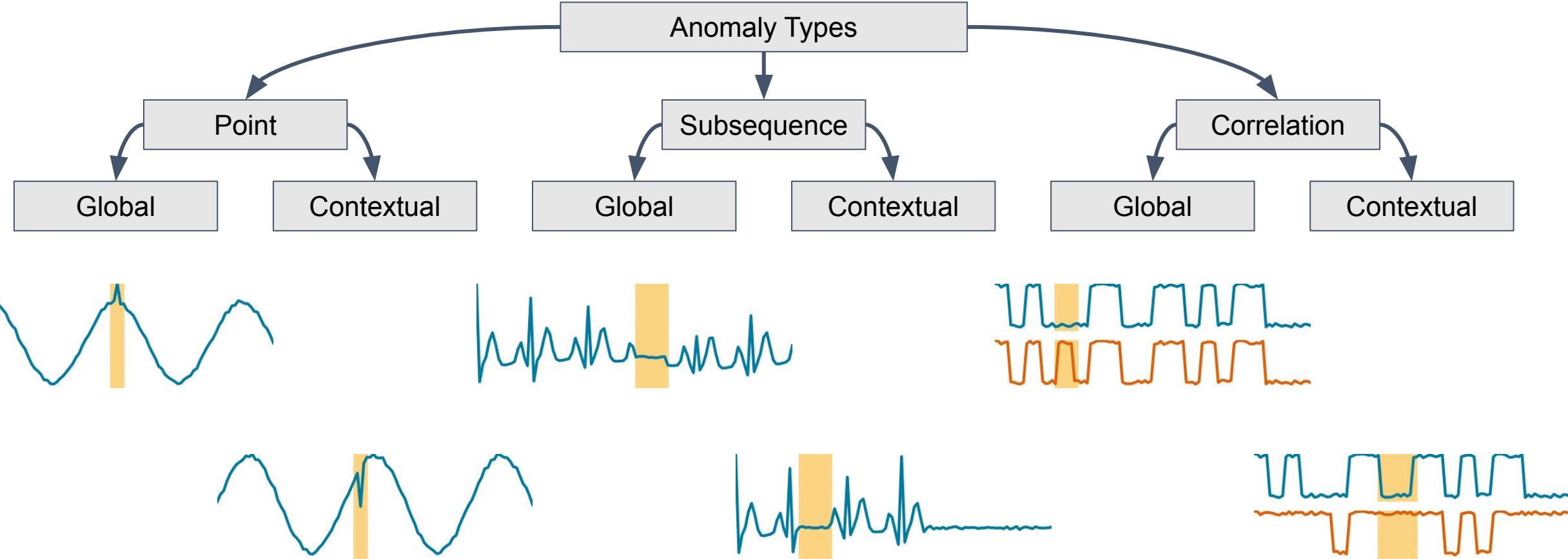




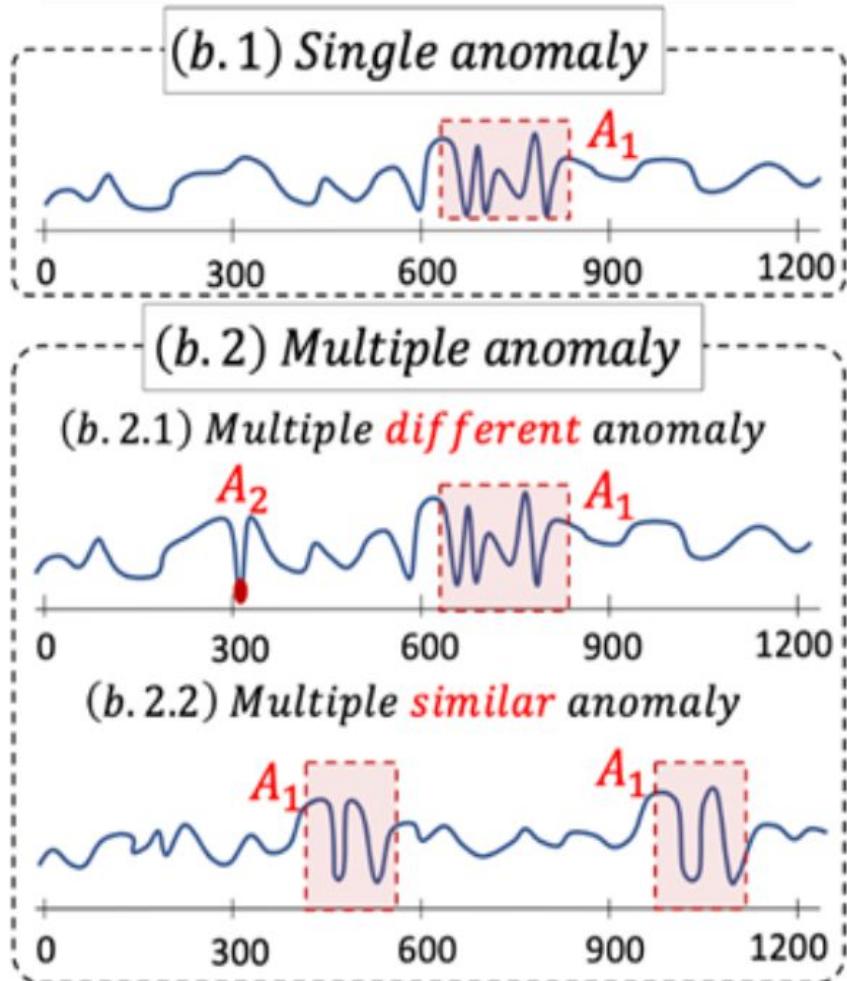
# Time Series Anomalies



# Anomaly Taxonomy



# Anomaly Taxonomy



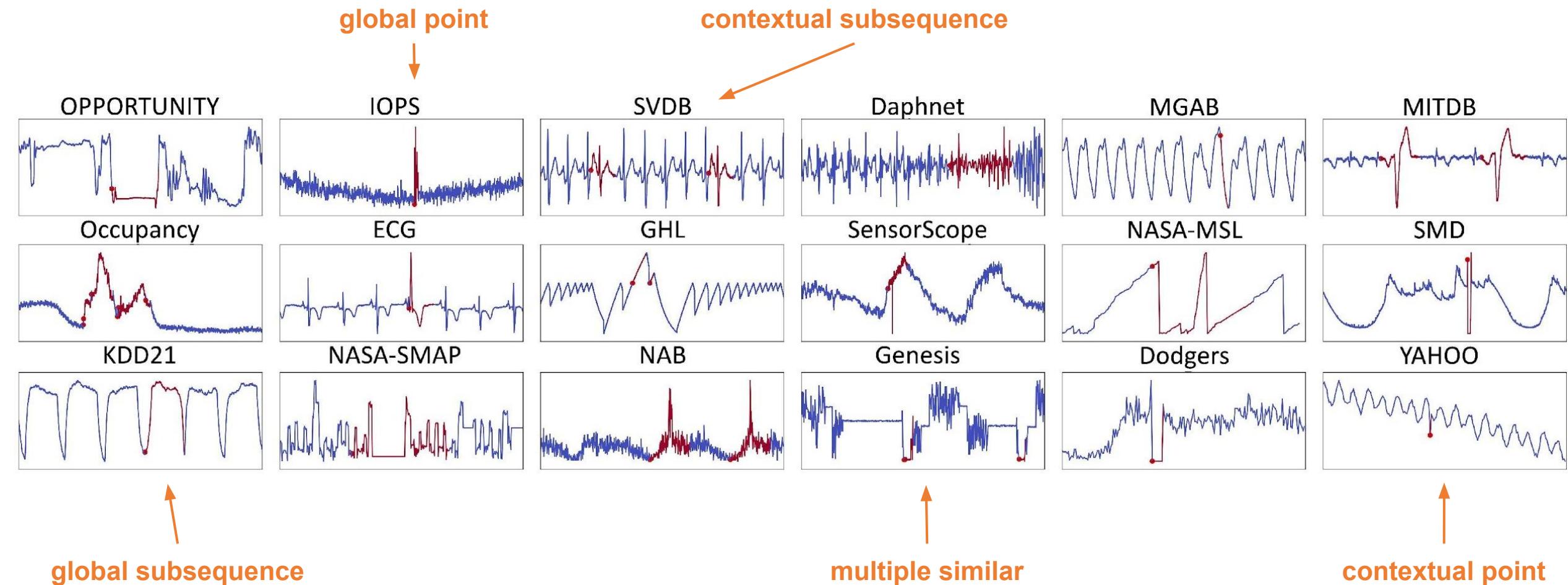
## Anomaly Arity

- for multivariate time series
- how many channels are affected

*n-ary anomaly:*

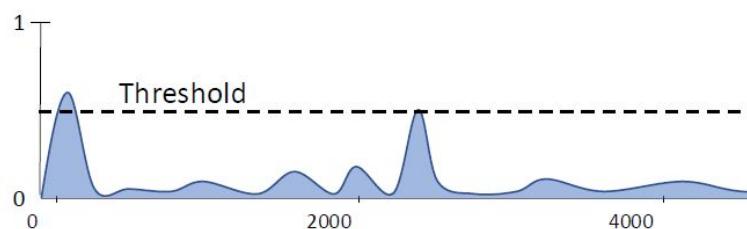
anomaly affects  $n$  channels/dimensions of the time series

# Real-world examples

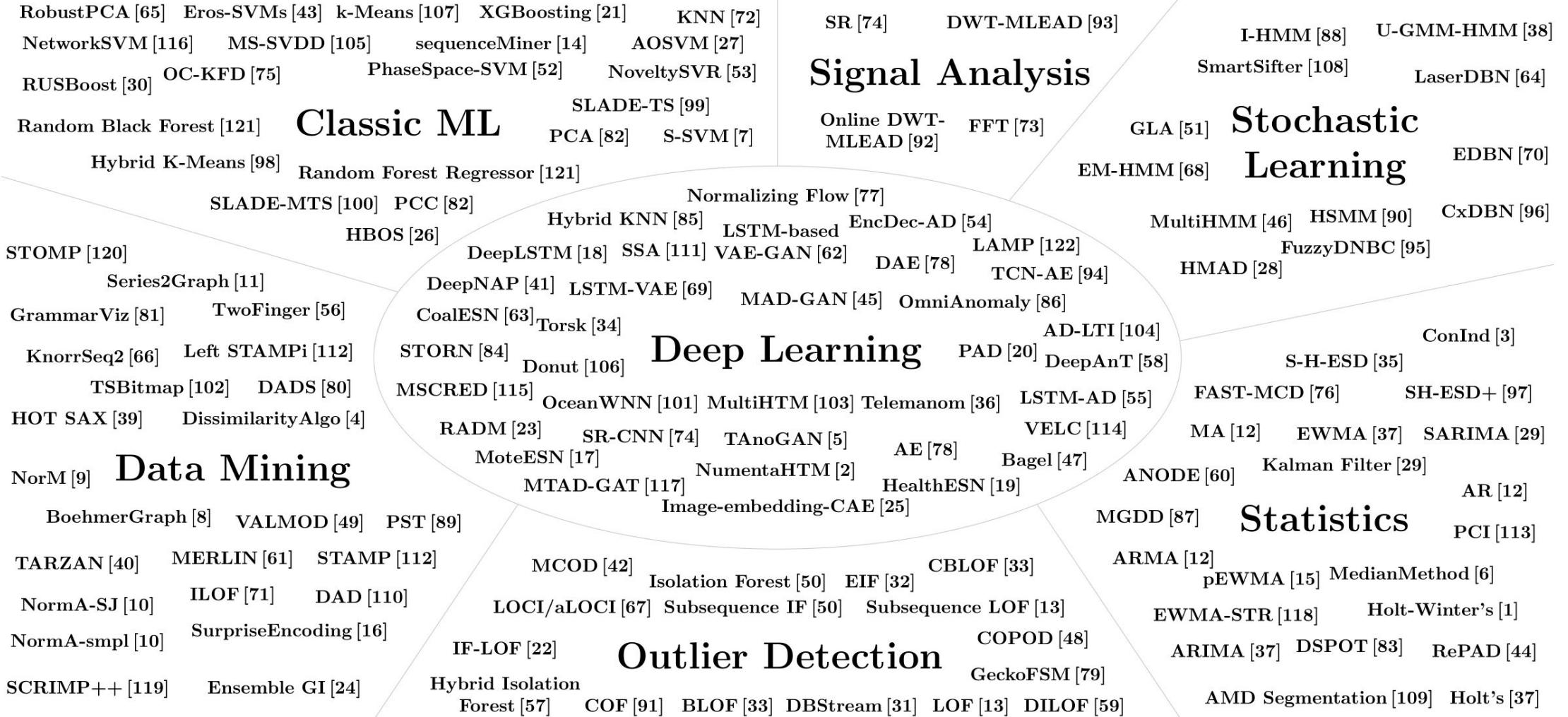




# Anomaly Detection Methods



# Anomaly Detection Methods – by Research Domains



# Anomaly Detection Methods – by Learning Type

**Unsupervised**  
(Type I [a])

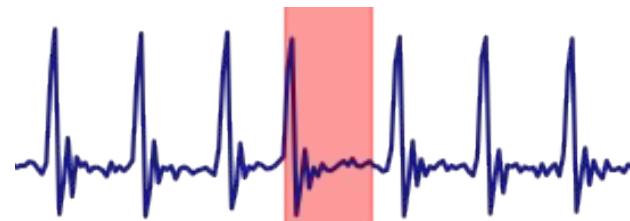
**Training**

$\emptyset$

**Testing**



**Supervised**  
(Type II [a])



**Semi-Supervised**  
(Type III [a])



# Anomaly Detection Methods – by Family

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★ **Forecasting**

■ **Reconstruction**

▼ **Encoding**

● **Distance**

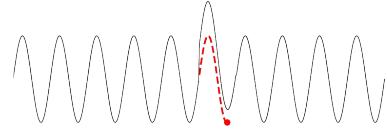
▲ **Distribution**

✚ **Isolation Tree**

# Anomaly Detection Methods – by Family



## Forecasting

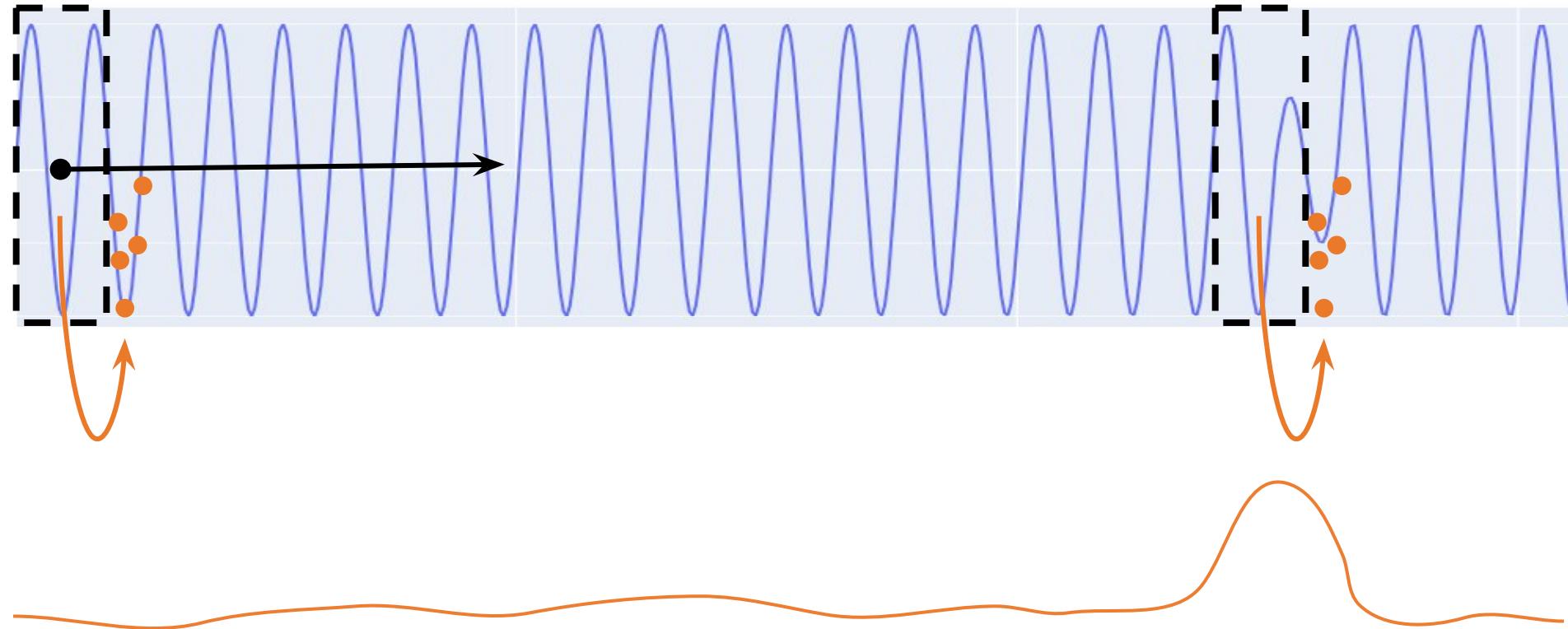


ARIMA, DeepAnT, DeepNAP, HealthESN, LSTM-AD, MedianMethod, MTAD-GAT, NumentaHTM, NoveltySVR, OceanWNN, RBForest, RForest, SARIMA, Telemanom, Torsk, Triple ES, XGBoosting

# ★ Forecasting Methods

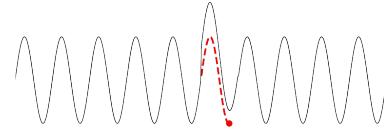
- Methods try to **forecast the next point or sequence of points** based on previous window
- Anomaly score = **prediction error**

window of length m



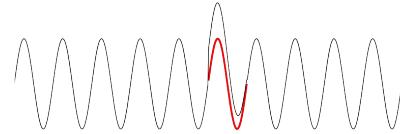
# Anomaly Detection Methods – by Family

## ★ Forecasting



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## ■ Reconstruction

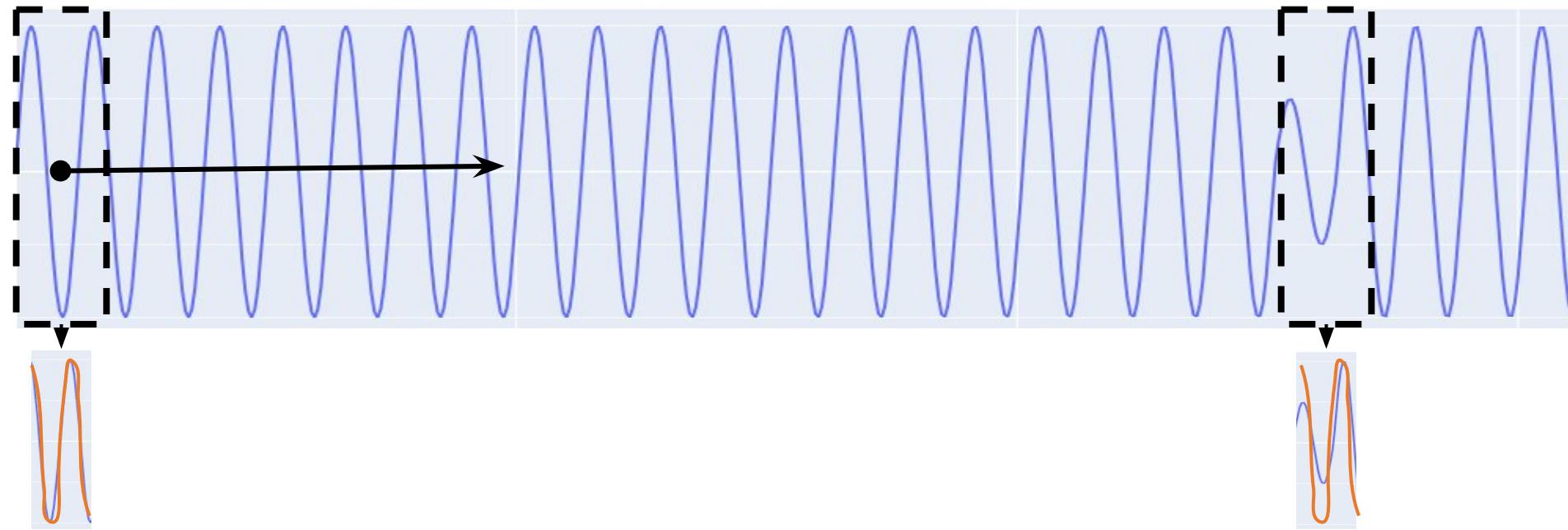


AE, Bagel, DAE, Donut, EncDec-AD, FFT, IE-CAE, LSTM-VAE, MSCRED, OmniAnomaly, PCI, PCC, RobustPCA, SR, SR-CNN, TAnoGan

# ■ Reconstruction Methods

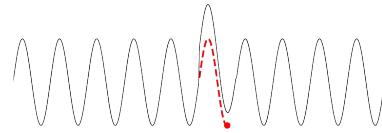
- Training: Methods build normal model by encoding normal subsequences in latent space
- Testing: Methods try to **reconstruct subsequences from latent space**
- Anomaly score = **reconstruction error**

window of length m



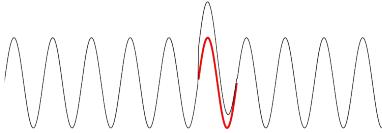
# Anomaly Detection Methods – by Family

## ★ Forecasting



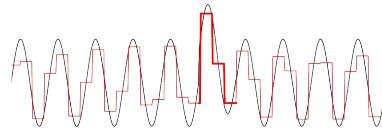
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## ■ Reconstruction



AE, Bagel, DAE, Donut, EncDec-AD, FFT, IE-CAE, LSTM-VAE, MSCRED, OmniAnomaly, PCI, PCC, RobustPCA, SR, SR-CNN, TAnoGan

## ▼ Encoding

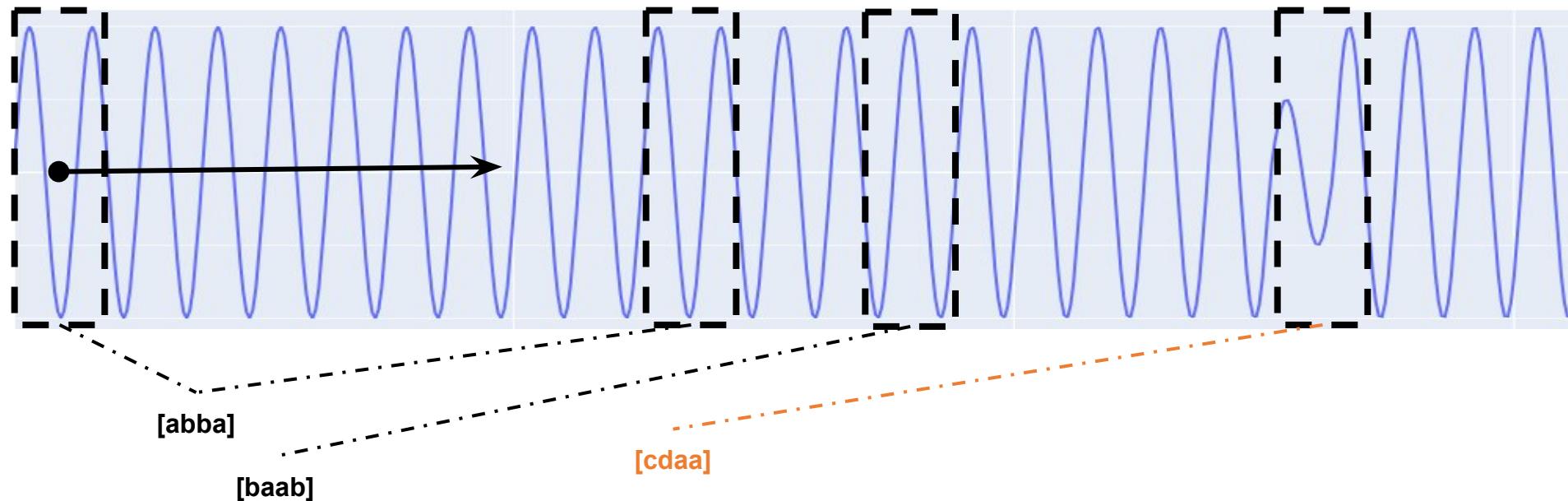


Ensemble GI, GrammarViz, LaserDBN, MultiHMM, PST, Series2Graph, TARZAN, TSBitmap

# ▼ Encoding Methods

- Methods **encode subsequences in latent space** and identify anomalies in this space
- Anomaly score = **depends on representation**

window of length m



GrammarViz: Coverage of grammar rules

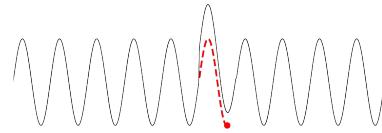
Series2Graph: Edge weight

TsBitmap: Bitmap similarity

...

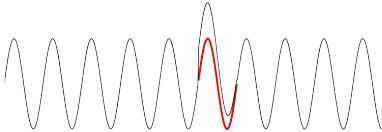
# Anomaly Detection Methods – by Family

## ★ Forecasting



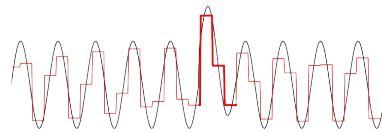
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## ■ Reconstruction



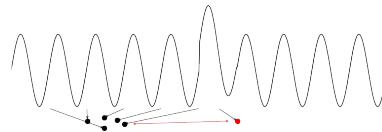
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## ▼ Encoding



Ensemble GI, GrammarViz, LaserDBN, MultiHMM, PST, Series2Graph, TARZAN, TSBitmap

## ● Distance

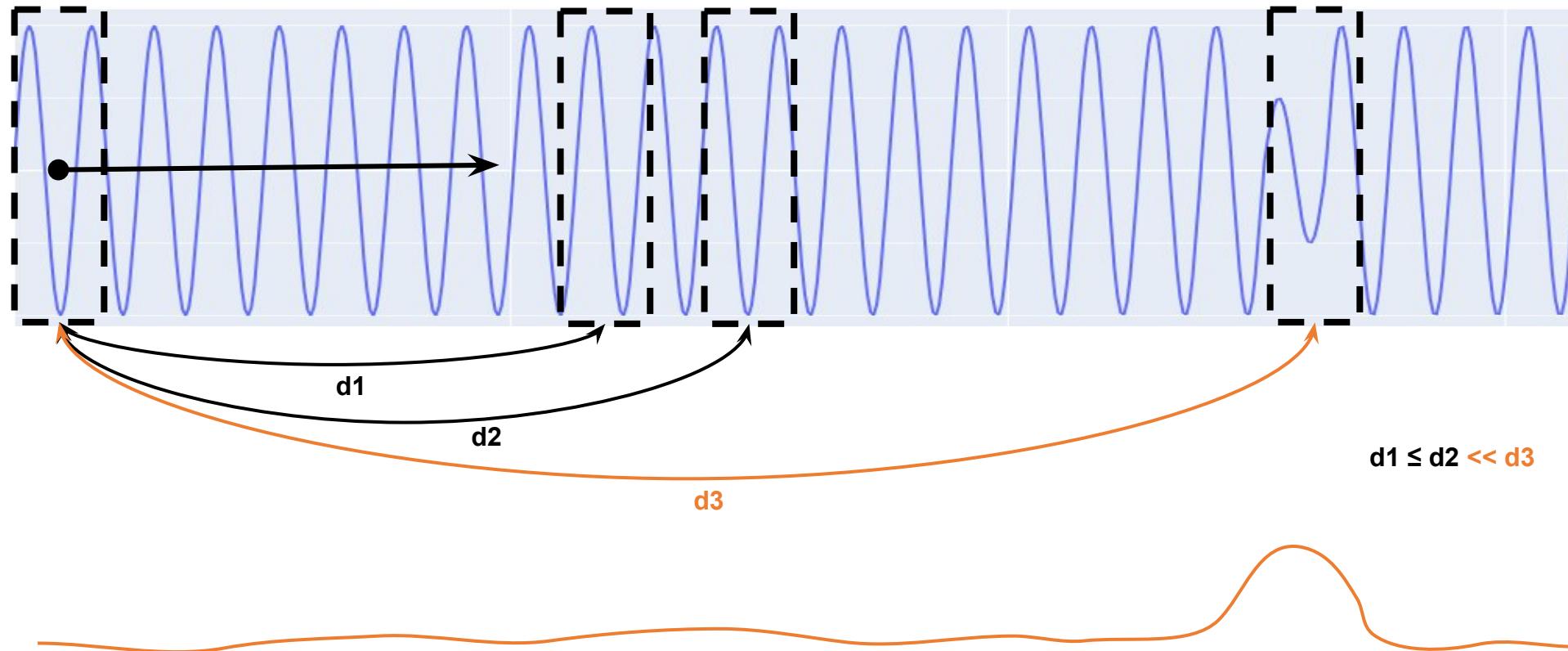


CBLOF, COF, DBStream, HOT SAX, Hybrid KNN, k-Means, KNN, LOF, NormA-SJ, PS-SVM, SAND, SSA, STAMP, STOMP, Sub-LOF, VALMOD, Left STAMPi

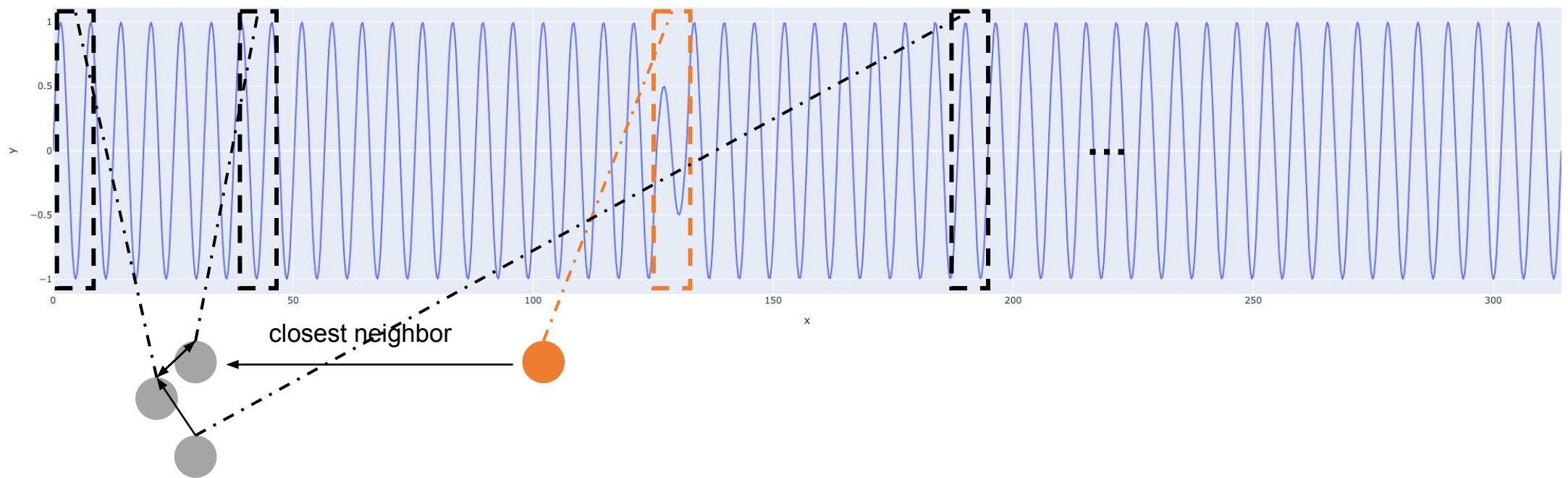
# Distance Methods

- Methods compute distances between points/subsequences (or groups of subsequences)
- Anomaly score = **distance value**

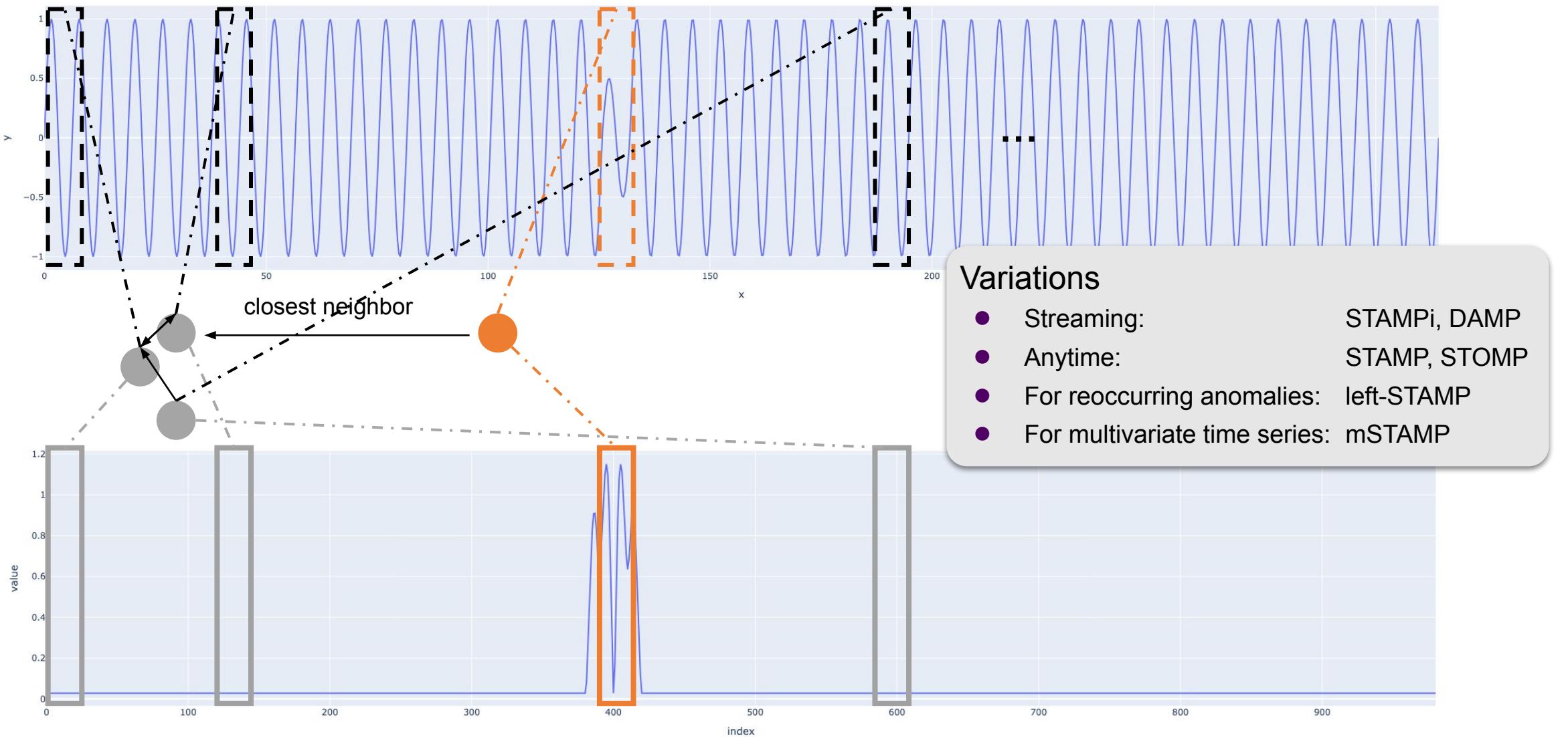
window of length m



# Distance Methods Example: MatrixProfile

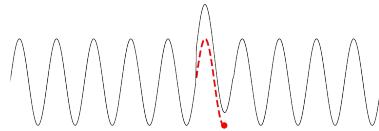


# Distance Methods Example: MatrixProfile



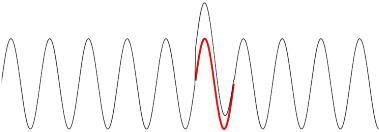
# Anomaly Detection Methods – by Family

## ★ Forecasting



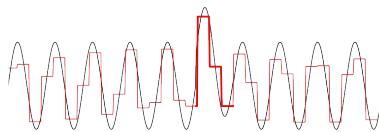
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## ■ Reconstruction



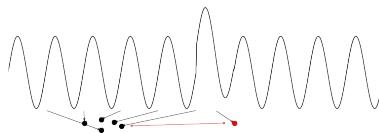
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## ▼ Encoding



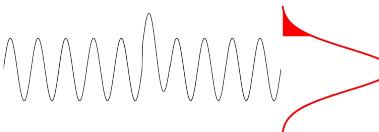
Ensemble GI, GrammarViz, LaserDBN, MultiHMM, PST, Series2Graph, TARZAN, TSBitmap

## ● Distance



CBLOF, COF, DBStream, HOT SAX, Hybrid KNN, k-Means, KNN, LOF, NormA-SJ, PS-SVM, SAND, SSA, STAMP, STOMP, Sub-LOF, VALMOD, Left STAMPi

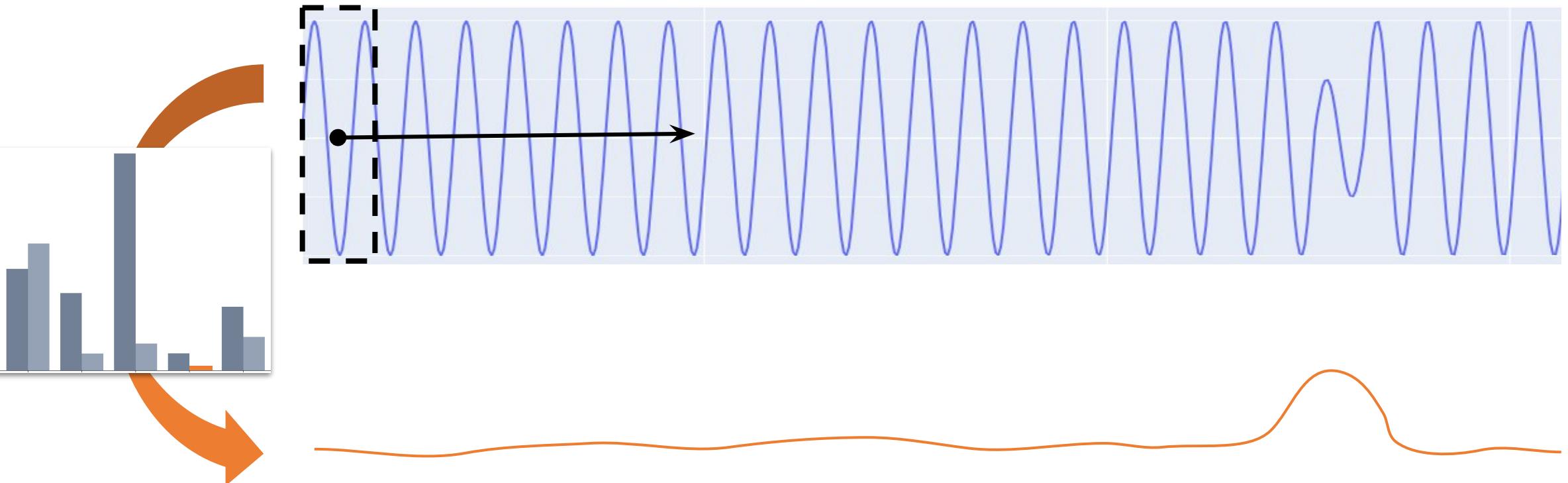
## ▲ Distribution



COPOD, DWT-MLEAD, Fast-MCD, HBOS, NF, S-H-ESD, DSPOT, Sub-Fast-MCD

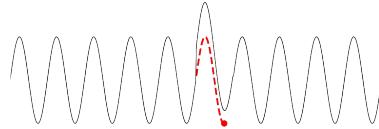
# ▲ Distribution Methods

- Methods **estimate the distribution** of the data or fit a distribution model to the data (frequency instead of distance)
- Anomaly score = **probabilities / likelihoods**



# Anomaly Detection Methods – by Family

## ★ Forecasting



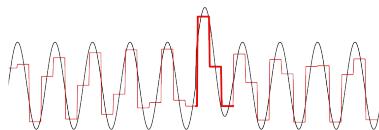
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## ■ Reconstruction



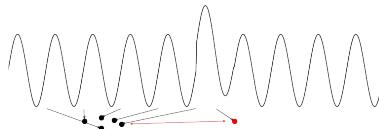
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## ▼ Encoding



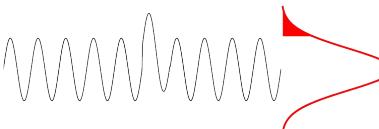
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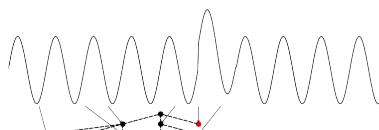
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## ▲ Distribution



COPOD, DWT-MLEAD, Fast-MCD, HBOS, NF, S-H-ESD, DSPOT, Sub-Fast-MCD

## ✚ Isolation Tree

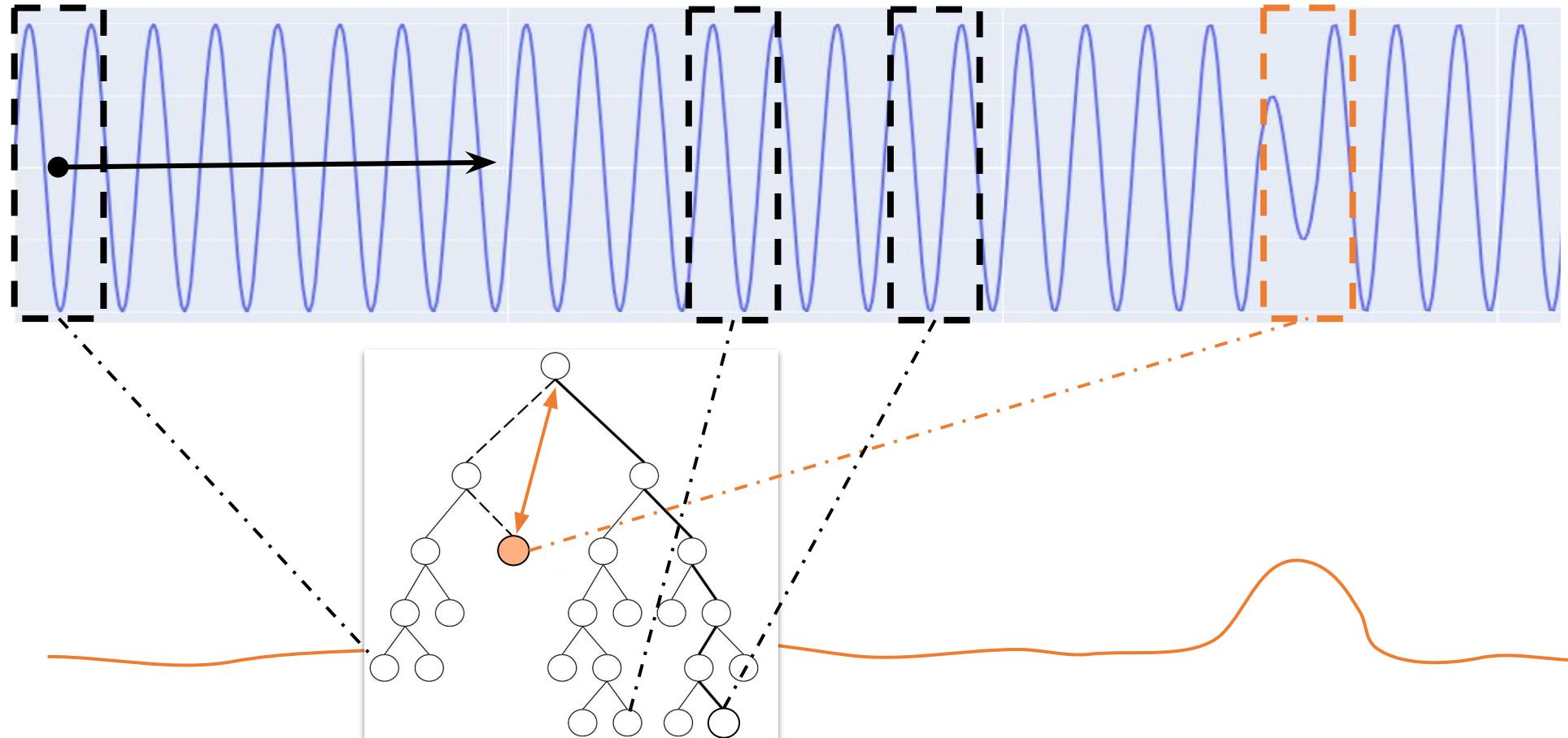


EIF, HIF, IF-LOF, iForest, Sub-IF

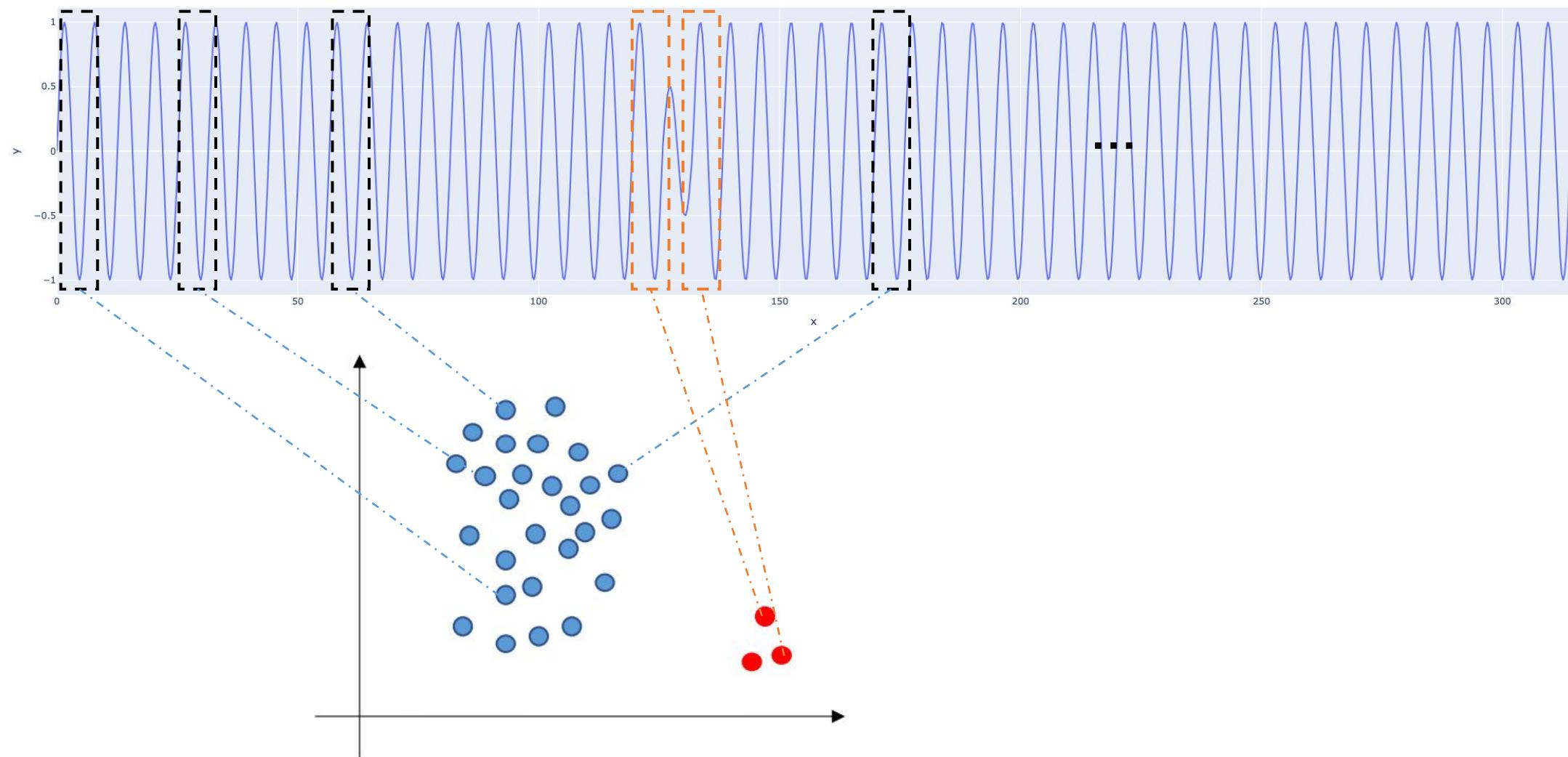
# +

# Isolation Tree Methods

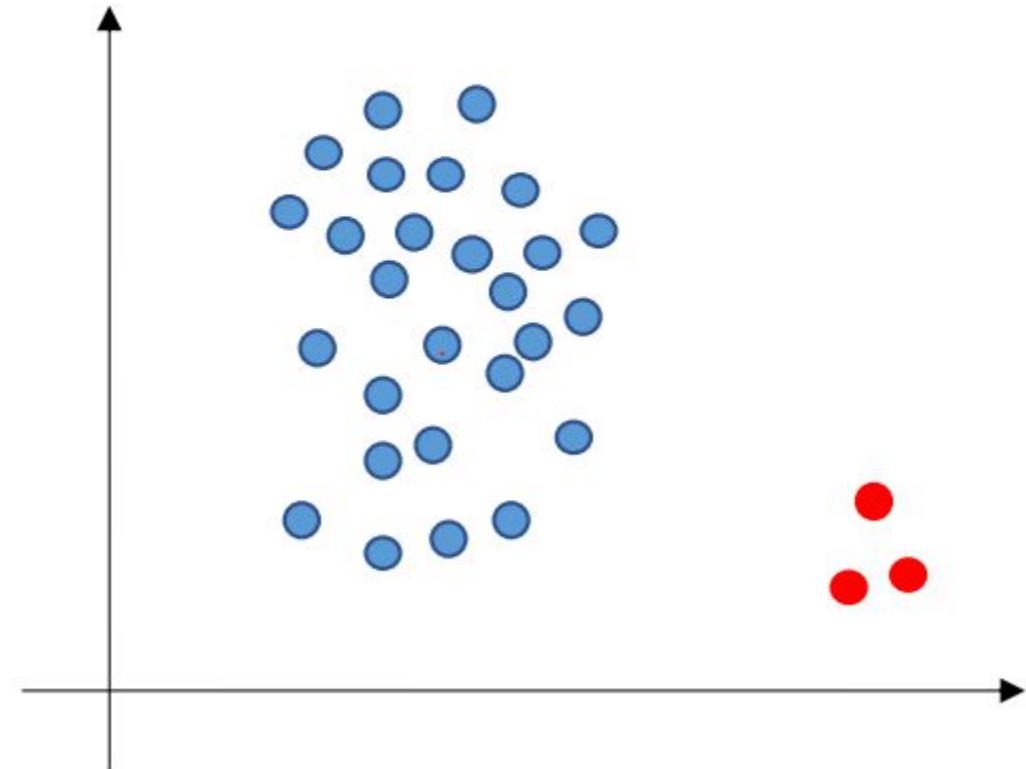
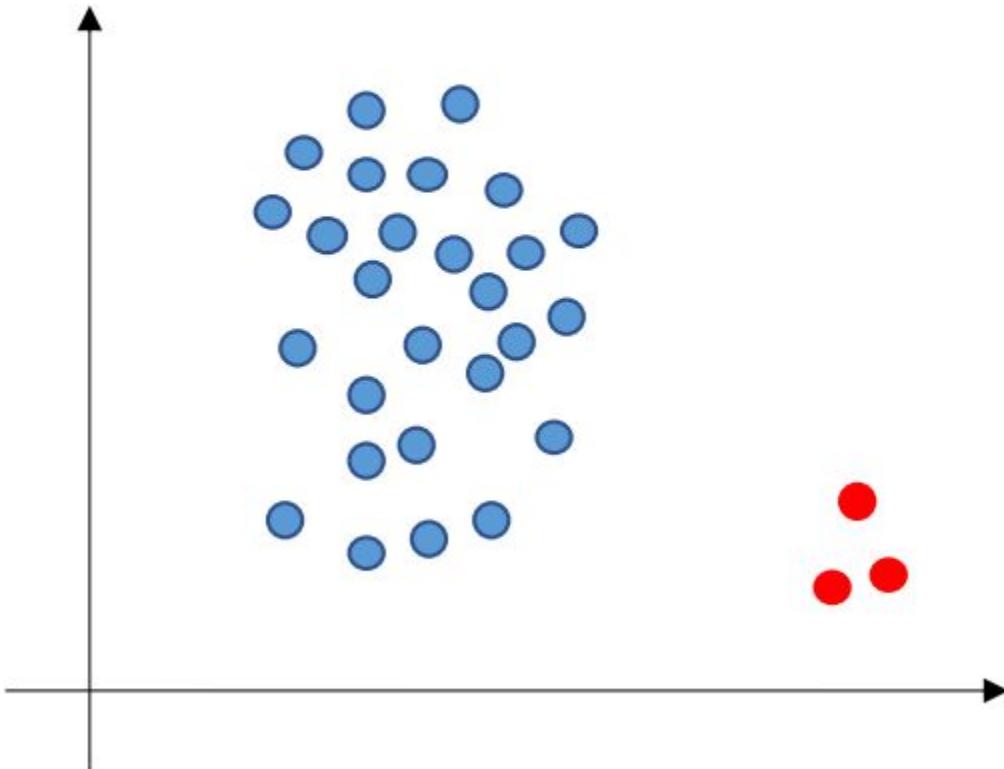
- Methods build an **ensemble of random trees that partition the samples** (points or subsequences)
- Anomaly score = **average reciprocal path length**



# Isolation Tree Methods Example: Isolation Forest

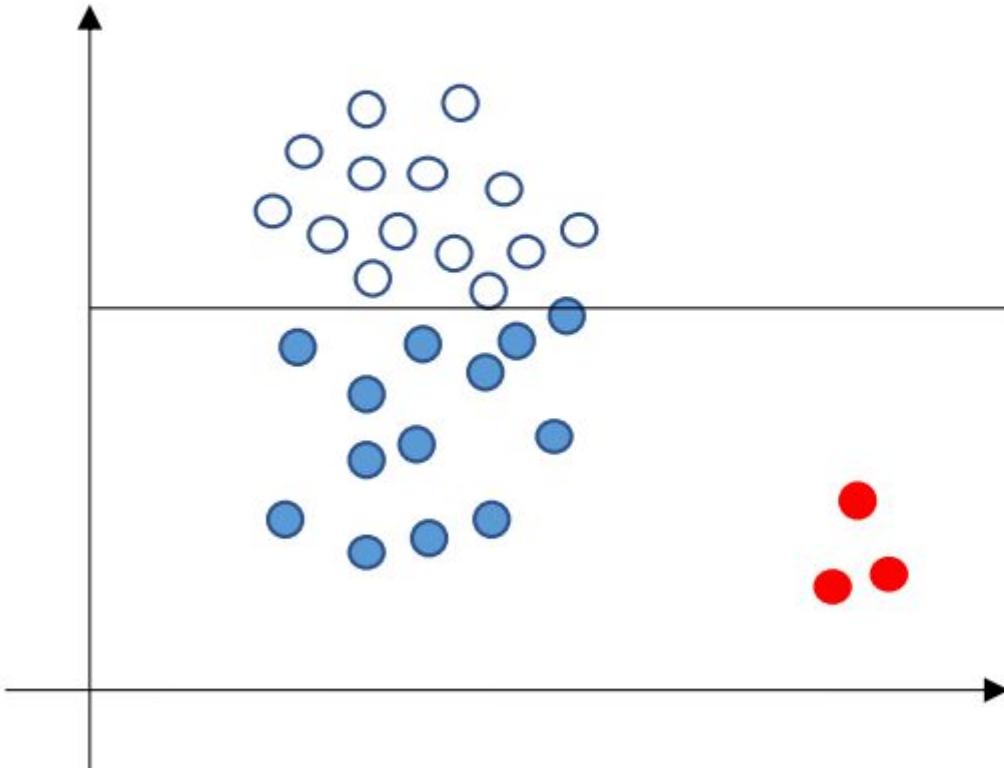


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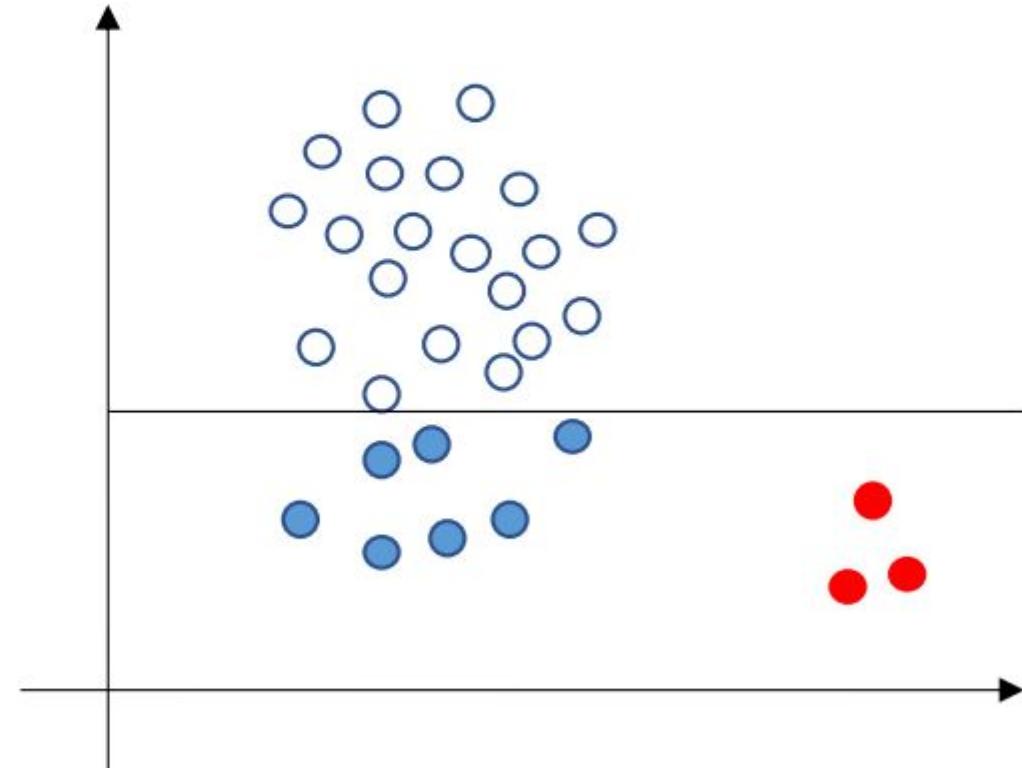


# Isolation Tree Methods Example: Isolation Forest

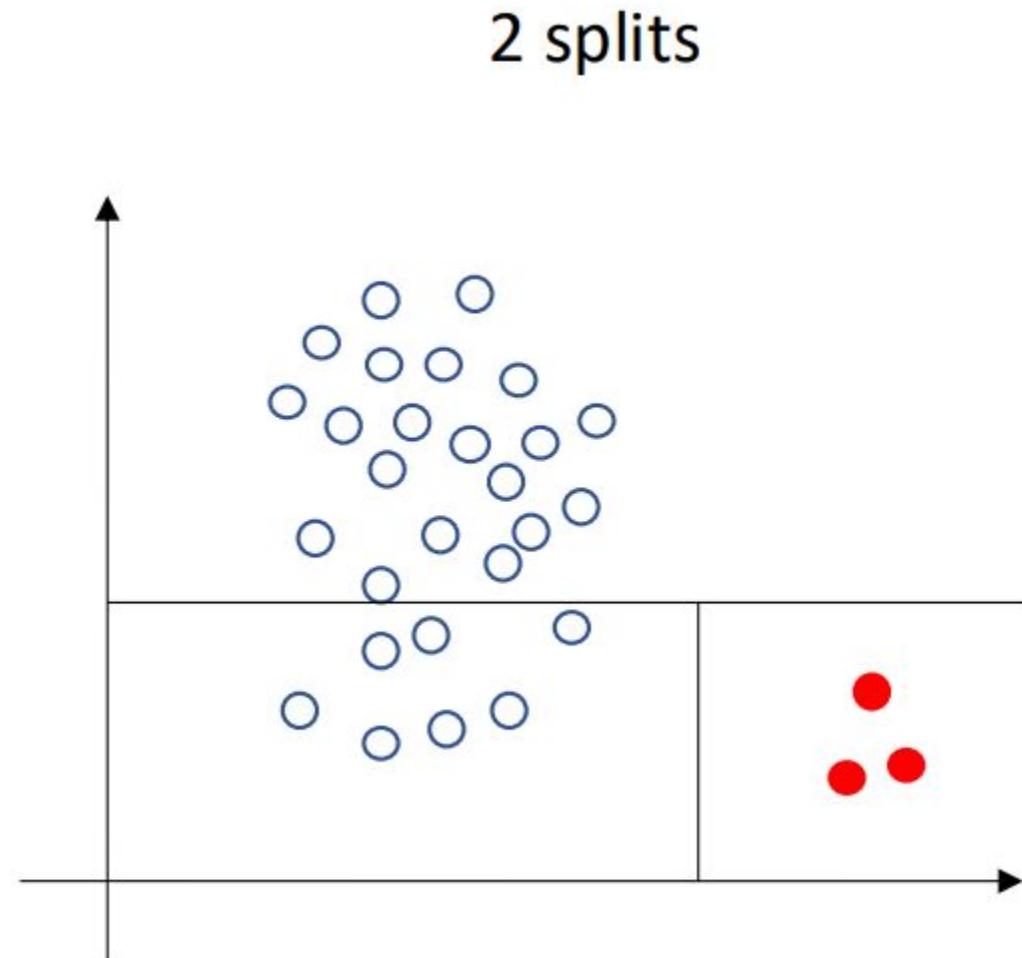
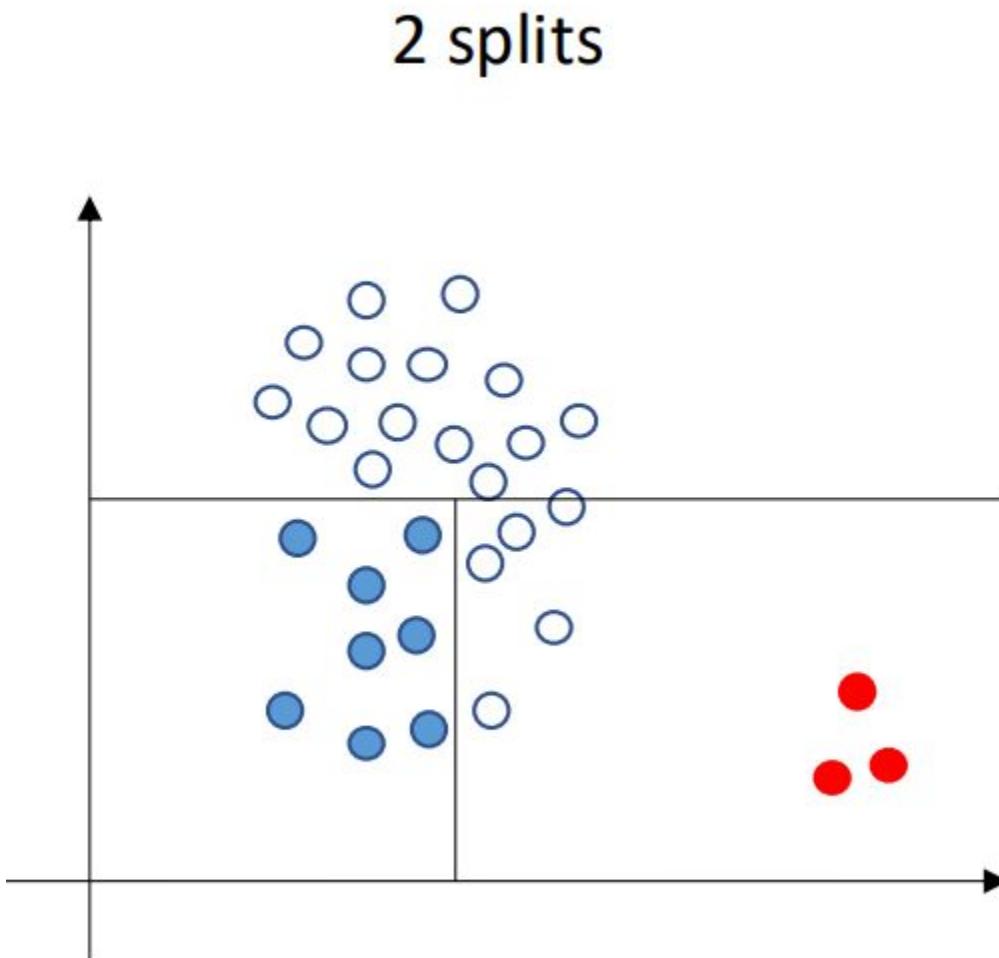
1 splits



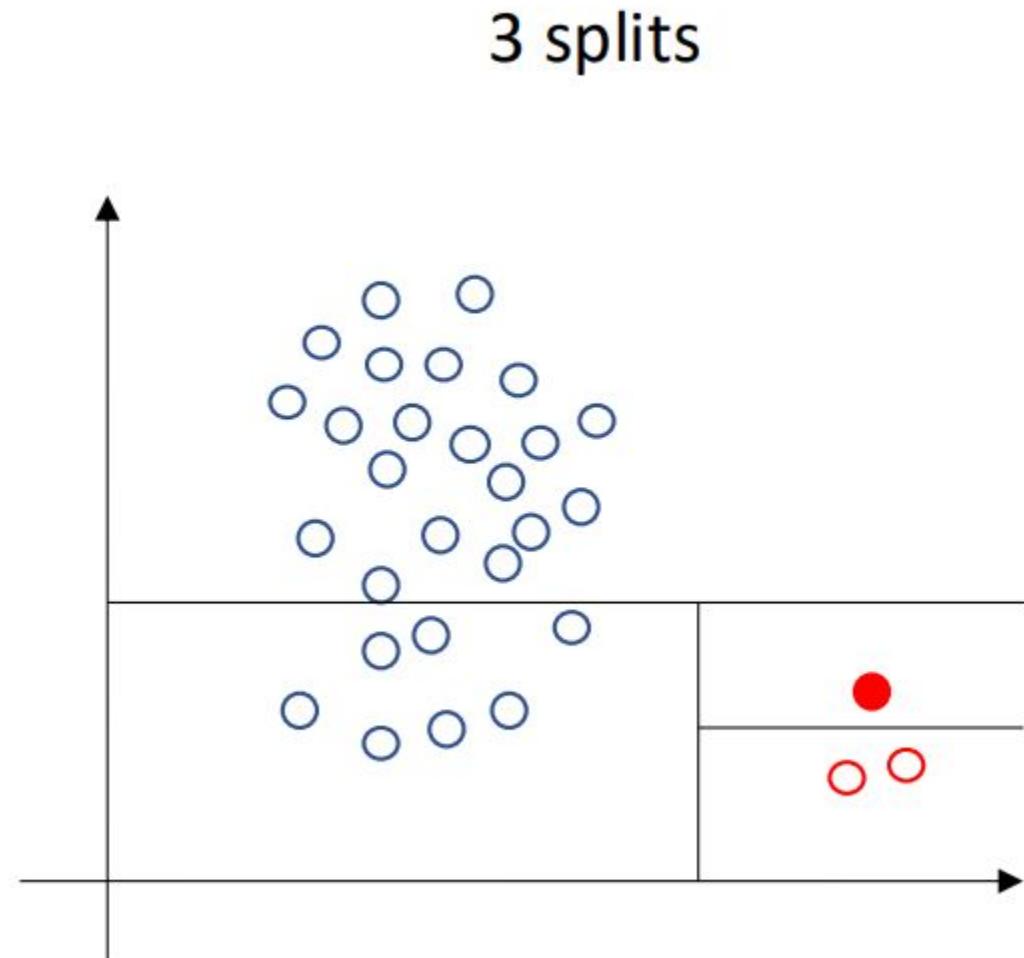
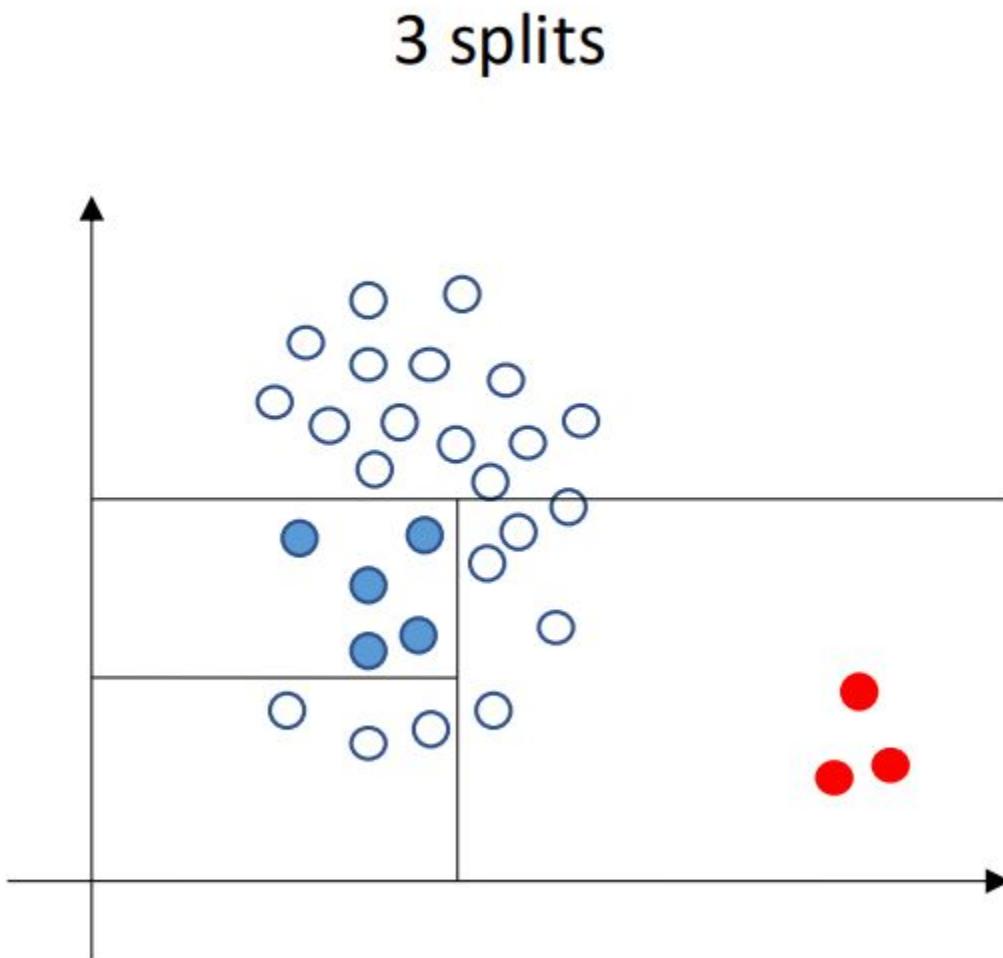
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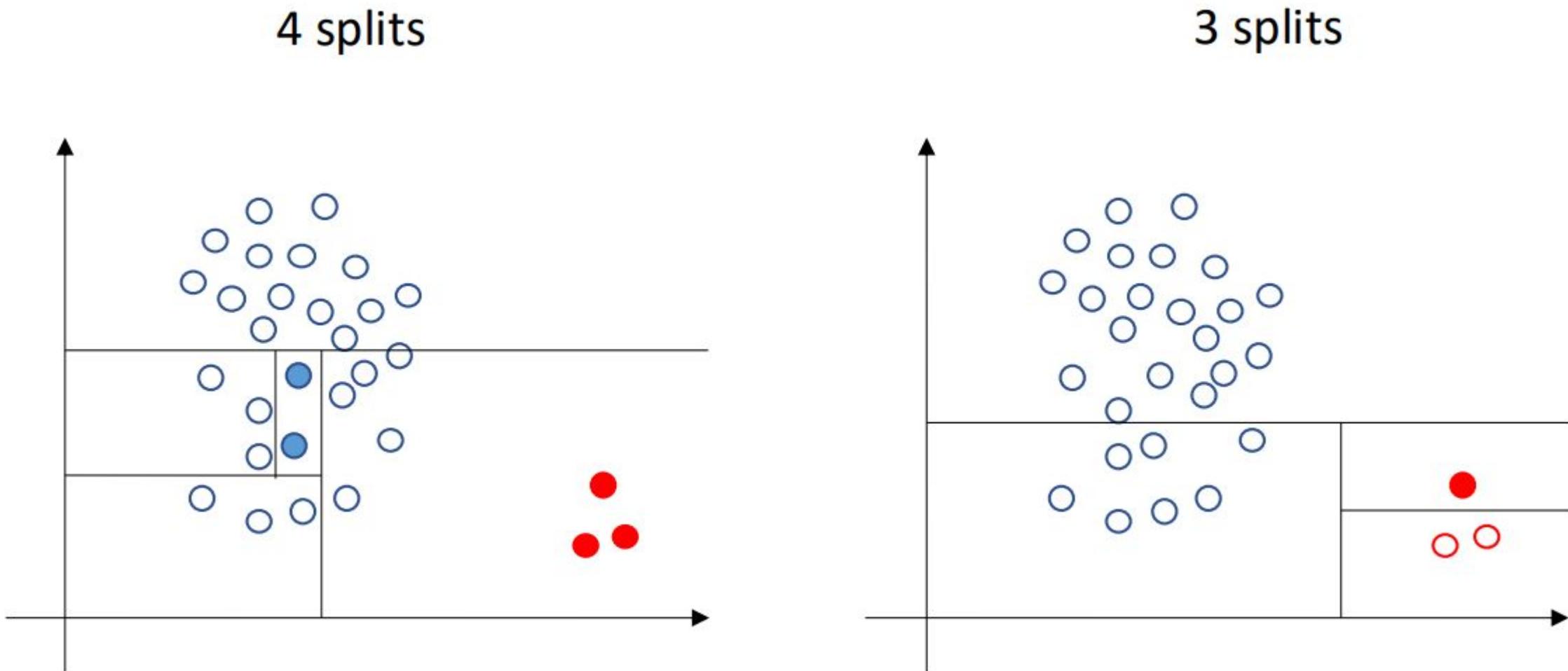
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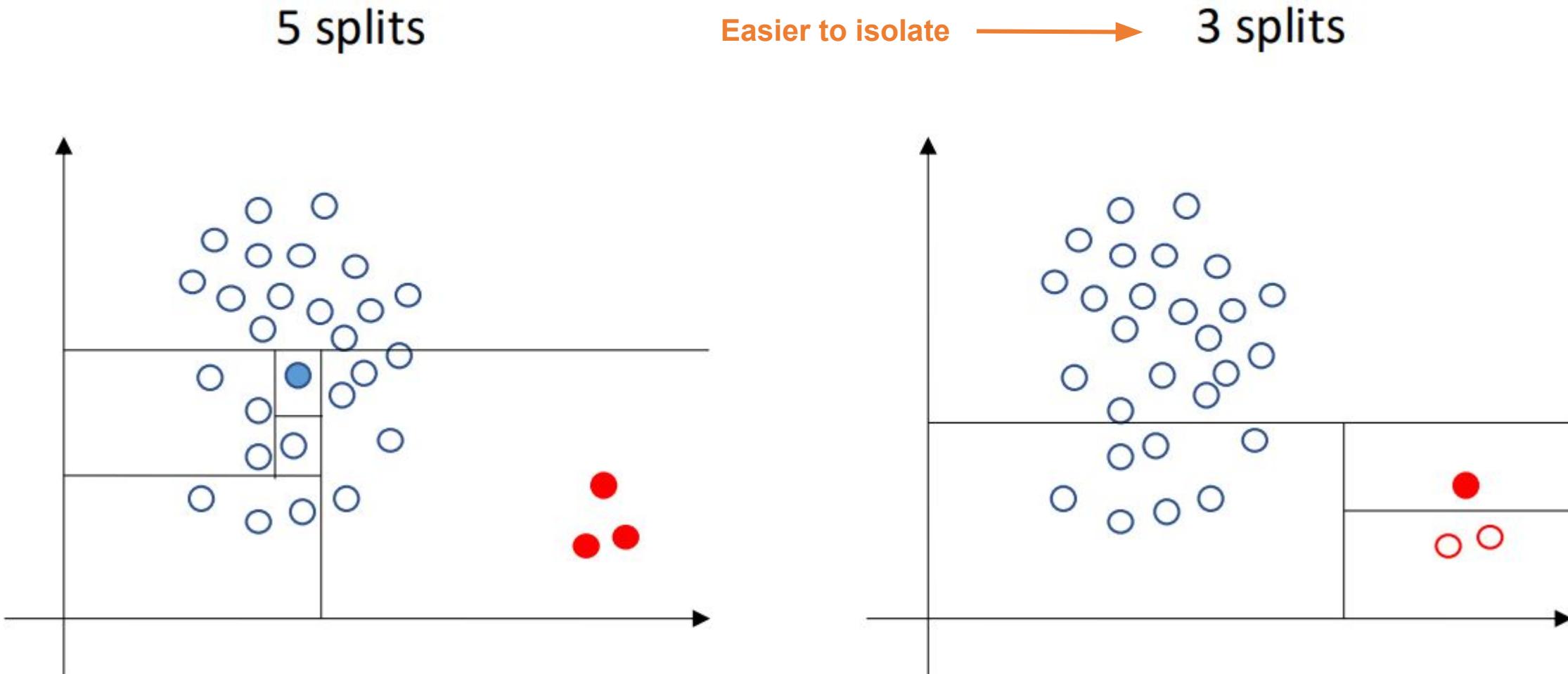
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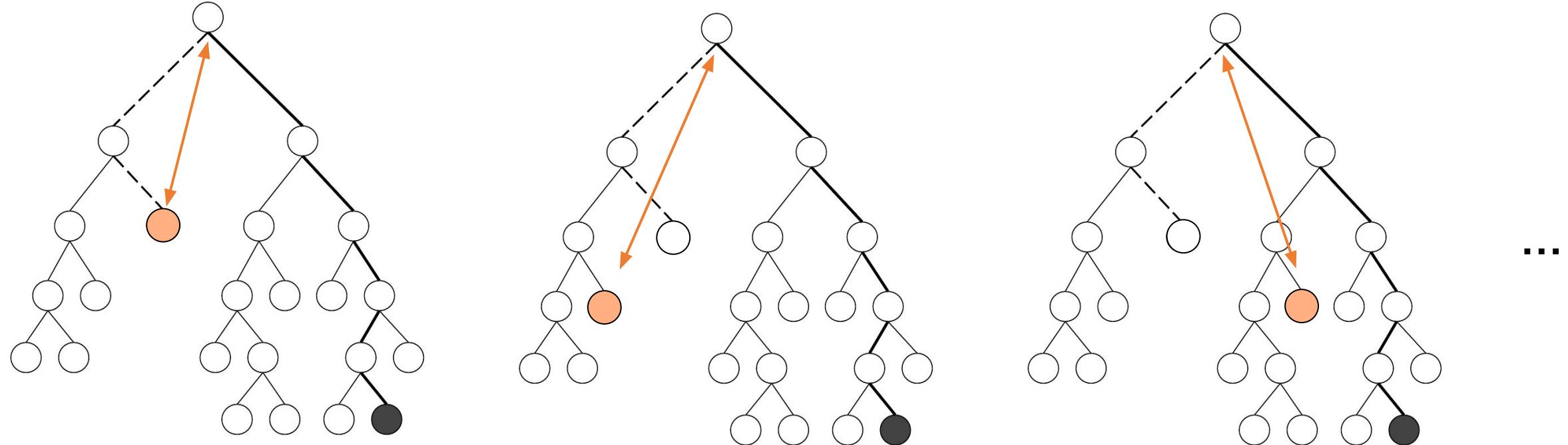
# + Isolation Tree Methods Example: Isolation Forest



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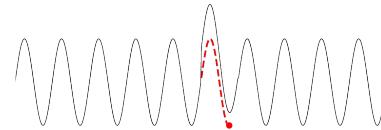


# Isolation Tree Methods Example: Isolation Forest



# Anomaly Detection Methods in aeon

## ★ Forecasting



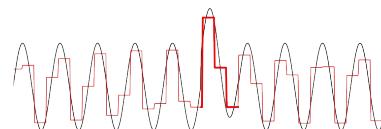
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## ■ Reconstruction



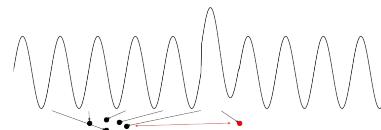
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## ▼ Encoding



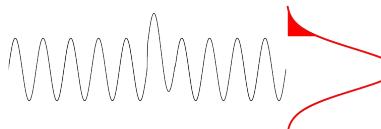
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## ● Distance



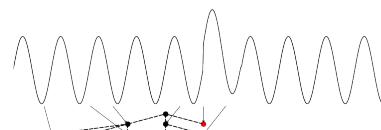
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## ▲ Distribution



**COPOD**, **DWT-MLEAD**, Fast-MCD, **HBOS**, NF, S-H-ESD, DSPOT, Sub-Fast-MCD

## ✚ Isolation Tree

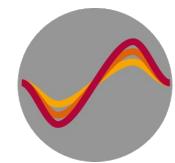
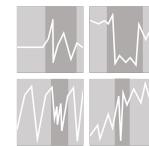


EIF, HIF, IF-LOF, **iForest**, **Sub-IF**





# TSAD Benchmark & Datasets



# Benchmarks & Datasets



NAB

**58 time series**

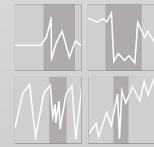
- Univariate
- Real-world and synthetic
- Streaming
- Own scoring mechanism
- Various domains



HEX/UCR

**250 time series**

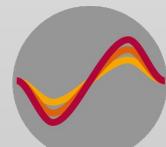
- Univariate
- Manually checked labels
- Only 1 annotated anomaly per time series
- Various domains



TSB-UAD

**2 000 time series**

- Univariate
- No filtering
- Proposes data transformations to introduce new anomalies in existing time series
- Includes time series generated from classification datasets



TimeEval

**976 time series**

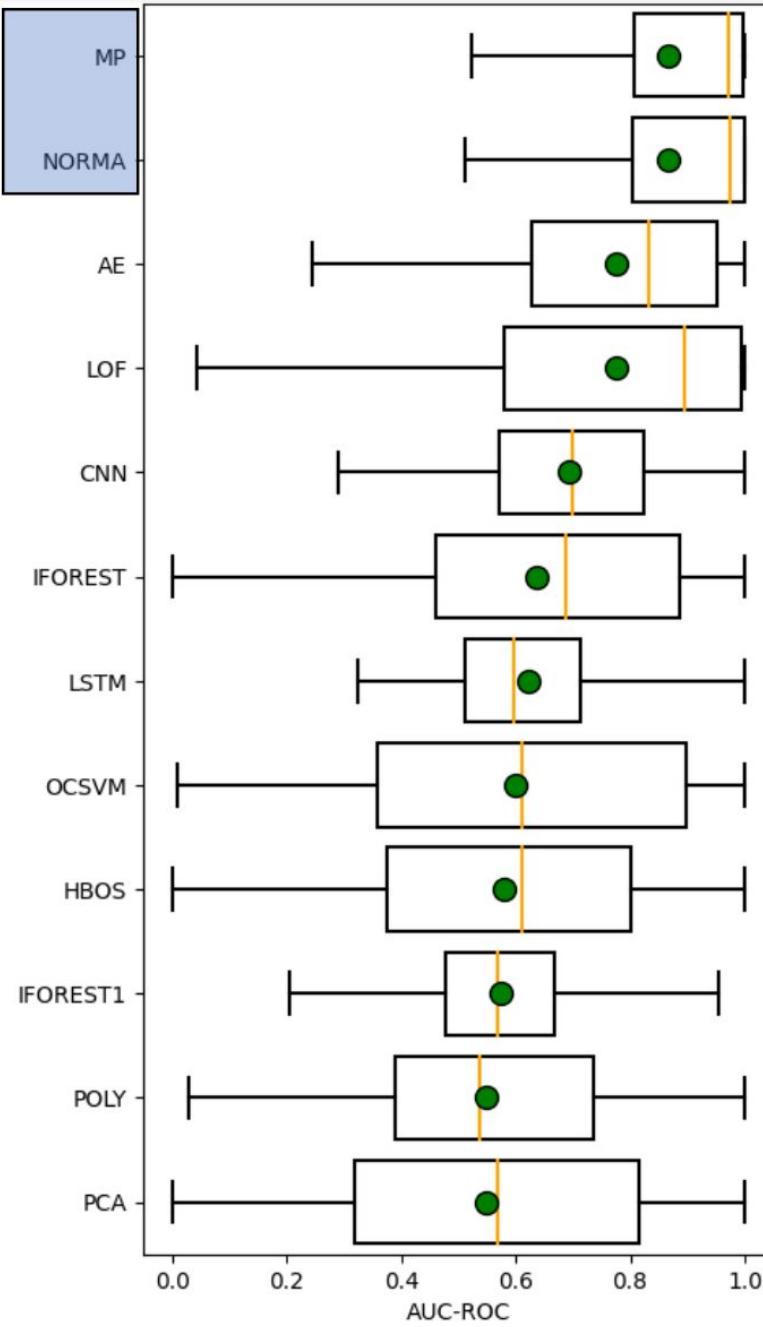
- Uni- & multivariate
- Only time series with contamination  $<0.1$ , at least one method above 0.8 ROC-AUC and at least one anomaly
- Synthetic time series generator GutenTAG for parameter tuning



All datasets are available in aeon!

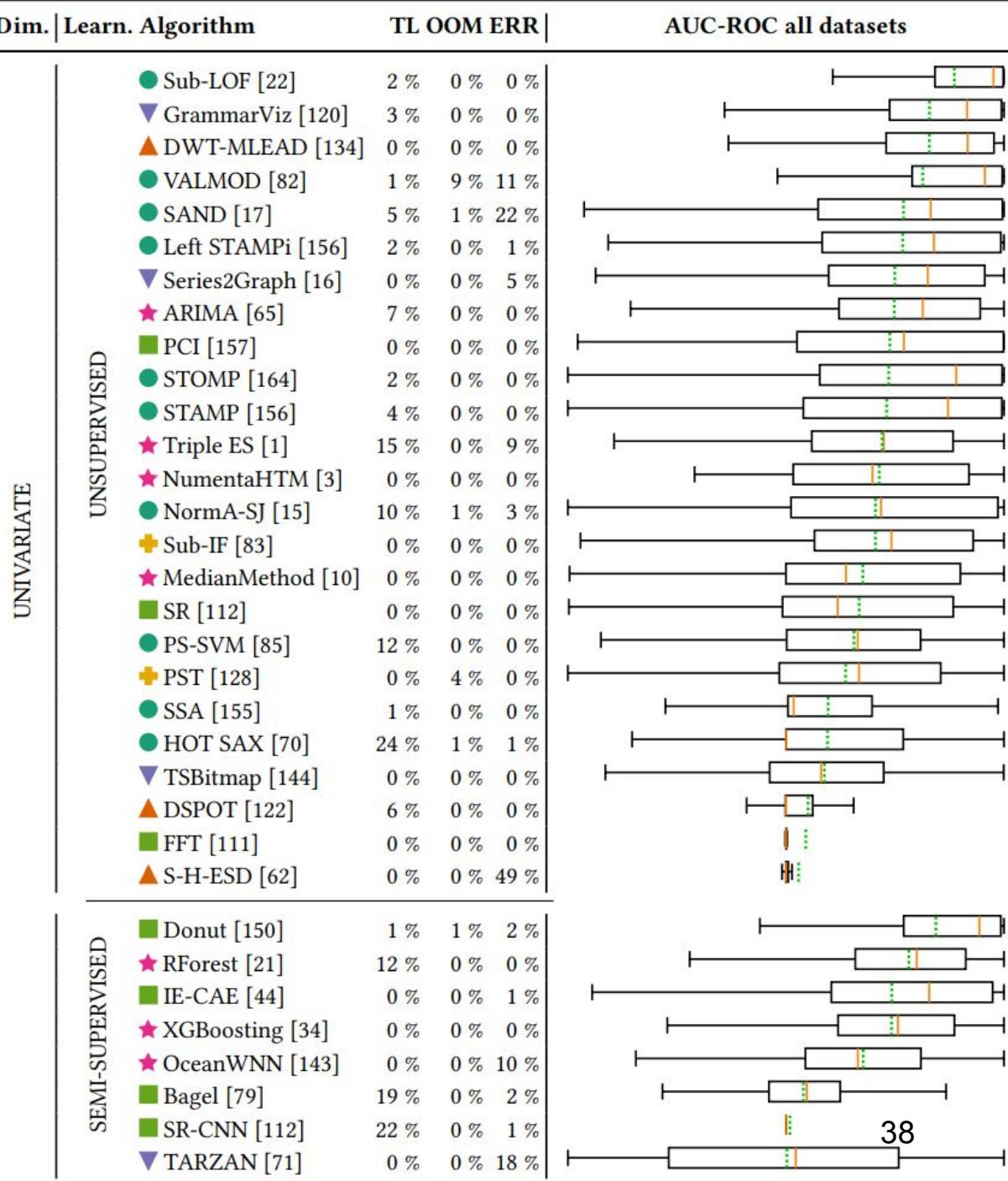
# HEX/UCR Insights

- Distance methods have better accuracy than forecasting or reconstruction methods



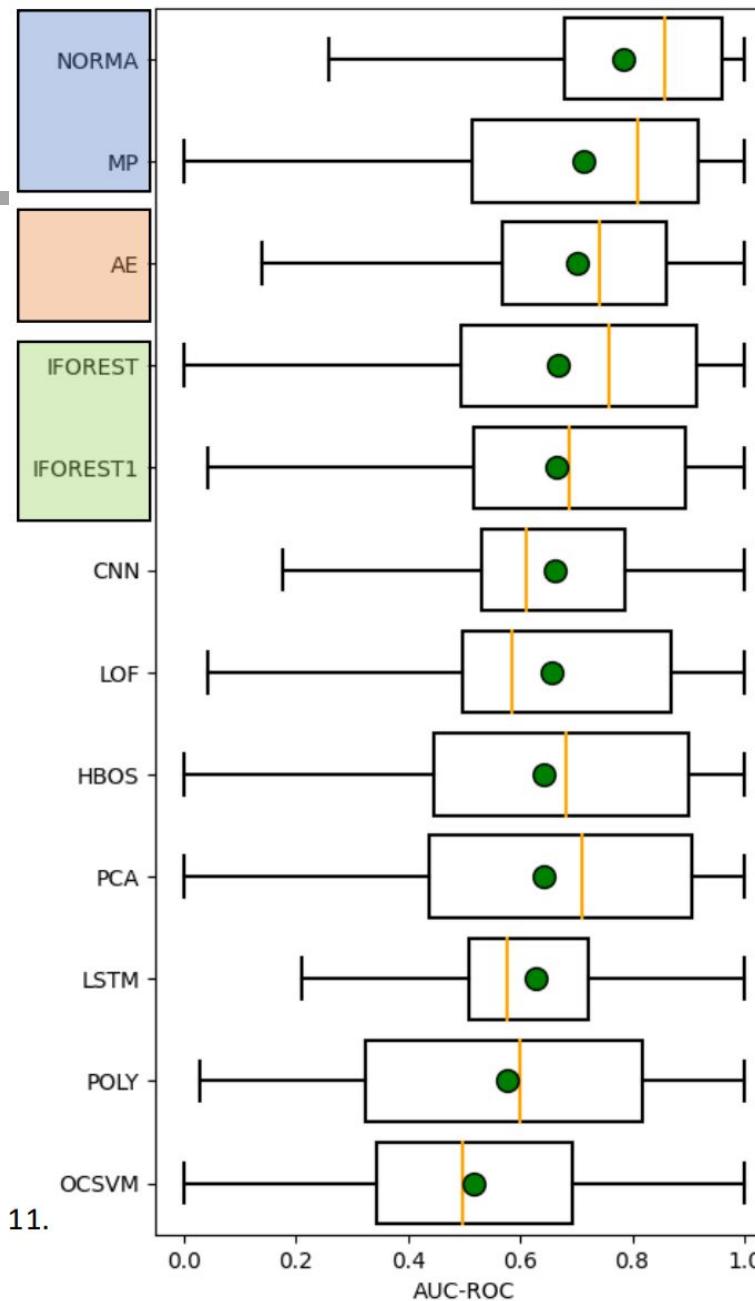
# TimeEval Insights

- Distance methods have better accuracy than forecasting or reconstruction methods
- Semi-supervised are NOT outperforming unsupervised
- **There is no overall winner!**



# TSB-UAD Insights

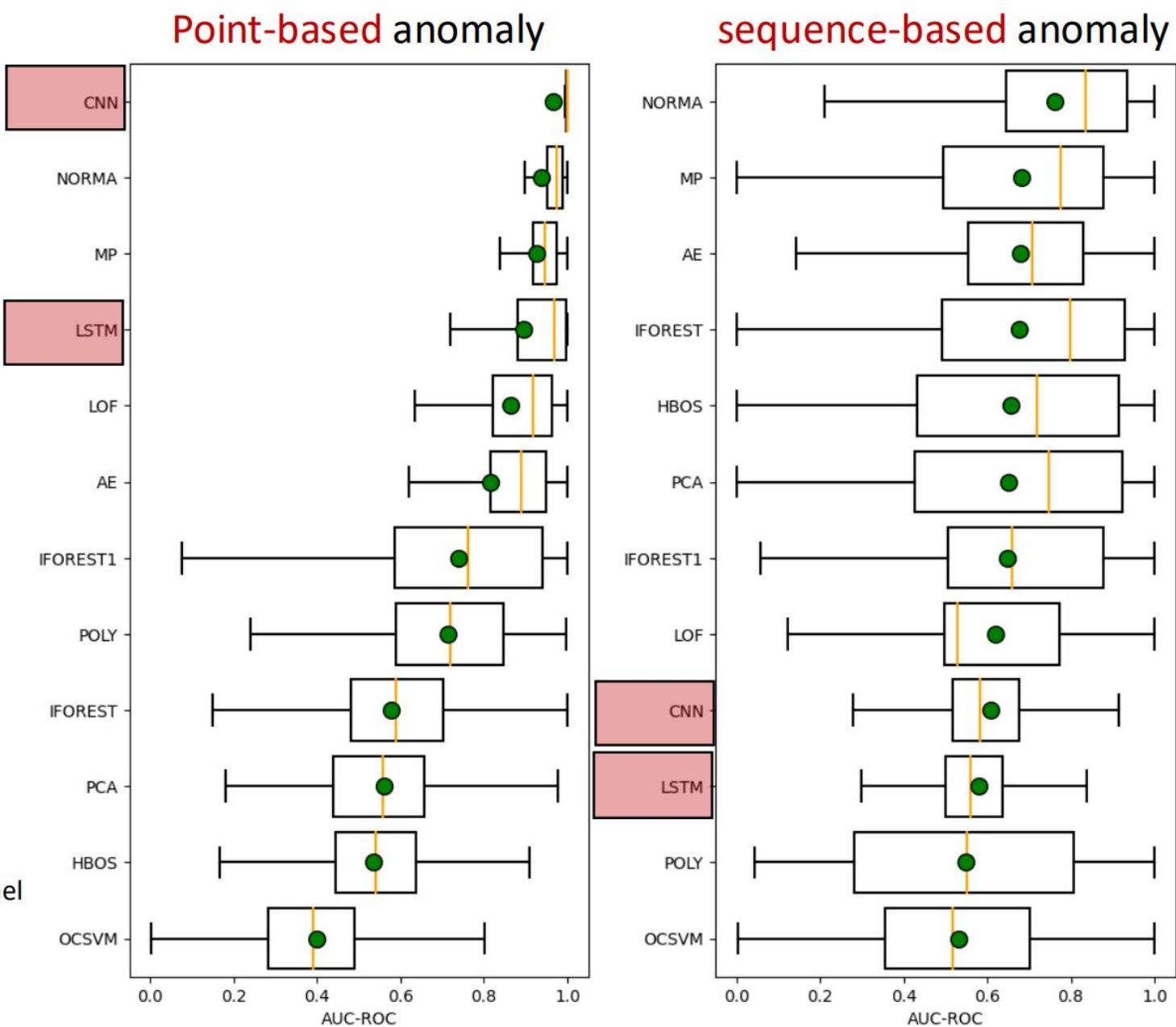
- Distance methods have better accuracy than forecasting methods
- Isolation Forest is very competitive



11.

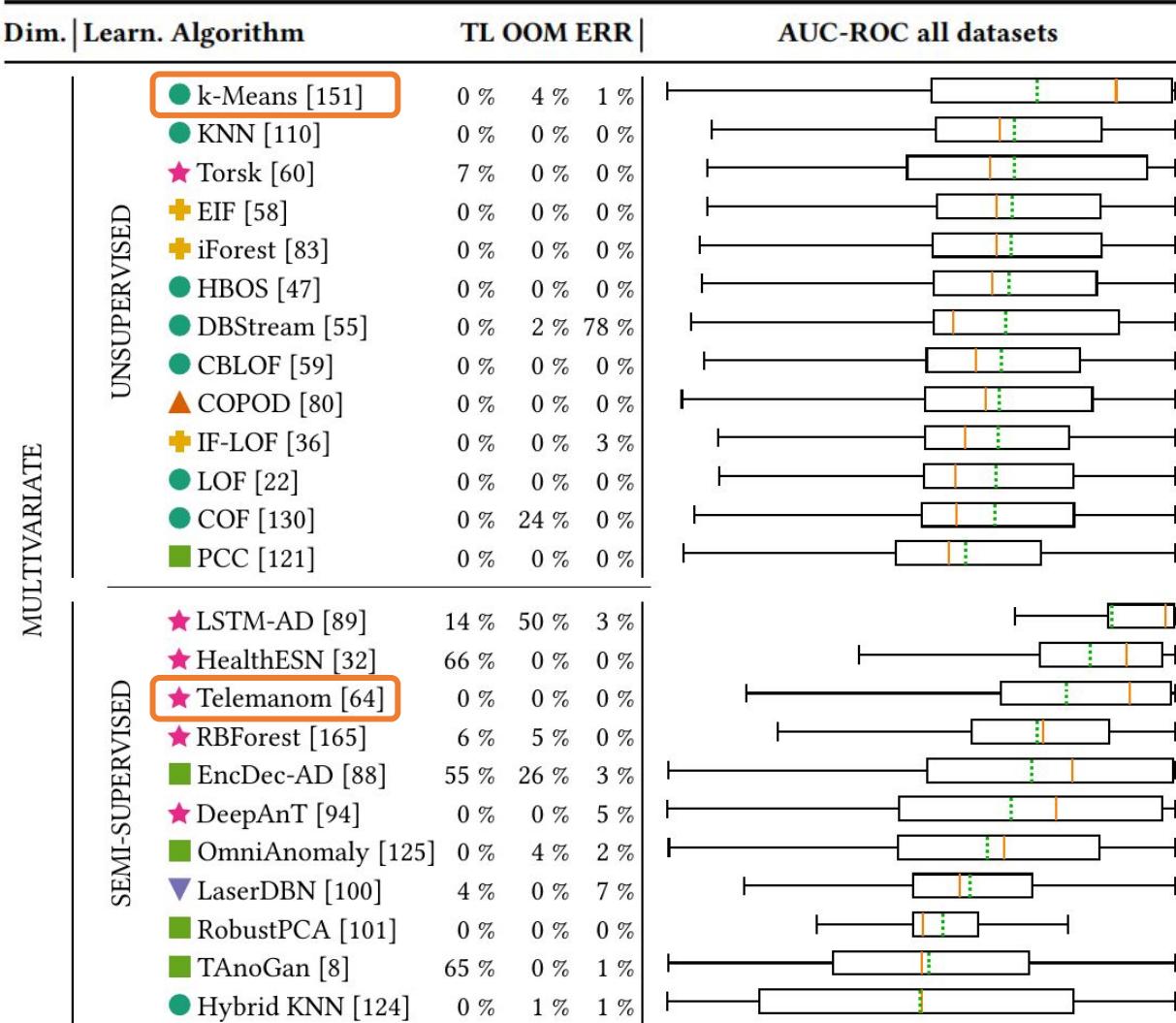
# TSB-UAD Insights

- Distance methods have better accuracy than forecasting methods
- Isolation Forest is very competitive
- Forecasting methods are good at detecting point anomalies, but bad at detecting subsequence anomalies
- **There is no overall winner!**

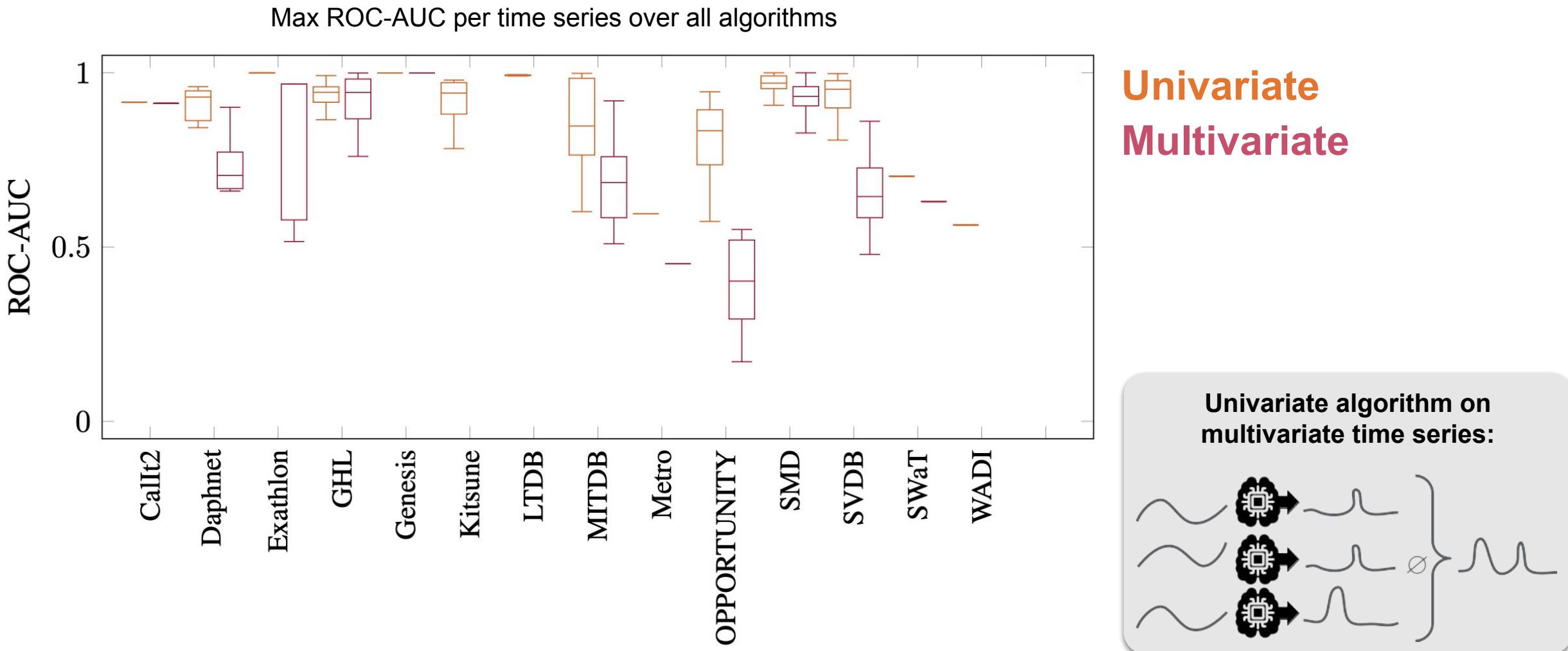


# Multivariate: TimeEval Insights

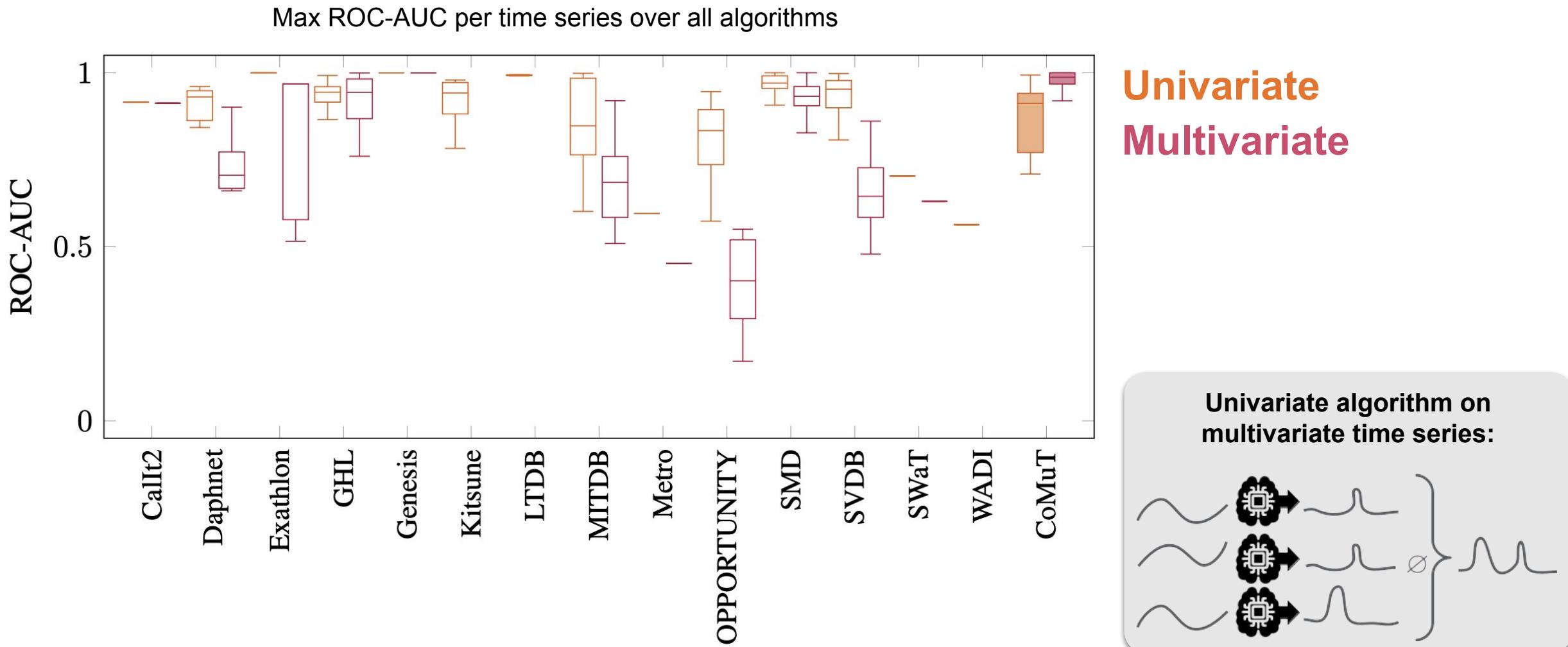
- k-Means and Telemanom stand out
- Overall bad accuracy
- Semi-supervised often exceed resource limits, but are outperforming unsupervised slightly
- **There is no overall winner!**



# Multivariate: Datasets are too easy

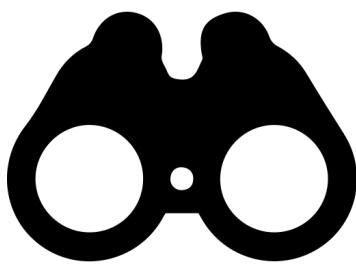


# Multivariate: Datasets are too easy





# Outlook



# Recommended Reads

## Evaluation and Survey Papers

### TSB-UAD: An End-to-End Benchmark Suite for Univariate Time-Series Anomaly Detection

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Rami S. Tay  
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**ABSTRACT**  
The detection of anomalies in time series has gained ample academic and industrial attention. However, no comprehensive benchmark exists to evaluate time-series anomaly detection methods. It is common for researchers to either (i) compare their results against a few particular datasets or (ii) a limited collection of publicly available

rapid growth of cost-effective IoT deployments already improves their quality of service application. Moreover, there are many more important applications in time series data such as financial finance applications to health care monitoring. An anomaly can indicate a system failure or a production fault, health defects, botnet attacks, system defects, or health anomalies in a field of general interest. Because time series are often large and exhibit complex patterns, it is difficult to detect anomalies in time series. This paper presents the automatic detection of such anomalous patterns. The

Paparrizos et al.  
VLDB (2022)  
[https://doi.org/10.1109/ICD\\_EW61823.2024.00018](https://doi.org/10.1109/ICD_EW61823.2024.00018)

#### VLDB Reference Format:

John Paparrizos, Yuhao Kang, Paul Boniol, Rami S. Tay, Theresa Palantas, Michael J. Franklin, and T. H. (Theresa) Palantas, "TSB-UAD: An End-to-End Benchmark Suite for Univariate Time-Series Anomaly Detection," *VLDB*, 19(9) 1697–1711, 2022.

#### 1 INTRODUCTION

A wide range of technological advances in sensing solutions enables collecting extensive amounts of time series data from various domains. In particular, analysis estimates that, shortly, billions of Internet-of-Things (IoT) devices will be generating terabytes of time series data daily [1].

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recent advances in deep learning technologies have sparked a surge of research in time series anomaly detection for univariate tasks [37, 38, 40, 52], including for AD [22, 28, 42, 74, 96]. This sudden enthusiasm and a slew of proposed methods in the preceding years have led to a lack of a clear taxonomy of anomalies and their types.

To address the aforementioned issues and provide an objective comparison of different methods, we propose a new benchmark suite, TSB-UAD. Unlike previous benchmarks that focus on specific methods, we introduce TSB-UAD, an open-to-end benchmark suite that covers all major types of anomalies. TSB-UAD originates from the laborious tasks of identifying, collecting, processing, and formulating relevant datasets that are periodically becoming available. We collected a large number of datasets from various sources suitable for handling pre-processing and post-processing steps, such as data cleaning, feature extraction, and model evaluation. TSB-UAD performs a rigorous statistical analysis of the resulting datasets and provides a detailed description of each dataset. TSB-UAD is the summary of a long process of thoroughly studying over one hundred papers that appeared in the literature in the

### Anomaly Detection in Time Series: A Comprehensive Evaluation

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**ABSTRACT**  
Detecting anomalous subsequences in time series data is an important task in many domains. For example, it is used in financial finance applications to health care monitoring. An anomaly can indicate a system failure or a production fault, health defects, botnet attacks, system defects, or health anomalies in a field of general interest. Because time series are often large and exhibit complex patterns, it is difficult to detect anomalies in time series. This paper presents the automatic detection of such anomalous patterns. The

Schmidl et al.  
VLDB (2022)  
<https://doi.org/10.14778/3538598.3538602>

#### VLDB Reference Format:

Sebastian Schmid, Philipp Wenig, and Thorsten Papenbrock, "Anomaly Detection in Time Series: A Comprehensive Evaluation," *VLDB*, 19(9) 1712–1730, 2022.

**VLDB Artifact Availability:**  
The source code, data, and/or other artifacts have been made available at <https://ipb.hpi.de/nanomis/time-series-anomaly-detection-evaluation>.

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### Anomaly Detectors for Multivariate Time Series: The Proof of the Pudding is in the Eating

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**Abstract—** Anomaly detection is a popular task in time series analysis and requires having more than one dimension. In this paper, we propose a novel taxonomy of anomalies for multivariate time series and compare their ROC-AUC and PR-AUC scores. Contrary to common assumptions, the measured scores are overall better for univariate approaches than for multivariate ones. With a special type of anomaly, namely *correlation outliers*, we demonstrate that univariate approaches outperform multivariate benchmarks on non-meaningful datasets and often outperform them.

Wenig et al.  
ICDEW (2024)  
[https://doi.org/10.1109/ICD\\_EW61823.2024.00018](https://doi.org/10.1109/ICD_EW61823.2024.00018)

#### ICDEW Reference Format:

Sebastian Schmid, Philipp Wenig, and Thorsten Papenbrock, "Anomaly Detectors for Multivariate Time Series: The Proof of the Pudding is in the Eating," *ICDEW*, 1(1) 1–10, 2024.

**ICDEW Artifact Availability:**  
The source code, data, and/or other artifacts have been made available at <https://ipb.hpi.de/nanomis/time-series-anomaly-detection-evaluation>.

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### Current Time Series Anomaly Detection Benchmarks are Flawed and are Creating the Illusion of Progress

Renjie Wu and Eamonn J. Keogh

**Abstract—** Time series anomaly detection has been a perennially important topic in data science, with papers dating back to the 1950s. However, in recent years there has been an explosion of interest in this topic, much of it driven by the success of deep learning models. In this paper, we analyze the current state of the art in time series anomaly detection benchmarks, created by Yahoo!, Numeria, NASA, etc. In this work we make a surprising claim: the majority of the individual examples in these datasets suffer from one or more of four flaws. Because of these four flaws, we believe that many published comparisons of anomaly detection algorithms are misleading, and that the reported progress in recent years may be illusory. In addition to demonstrating these claims, with this paper we introduce the UCR Time Series Anomaly Archive. We believe that this archive will perform a similar role as the UCR Time Series Classification Archive, by making the community a lot more aware of the limitations of current benchmarks.

Wu et al.  
TKDE (2023)  
[https://doi.org/10.1109/TKD\\_E.2021.3112126](https://doi.org/10.1109/TKD_E.2021.3112126)

#### TKDE Reference Format:

Renjie Wu and Eamonn J. Keogh, "Current Time Series Anomaly Detection Benchmarks are Flawed and are Creating the Illusion of Progress," *TKDE*, 35(10) 3033–3050, 2023.

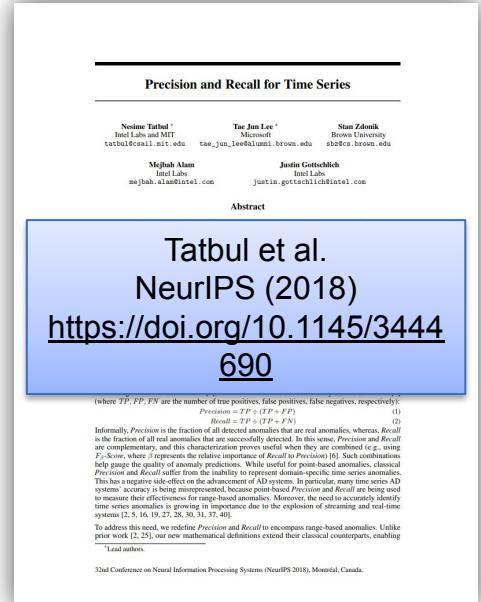
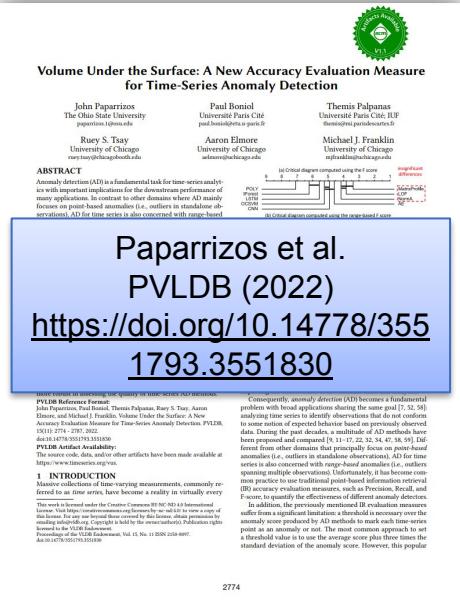
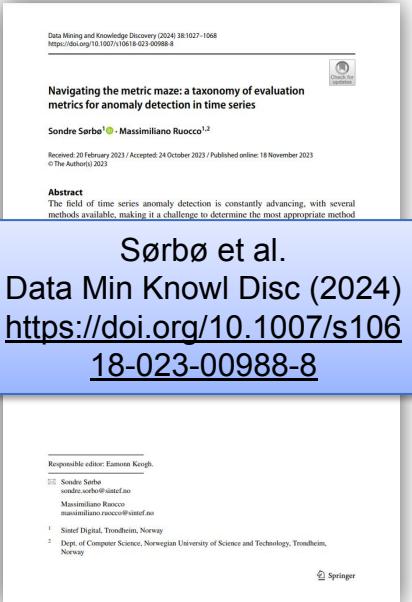
**TKDE Artifact Availability:**  
The source code, data, and/or other artifacts have been made available at <https://ipb.hpi.de/nanomis/time-series-anomaly-detection-evaluation>.

**TKDE License:**  
This work was first introduced in four smaller types [1] to [4]. This work is now a full paper. Since then, many definitions of the term outlier and numerous detection methods have been proposed in the literature. However, to this day, there is still no consensus on the terms used [Carrasco et al. 2019]; for example, outlier observations are often referred to as anomalies, discordant observations, discordants, exceptions, aberrations, surprises, peculiarities or contaminants.

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# Recommended Reads

## Metric Papers



### Local Evaluation of Time Series Anomaly Detection Algorithms

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**INTRODUCTION**  
Time series anomaly detection is the field consisting in detecting elements of a time series that behave differently from the rest of the data. This field attracted interest in recent years with the rise of streaming data and the need for real-time monitoring and diagnosis, mainly for the purpose of troubleshooting and security. Many scientific domains are involved: water control industrial systems [8, 24], energy management [1, 2, 10, 11, 12, 13, 14, 15, 16, 17, 18], aerospace telemetry [10], and also medicine or robotics [30, 1]. Due to the nature of the series, each anomaly (referred as an event in the context of time series) can be a point in time (point-based anomalies) or a sequence of points in time (range-based anomalies).

In recent years, specific evaluation metrics have been developed to handle the limitations of the classical precision and recall. However, such metrics are heavily domain-specific and lack the generalization power of the metrics used mainly for the purpose of troubleshooting and security. Many scientific domains are involved: water control industrial systems [8, 24], energy management [1, 2, 10, 11, 12, 13, 14, 15, 16, 17, 18], aerospace telemetry [10], and also medicine or robotics [30, 1]. Due to the nature of the series, each anomaly (referred as an event in the context of time series) can be a point in time (point-based anomalies) or a sequence of points in time (range-based anomalies).

Classical metrics are convenient for the tasks that regard each sample separately; however, this does not hold for time series datasets, where the time component is inherently continuous. Researchers developed new metrics to handle this challenge, such as *Precision* and *Recall*, originally proposed for classification problems, and adapting the evaluation process and have come up with metrics fitting their specific use-case: range precision/recall [27] for evaluating the NeurIPS dataset [14], and range precision/recall [24] for evaluating the HAD dataset [24], Numenta benchmark [16] for evaluating the Numenta corpus [1], etc.

However, these metrics provide a very incomplete picture of the limitations of the classical metrics, along with the different directions of research that have been explored to handle them. Against this background, we propose a taxonomy of metrics for time series anomalies named the *affiliation metrics* – that exhibit a series of important properties as they are theoretically principled, parameter-free, robust, and easily interpretable. We show that these metrics are well-connected as they are connected to quantities expressed in time units, and are easily interpretable (allowing to troubleshoot detection at individual event level). Summarizing our main contributions:

• We propose a taxonomy of metrics for time series anomalies, called *affiliation metrics*, that are well-connected to the time series and are easily interpretable.

• We show that these metrics are well-connected to the time series and are easily interpretable.

# Future Work

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## For Research

- Automatic method selection and ensembling methods
  - No one-size-fits-all solution, but already 100s of methods
- More and better benchmarks
  - Existing benchmark datasets have flaws
  - Existing evaluations are biased
- TS Foundation Models
- Explainability / Precursor Detection / Anomaly Classification

## In aeon

- Add more detectors (especially deep learning)
- Add missing metrics



# Example code

See *part6\_anomaly\_detection.ipynb*



# Thank you!

NEXT: Deep Learning by Ali Ismail-Fawaz

# Datasets repositories

