SPARK+AI
SUMMIT EUROPE

# Spark-ITS: Indexing for Large-Scale Time Series Data on Spark

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WPI DATA SCIENCE

#SAISEco5

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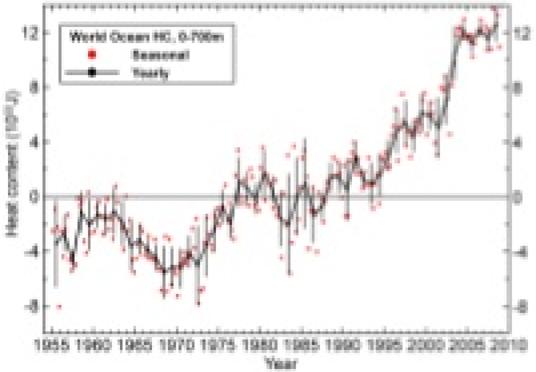
Liang Zhang, Noura Alghamdi, Mohamed Y. Eltabakh, Elke A. Rundensteiner. *TARDIS: Distributed Indexing Framework for Big Time Series Data*. Proceedings of 35th IEEE International Conference on Data Engineering **ICDE**, 2019

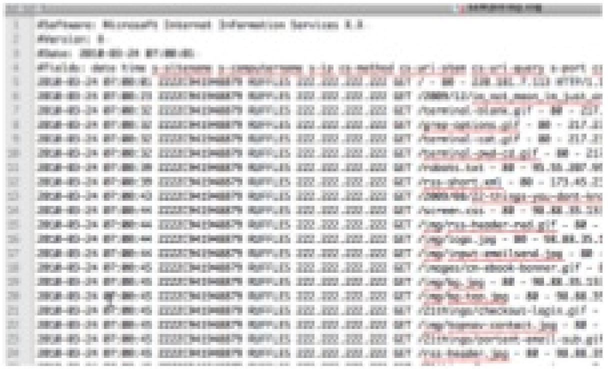
# Outline

- Motivation
- Background
- Spark-ITS Framework
  - Overview
  - Index Construction
  - Query Processing
- Performance Evaluation

# Time Series are Continuously Produced Everywhere

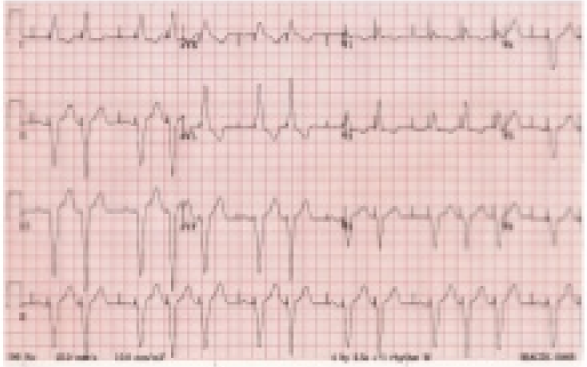


Climate data



```
#Software: Microsoft Internet Information Services 6.0
#Version: 1.0
#Date: [illegible]
#Fields: date time [illegible]
[illegible]
```

Web log

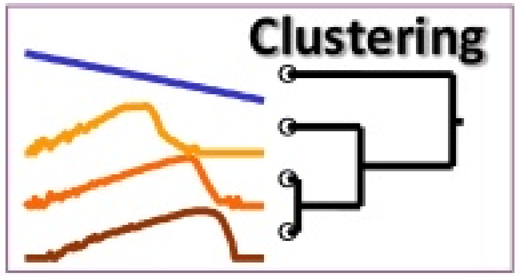


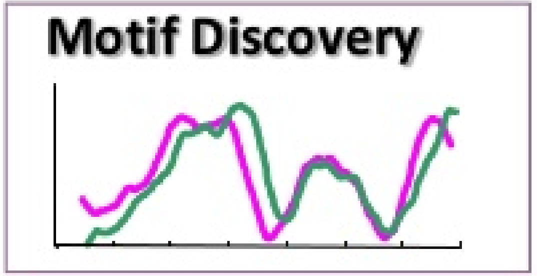
EEG

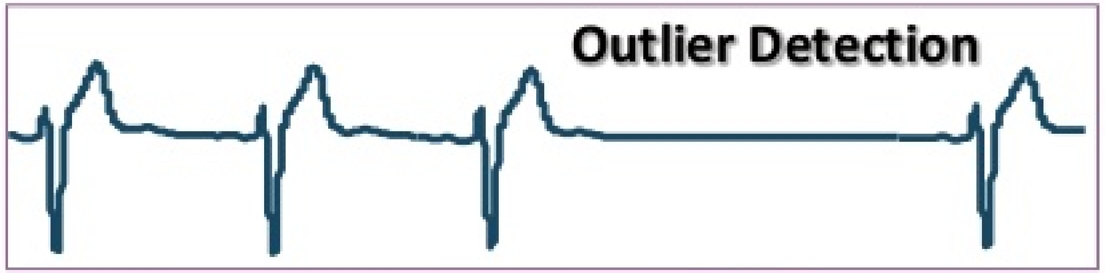
Stock price

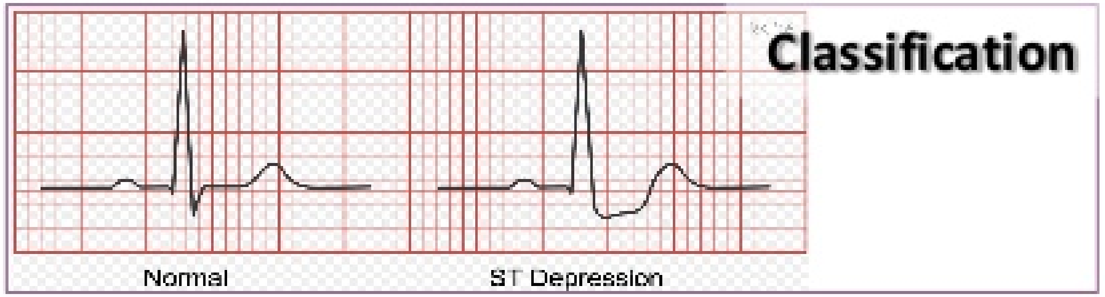
- How to deal with billions of time series?

# Almost all Time Series Data Mining Tasks rely on **Similarity Query**

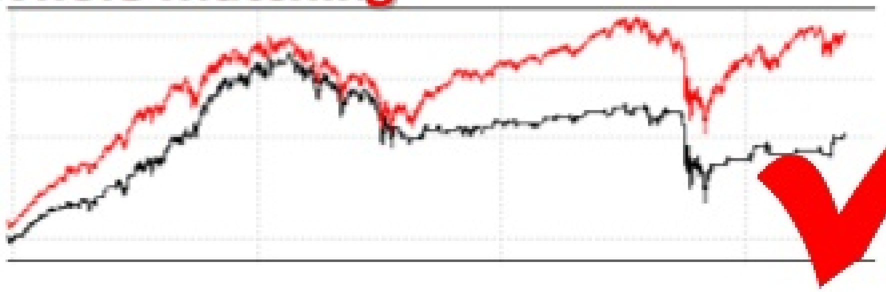

Clustering


Motif Discovery

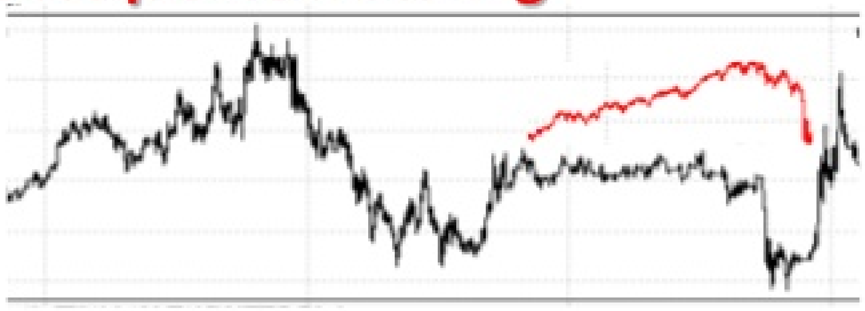

Outlier Detection


Classification

Whole Matching



Subsequence Matching



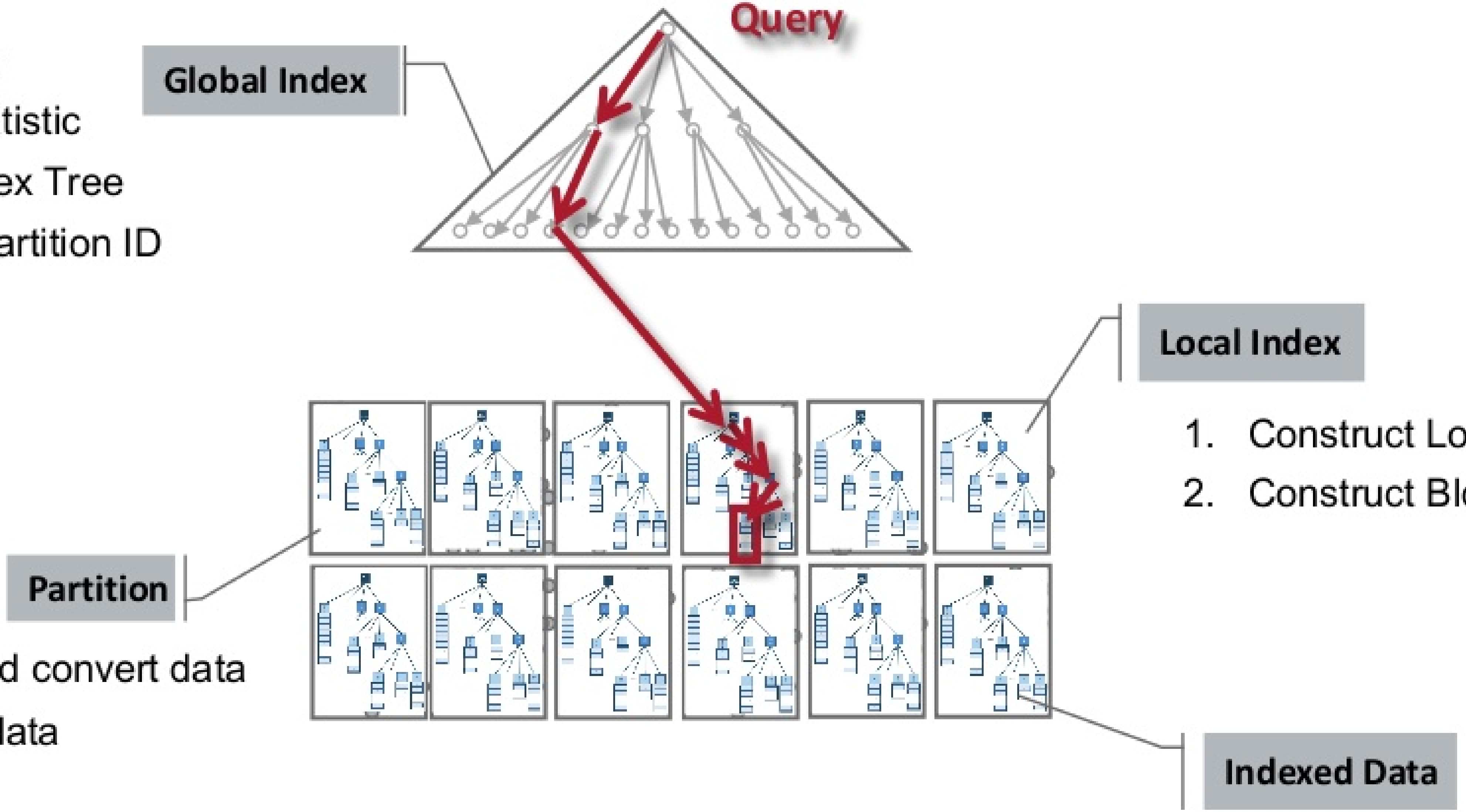
Esling, Philippe, and Carlos Agon. "Time-series data mining." *ACM (CSUR)* 45.1 (2012): 12.

# Spark-ITS

- A new **Index Tree** and an effective **Signature** to simplify the cardinality conversion and keep better similarity
- A **Distributed Index Framework** to support **large-scale** time series dataset
- Efficient algorithms for **Exact Match** and **kNN Approximate** queries process

# Spark-ITS Overview

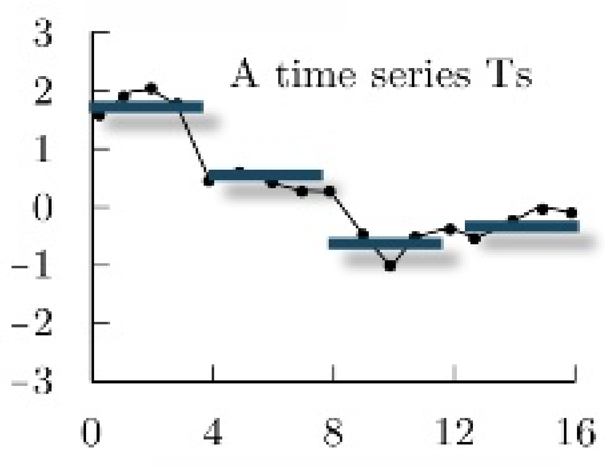
1. Sampling
2. Node Statistic
3. Build Index Tree
4. Assign Partition ID



1. Construct Local Structure
2. Construct Bloom Filter

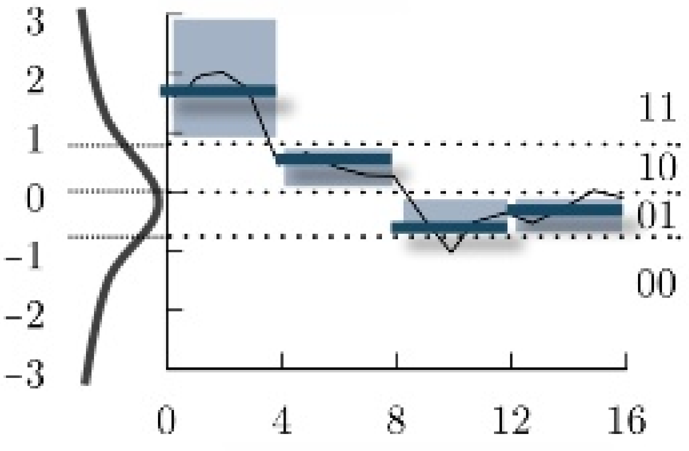
1. Read and convert data
2. Shuffle data

# Background: iSAX Representation



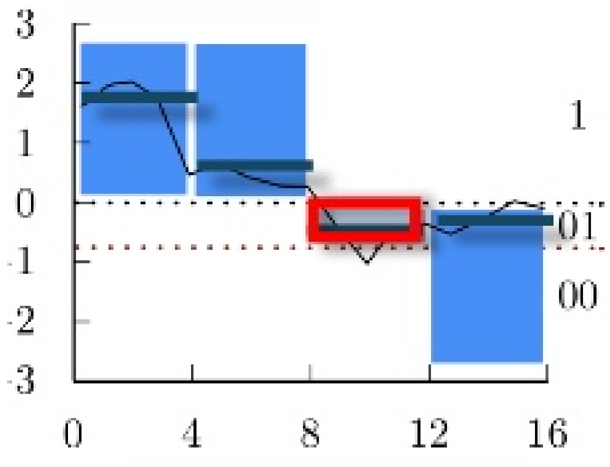
A time series of length 16

PAA representation with 4 segments



SAX representation with 4 segments and *cardinality* 4

[11,10,01,00]



iSAX representation with 4 segments and *variable cardinality*

$[1_2, 1_2, \mathbf{01_4}, 0_2]$

PAA: Piecewise Aggregate Approximation

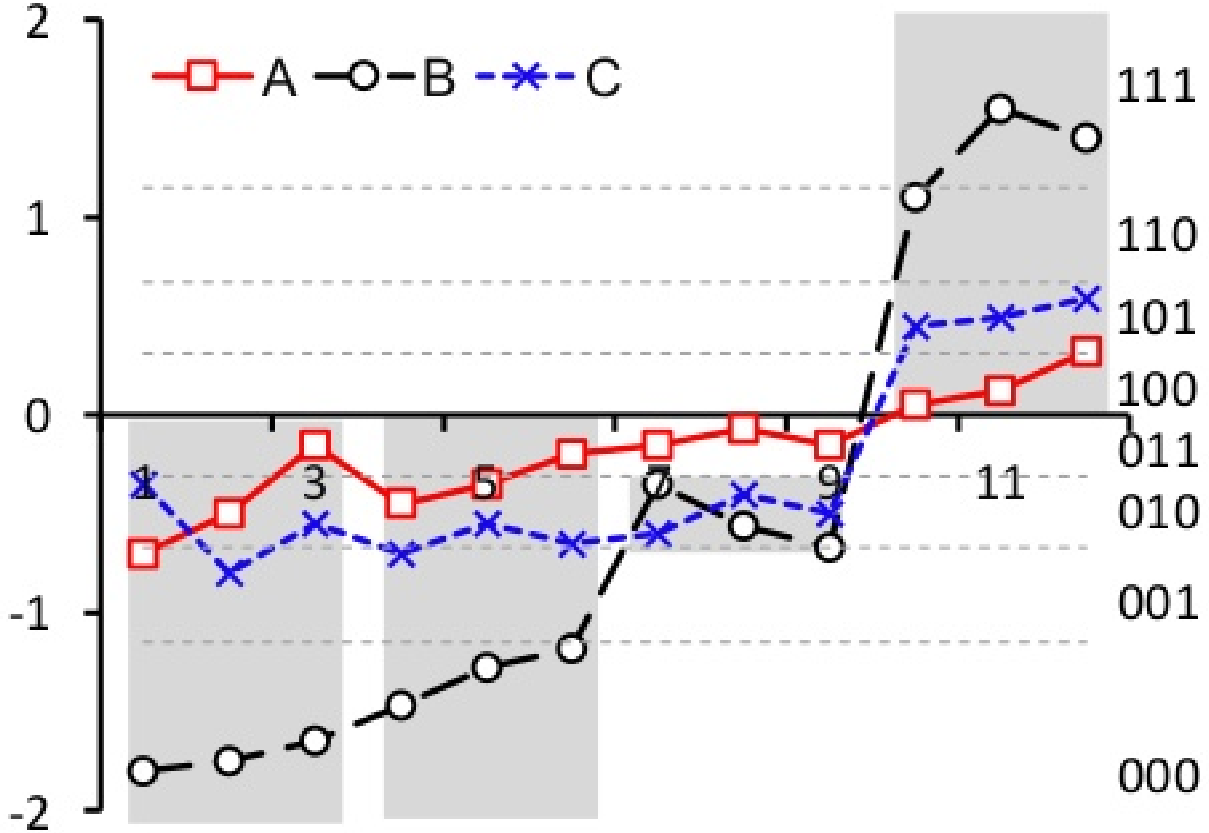
iSAX: indexable Symbolic Aggregate approXimation

Shieh, Jin, and Eamonn Keogh. "iSAX: indexing and mining terabyte sized time series." *SIGKDD* ACM, 2008.

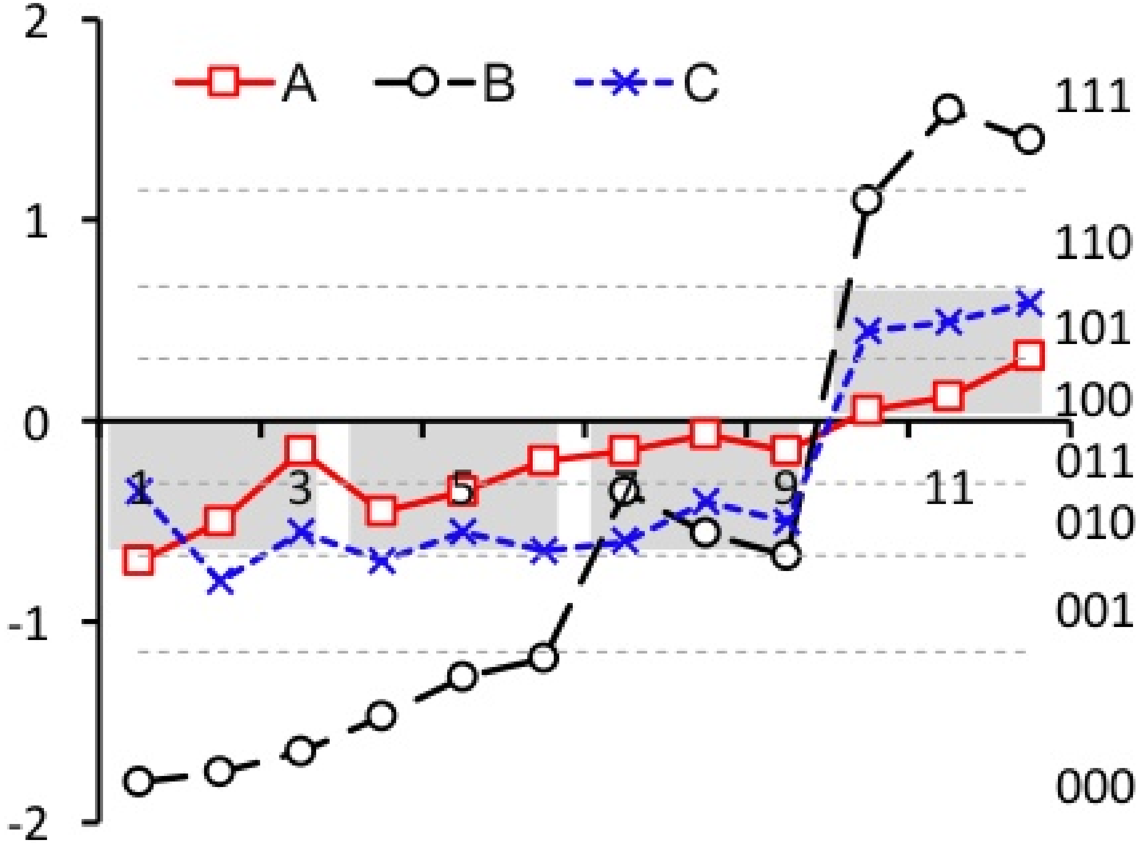
Camerra, A., Palpanas, T., Shieh, J., & Keogh, E. "iSAX 2.0: Indexing and mining one billion time series." ICDM, 2010

# Word-level Similarity

**State-of-the-art: Character-level Similarity**



**Proposed: Word-level Similarity**



**A: $[0_1, 0_1, 011_3, 1_1]$**
**B: $[0_1, 0_1, 010_3, 1_1]$**
**C: $[0_1, 0_1, 010_3, 1_1]$**

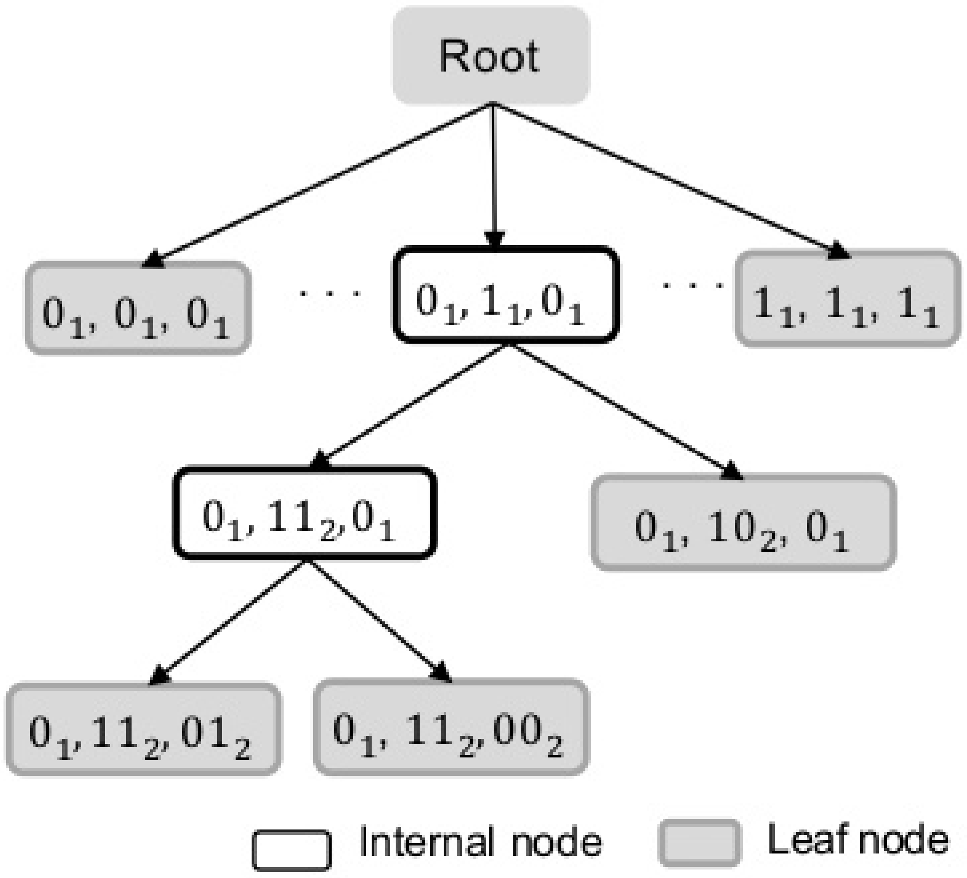
**B** and **C** are similar

**A: $[01_2, 01_2, 01_2, 10_2]$**
**B: $[00_2, 00_2, 01_2, 11_2]$**
**C: $[01_2, 01_2, 01_2, 10_2]$**

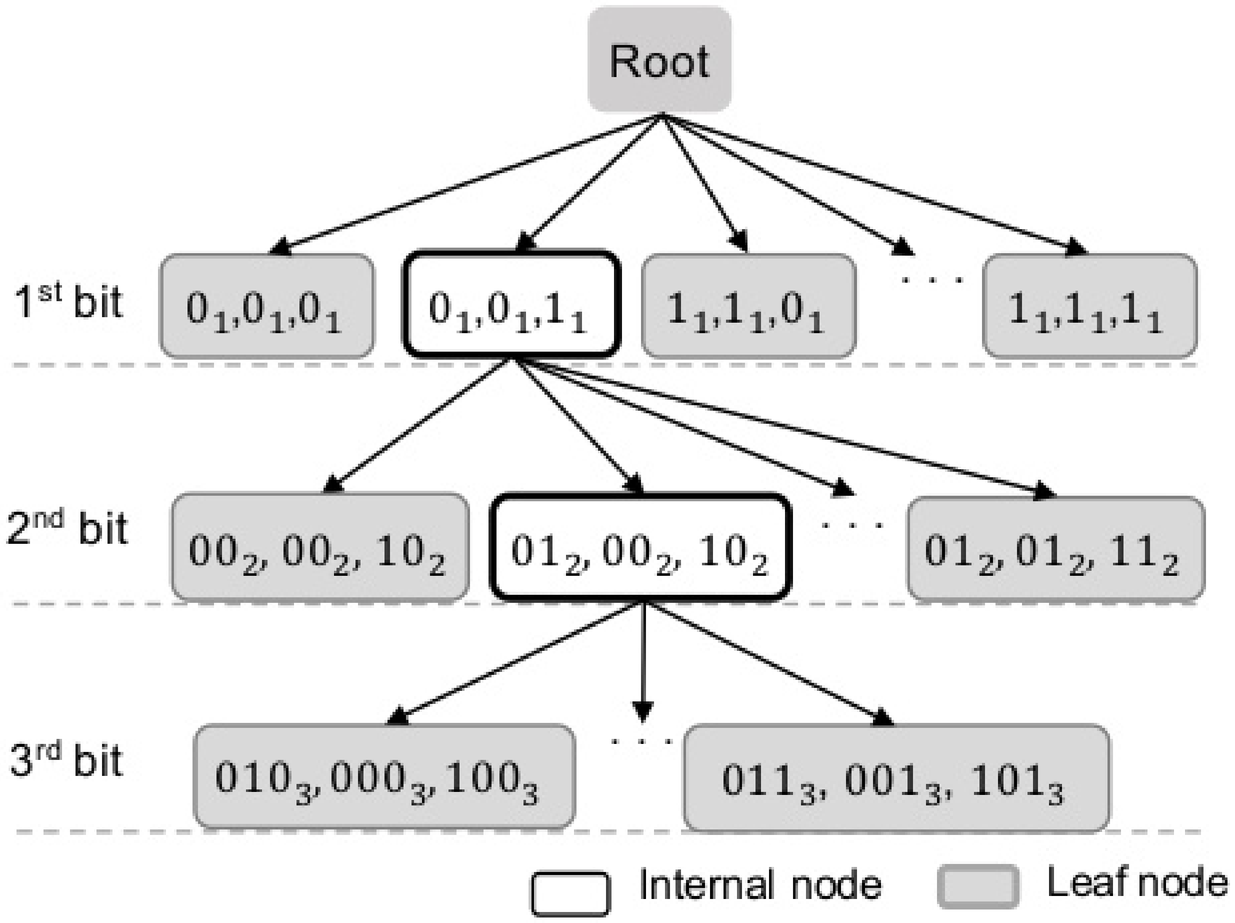
**A** and **C** are similar

# New Index Tree Supports Word-level Similarity

**State-of-the-art: iSAX Binary Tree**



**Proposed: iSAX-T K-ary Tree**



# iSAX-T(Transpose) Signature

**Time series:**

**[1100, 1101, 0110, 0001]**

$$\begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \xrightarrow{\text{Transpose}} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix} \xrightarrow{\text{Hex}} \begin{bmatrix} C \\ E \\ 2 \\ 5 \end{bmatrix}$$

| | | | | | iSAX-T |
|---|---|---|---|---|---|
| **SAX(T,4,16) =** | **{1100,** | **1101,** | **0110,** | **0001}** | **= CE25** |
| **SAX(T,4,8) =** | **{110,** | **110,** | **011,** | **000 }** | **= CE2** |
| **SAX(T,4,4) =** | **{11,** | **11,** | **01,** | **00 }** | **= CE** |
| **SAX(T,4,2) =** | **{1,** | **1,** | **0,** | **0 }** | **= C** |

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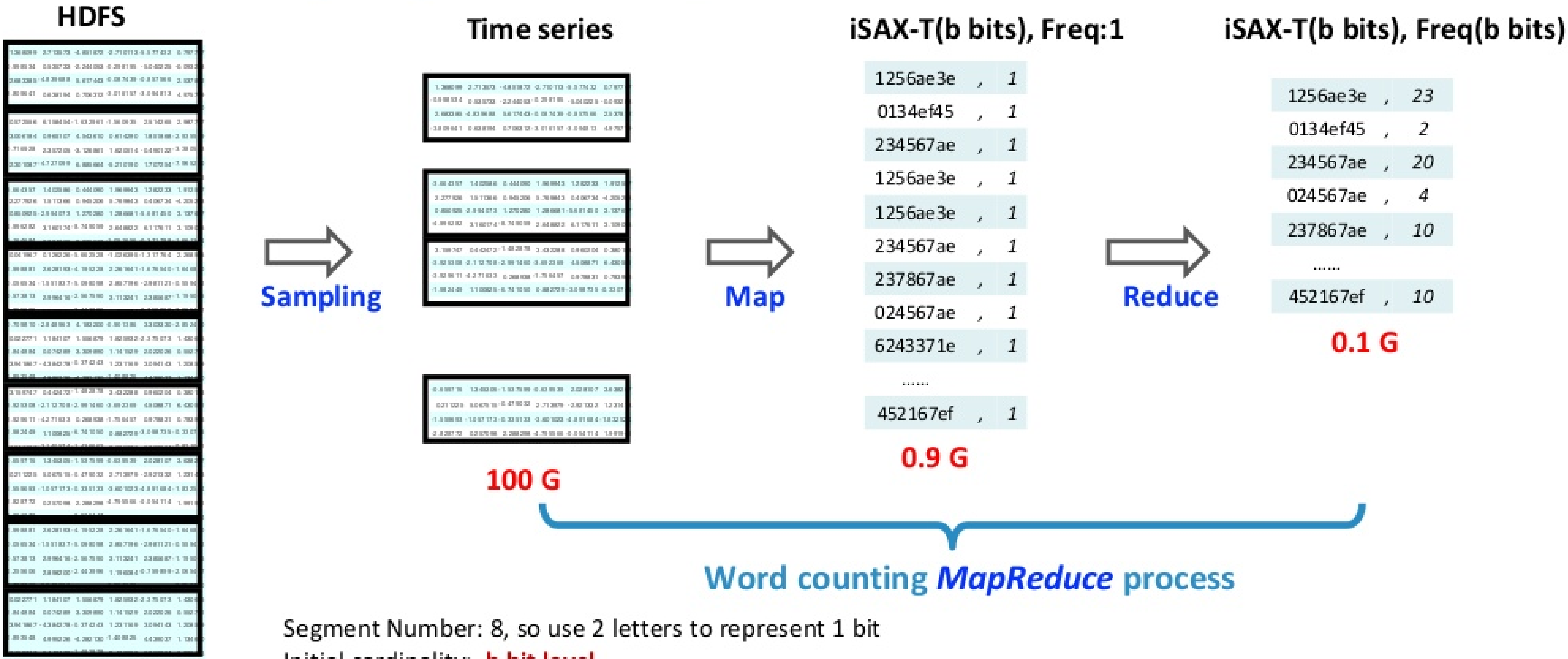
# Global Index[1/4]: Sampling



iSAX-T(b bits), Freq:1

| | |
|---|---|
| 1256ae3e , | 1 |
| 0134ef45 , | 1 |
| 234567ae , | 1 |
| 1256ae3e , | 1 |
| 1256ae3e , | 1 |
| 234567ae , | 1 |
| 237867ae , | 1 |
| 024567ae , | 1 |
| 6243371e , | 1 |
| …… | |
| 452167ef , | 1 |

iSAX-T(b bits), Freq(b bits)

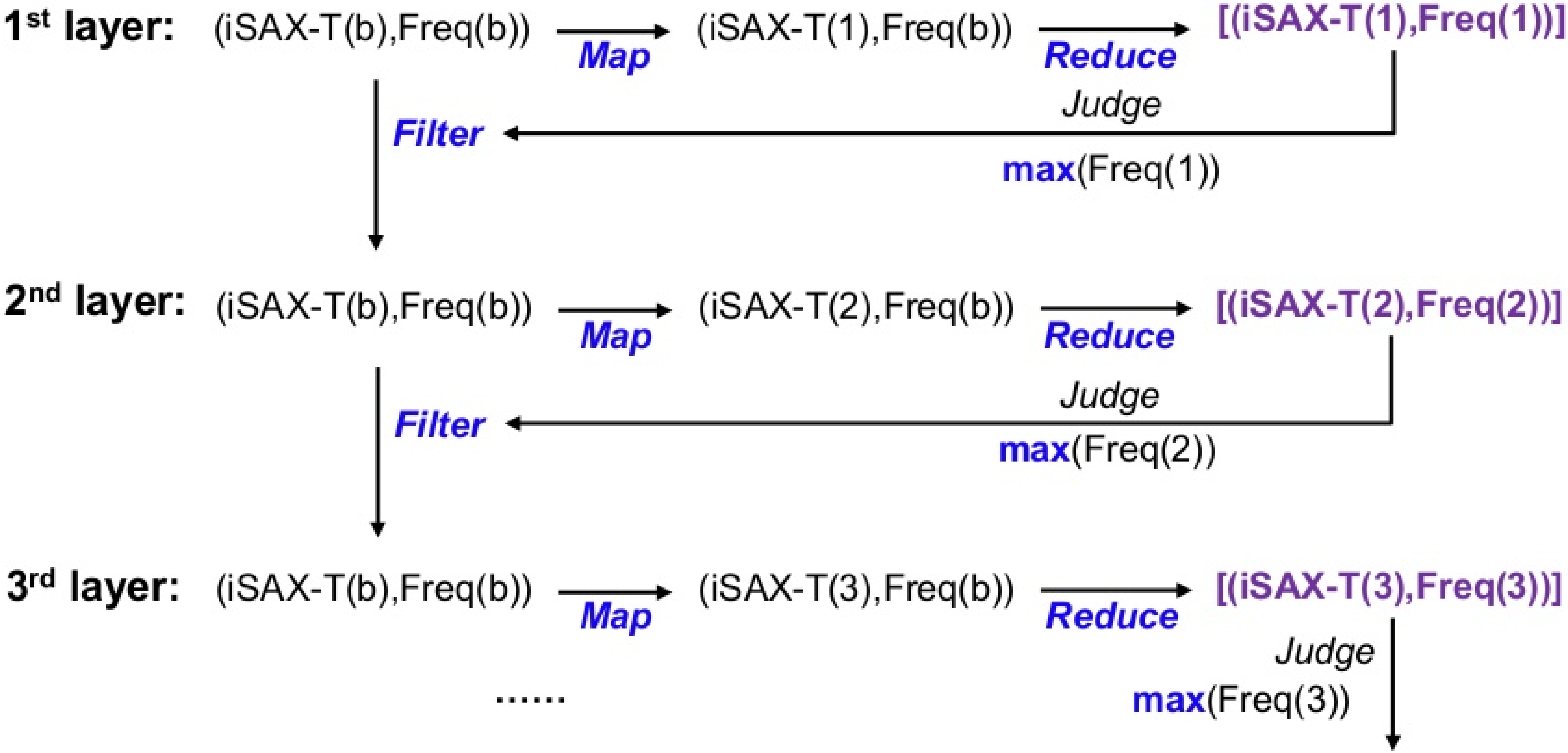
| | |
|---|---|
| 1256ae3e , | 23 |
| 0134ef45 , | 2 |
| 234567ae , | 20 |
| 024567ae , | 4 |
| 237867ae , | 10 |
| …… | |
| 452167ef , | 10 |

Segment Number: 8, so use 2 letters to represent 1 bit

Initial cardinality: **b bit level**

The data size is based on 1 billion time series with 256 length

# Global Index[2/4]: Node Statistic



1st layer: (iSAX-T(b),Freq(b)) → *Map* → (iSAX-T(1),Freq(b)) → *Reduce* → [(iSAX-T(1),Freq(1))]

*Judge* max(Freq(1)) → *Filter*

2nd layer: (iSAX-T(b),Freq(b)) → *Map* → (iSAX-T(2),Freq(b)) → *Reduce* → [(iSAX-T(2),Freq(2))]

*Judge* max(Freq(2)) → *Filter*

3rd layer: (iSAX-T(b),Freq(b)) → *Map* → (iSAX-T(3),Freq(b)) → *Reduce* → [(iSAX-T(3),Freq(3))]

*Judge* max(Freq(3))

……

# Global Index[3/4]: Build Tree

**1st layer (iSAX-T, Freq)**

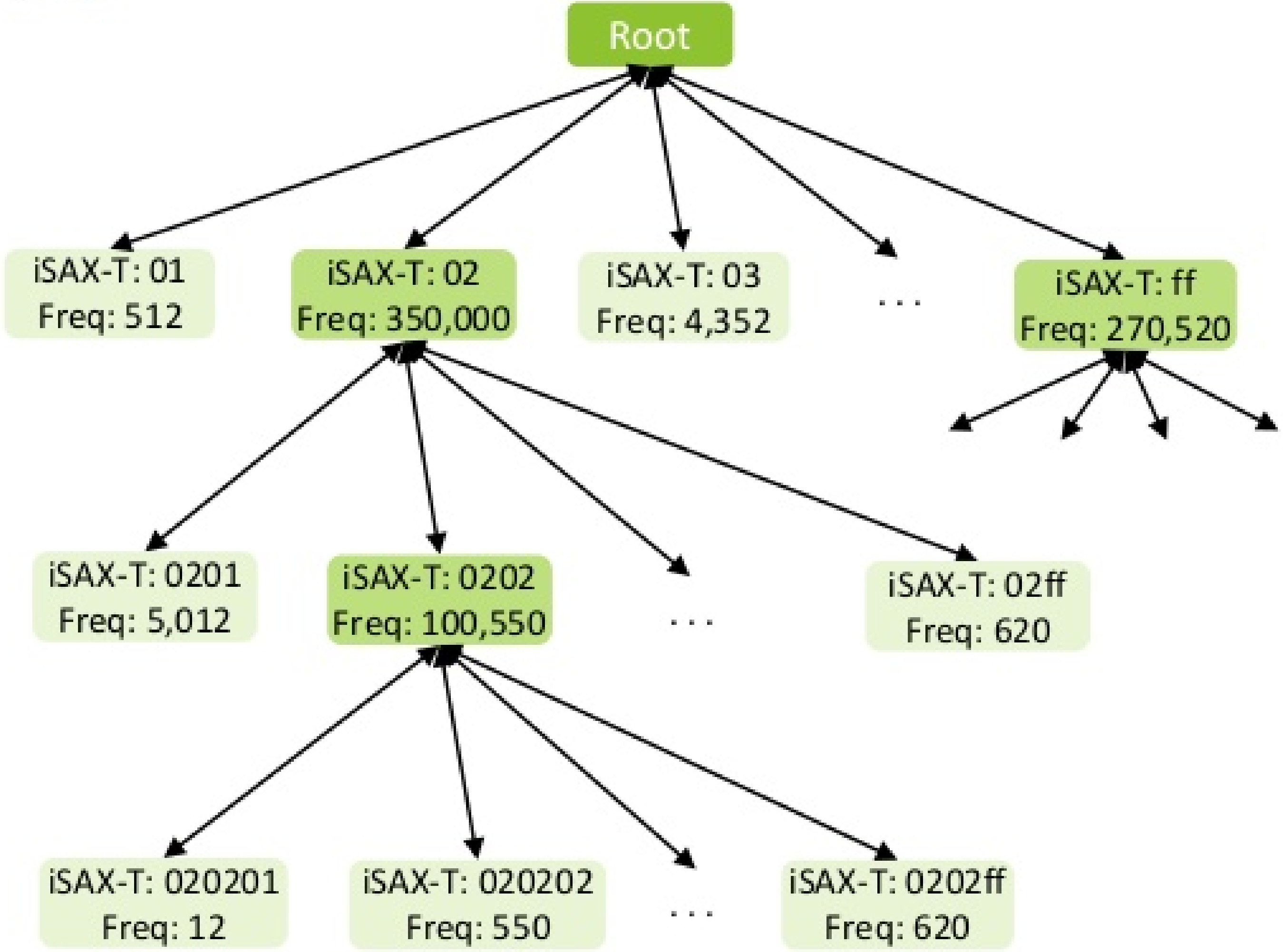
- ("01", 512)
- ("02", 355,000)
- ....
- ("ff", 270,520)

**2nd layer (iSAX-T, Freq)**

- ("0201", 5,012)
- ("0202", 100,550)
- ....
- ("ffff", 10,520)

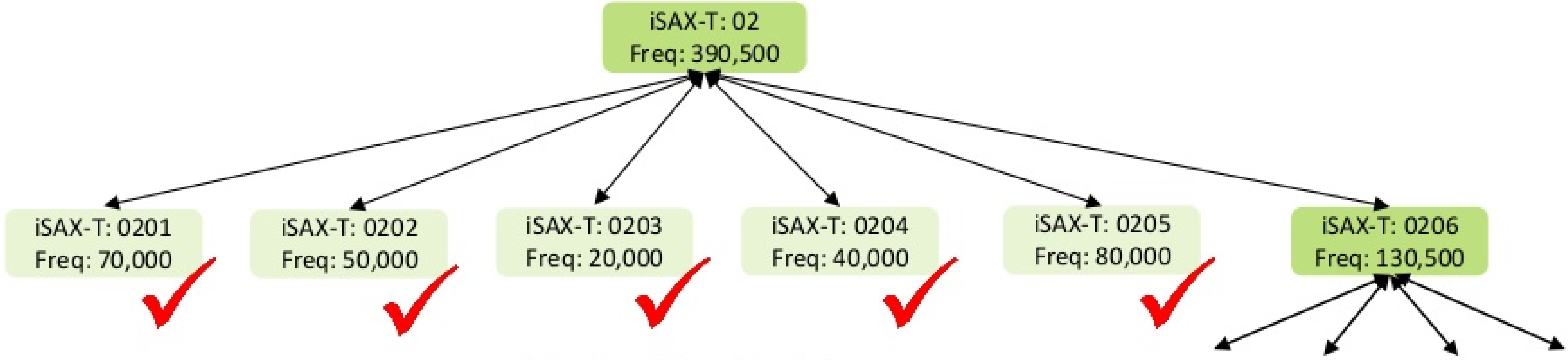
**3rd layer (iSAX-T, Freq)**

- ("020201", 12)
- ("020202", 550)
- ....
- ("0202ff", 620)



Segment number: 8
Partition Capacity: 100,000

# Global Index[4/4]: Assign Partition Id to Leaf Nodes



iSAX-T: 02
Freq: 390,500

iSAX-T: 0201
Freq: 70,000 ✓

iSAX-T: 0202
Freq: 50,000 ✓

iSAX-T: 0203
Freq: 20,000 ✓

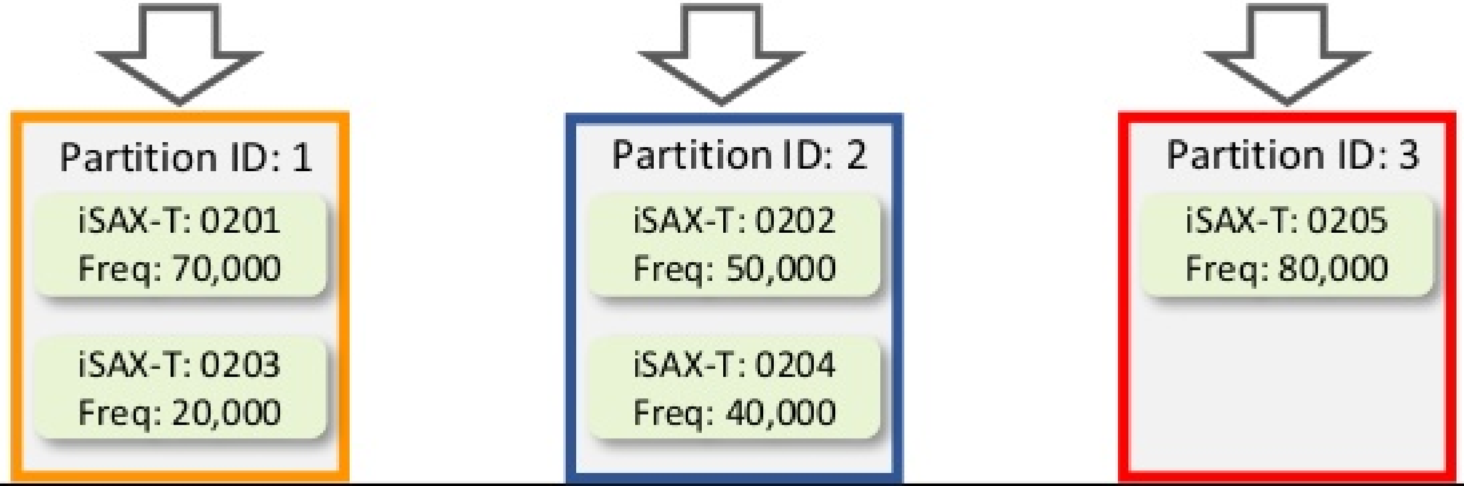
iSAX-T: 0204
Freq: 40,000 ✓

iSAX-T: 0205
Freq: 80,000 ✓

iSAX-T: 0206
Freq: 130,500

**Bin Packing Problem:**

How to fit a set of nodes in the smallest numbers of partitions?



Partition ID: 1
iSAX-T: 0201
Freq: 70,000
iSAX-T: 0203
Freq: 20,000

Partition ID: 2
iSAX-T: 0202
Freq: 50,000
iSAX-T: 0204
Freq: 40,000

Partition ID: 3
iSAX-T: 0205
Freq: 80,000

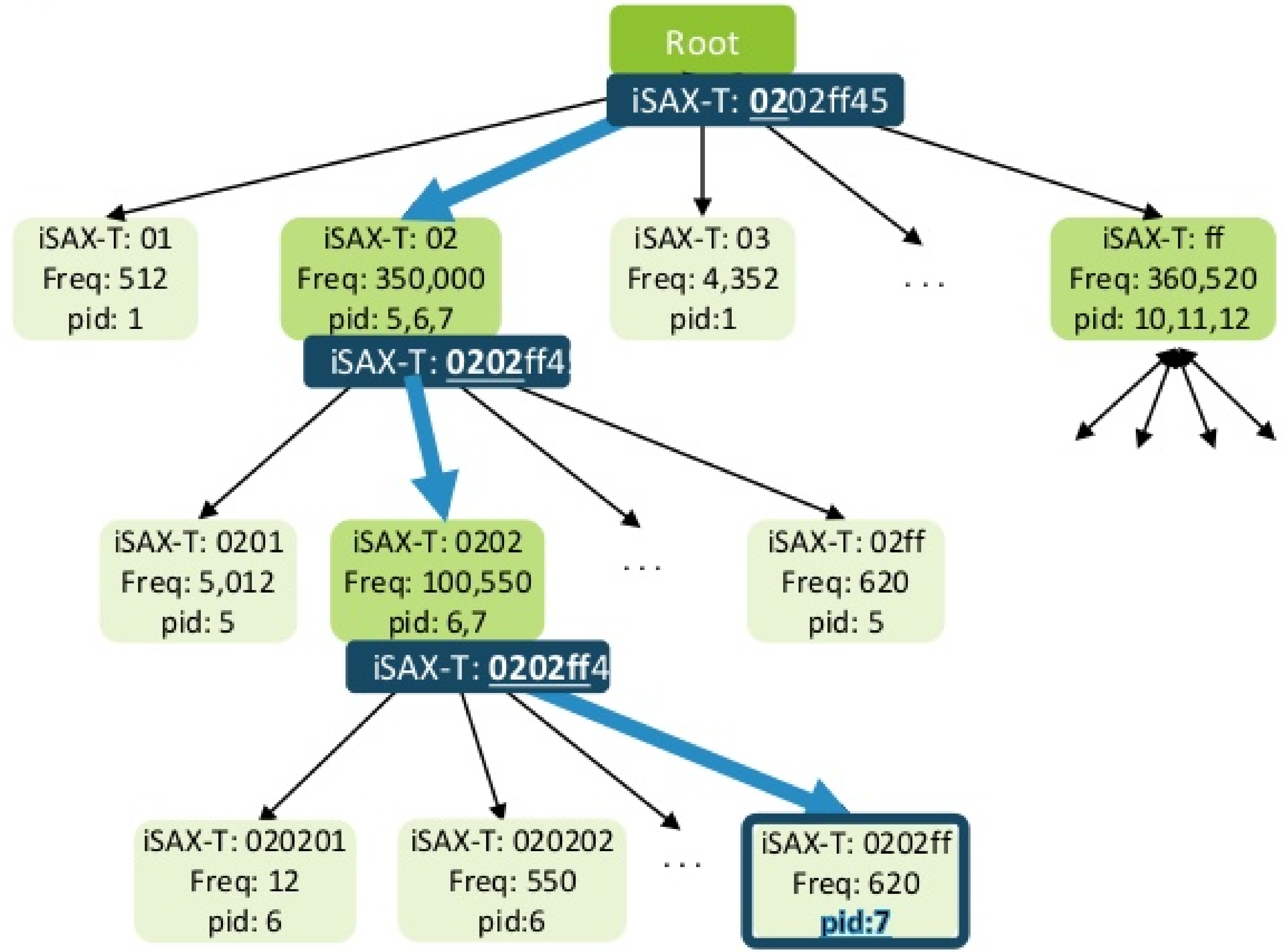
Partition capacity: 100,000

# Repartition: Wrap Global Index as the Partitioner

A Time Series

iSAX-T: 0202ff45
TS: [0.34, 0.31, 1.14...]

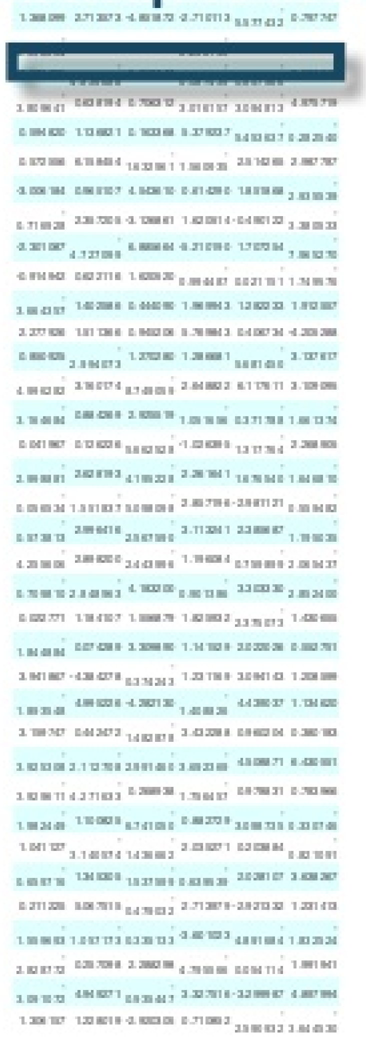
pid:7



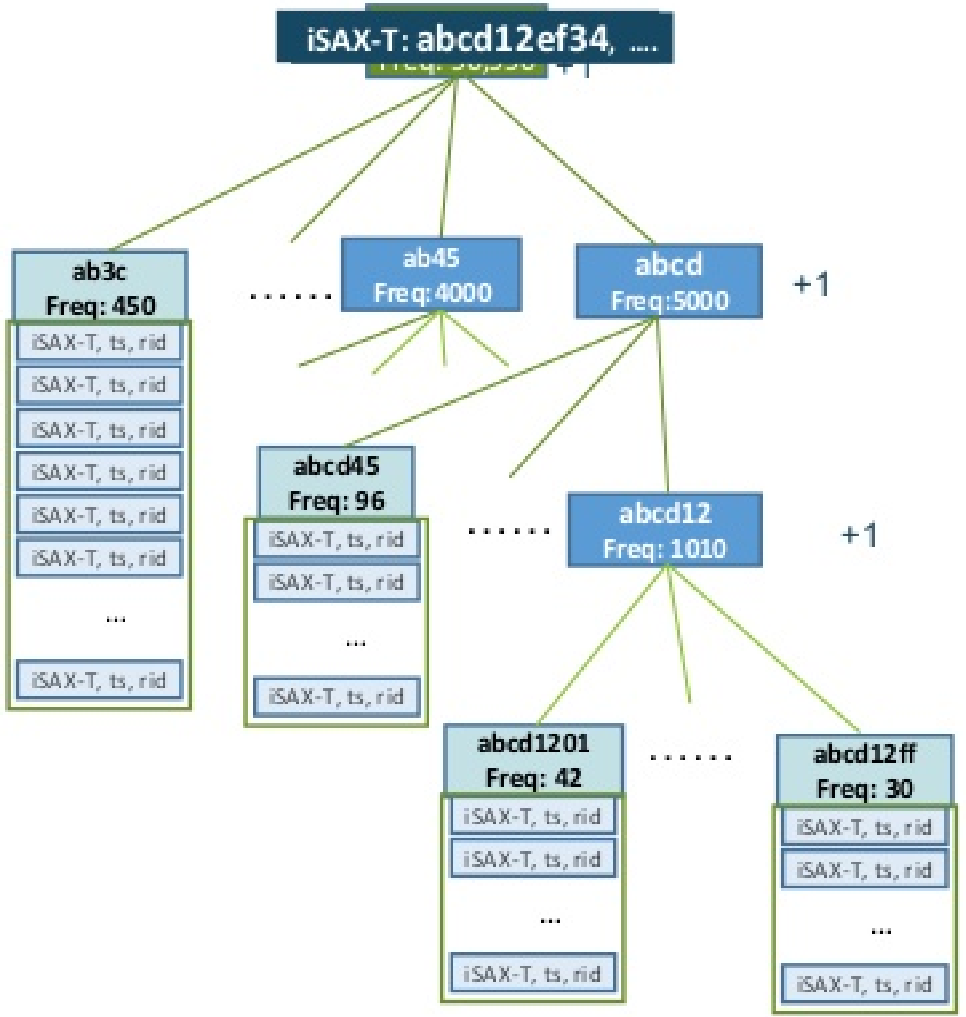
Root
iSAX-T: 0202ff45
iSAX-T: 01 Freq: 512 pid: 1
iSAX-T: 02 Freq: 350,000 pid: 5,6,7
iSAX-T: 03 Freq: 4,352 pid:1
. . .
iSAX-T: ff Freq: 360,520 pid: 10,11,12
iSAX-T: 0202ff4
iSAX-T: 0201 Freq: 5,012 pid: 5
iSAX-T: 0202 Freq: 100,550 pid: 6,7
. . .
iSAX-T: 02ff Freq: 620 pid: 5
iSAX-T: 0202ff4
iSAX-T: 020201 Freq: 12 pid: 6
iSAX-T: 020202 Freq: 550 pid:6
. . .
iSAX-T: 0202ff Freq: 620 pid:7

# Local Index: Construction Within Each Partition

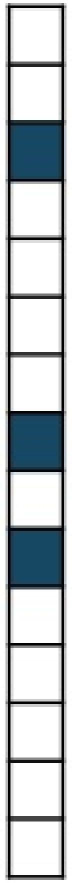
Time series
in one partition



Local Index



Bloom Filter



Partition capacity: 100,000
Node split threshold: 1000
Segment Number: 8

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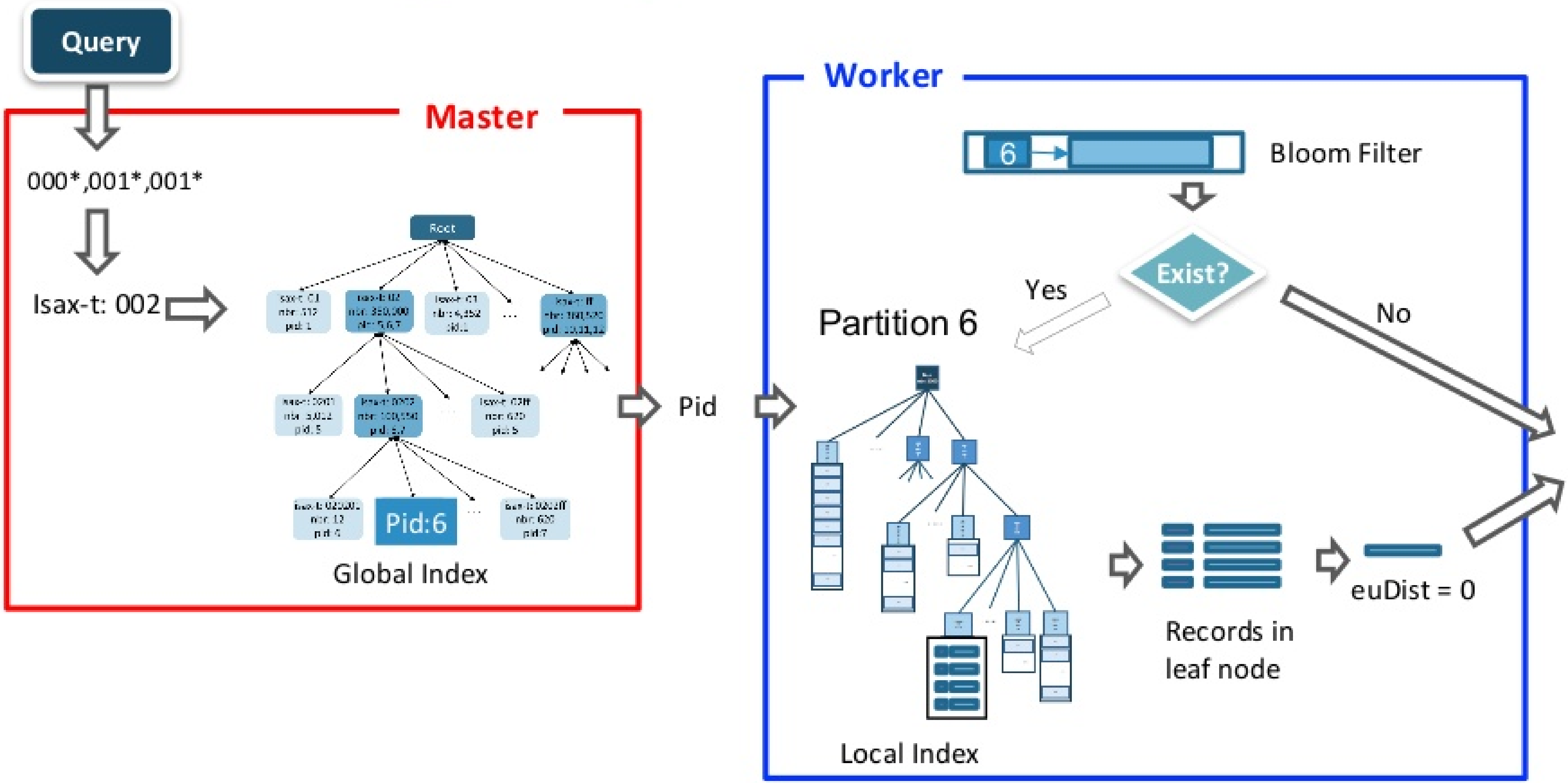
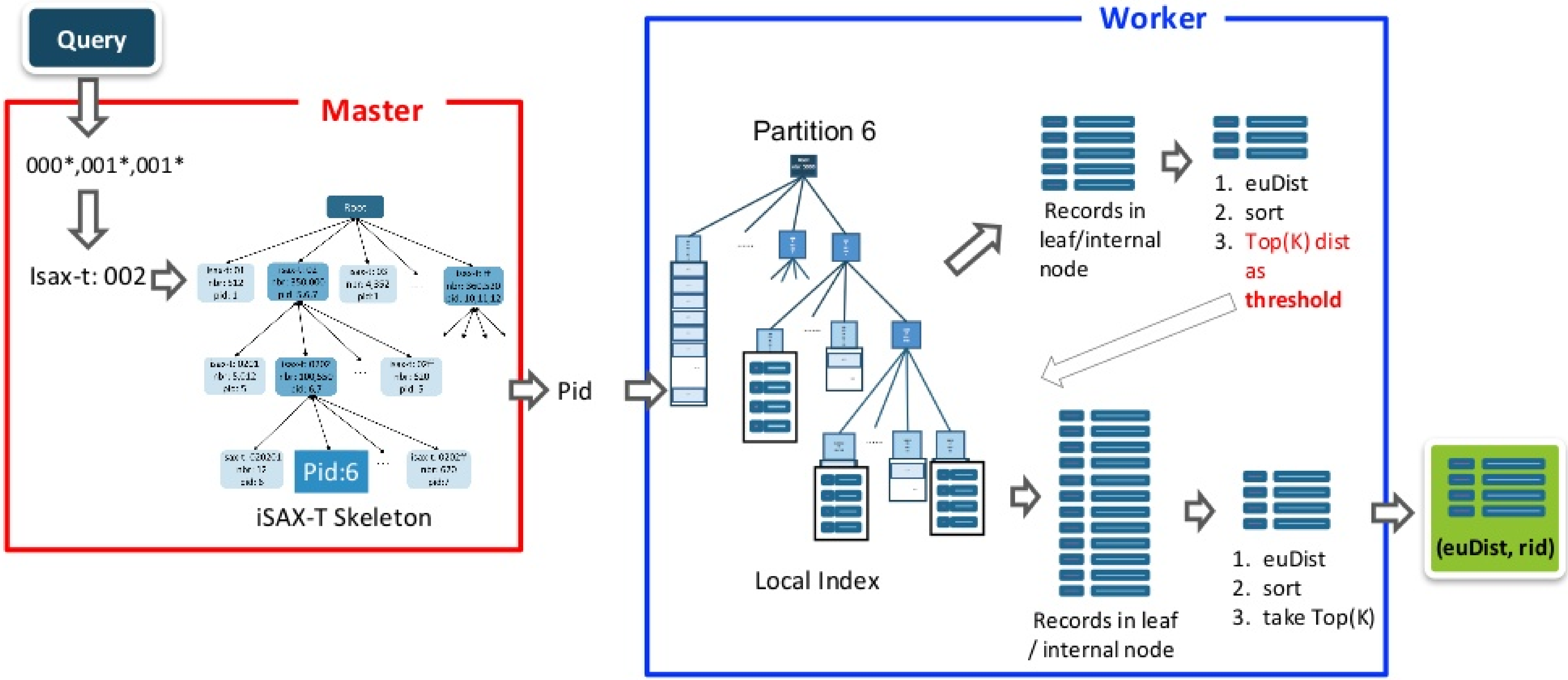
# Exact Matching Query



# KNN Approximate Query: One Partition Access



Query

Master

000*,001*,001*

Isax-t: 002

iSAX-T Skeleton

Pid

Worker

Partition 6

Local Index

Records in leaf/internal node

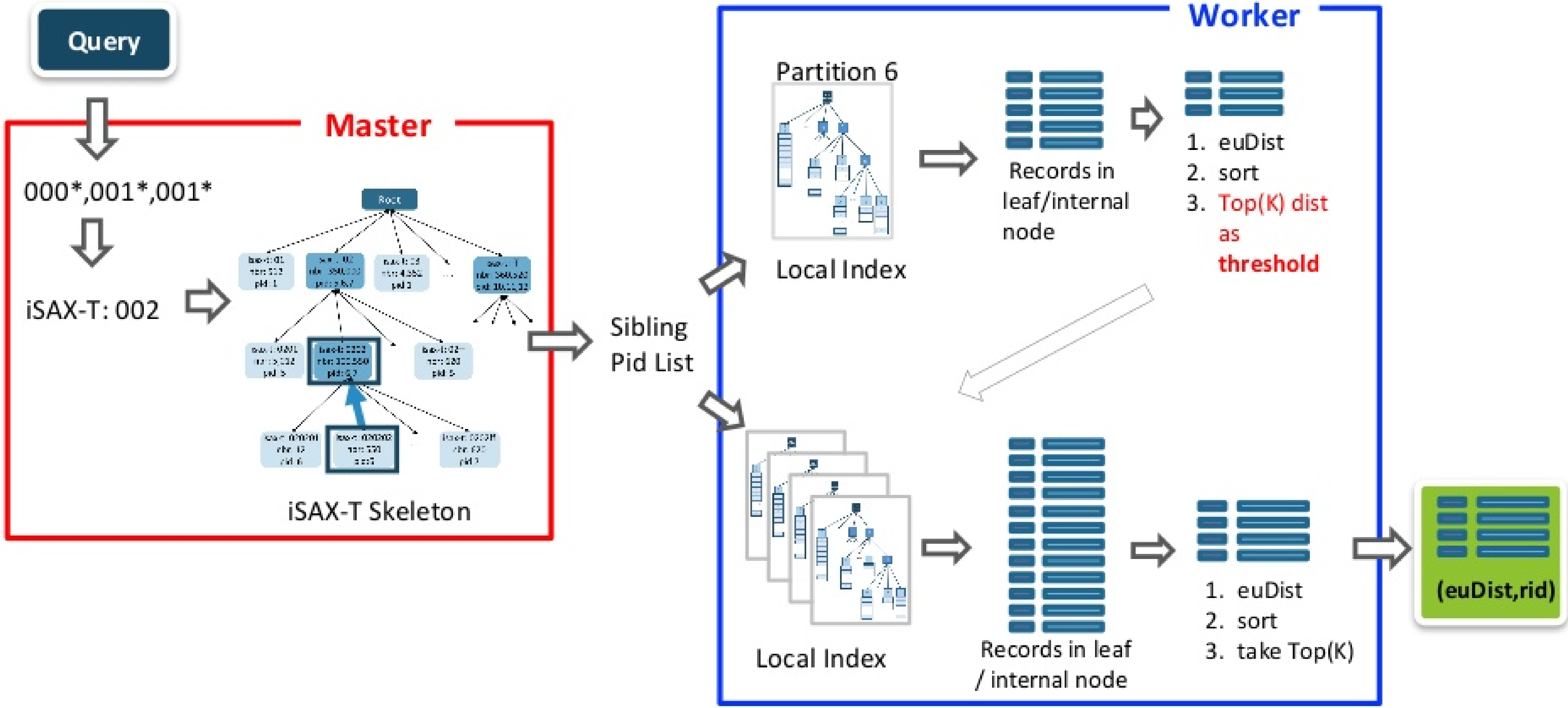
1. euDist
2. sort
3. Top(K) dist as threshold

Records in leaf / internal node

1. euDist
2. sort
3. take Top(K)

(euDist, rid)

# KNN Approximate Query: Multi-Partitions Access



Query

Master

000*,001*,001*

iSAX-T: 002

iSAX-T Skeleton

Sibling Pid List

Worker

Partition 6

Local Index

Records in leaf/internal node

1. euDist
2. sort
3. Top(K) dist as threshold

Local Index

Records in leaf / internal node

1. euDist
2. sort
3. take Top(K)

(euDist,rid)

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# Experimental Setup

| HW&SW | Configuration |
|---|---|
| Spark | 2.0.2, Standalone mode |
| Hadoop | 2.7.3 |
| Platform | Ubuntu 16.04. LTS |
| HW | 2 nodes, each node consist of 56 Xeon E5 processors, 500G RAM, 7TB SATA hard drive |

| Dataset | Size | Length |
|---|---|---|
| Random Walk | 1 billion | 256 |
| Texmex[1] | 1 billion | 128 |
| DNA[2] | 200 million | 192 |
| Noaa Climate[3] | 200 million | 64 |

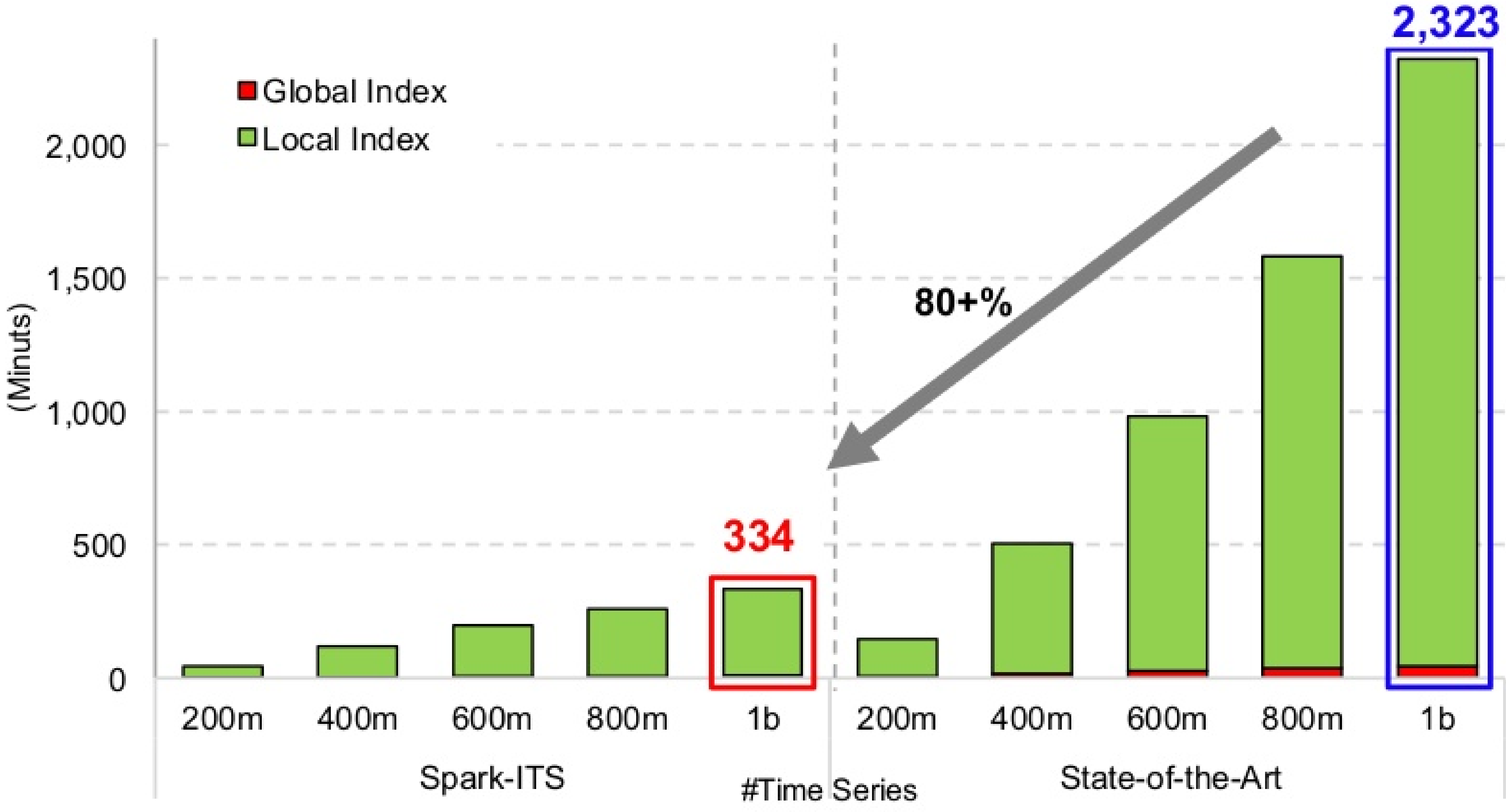
| | Baseline | Spark-ITS |
|---|---|---|
| Initial cardinality | 512 | 64 |
| Word length | 8 | 8 |
| Sampling percent | 10% | 10% |
| Leaf node split threshold of Local index | 1000 | 1000 |

**State-of-the-Art:** Yagoubi, Djamel-Edine, et al. "DPiSAX: Massively Distributed Partitioned iSAX." *ICDM 2017*
The initial cardinality of the baseline system is the default value and it needs a large initial value to guarantee enough bit level for binary split.

The dataset is normalized
Each point is saved as float format

Source:
1. http://corpus-texmex.irisa.fr/
2. https://genmone.ucsc.edu
3. https://www.ncdc.gov/

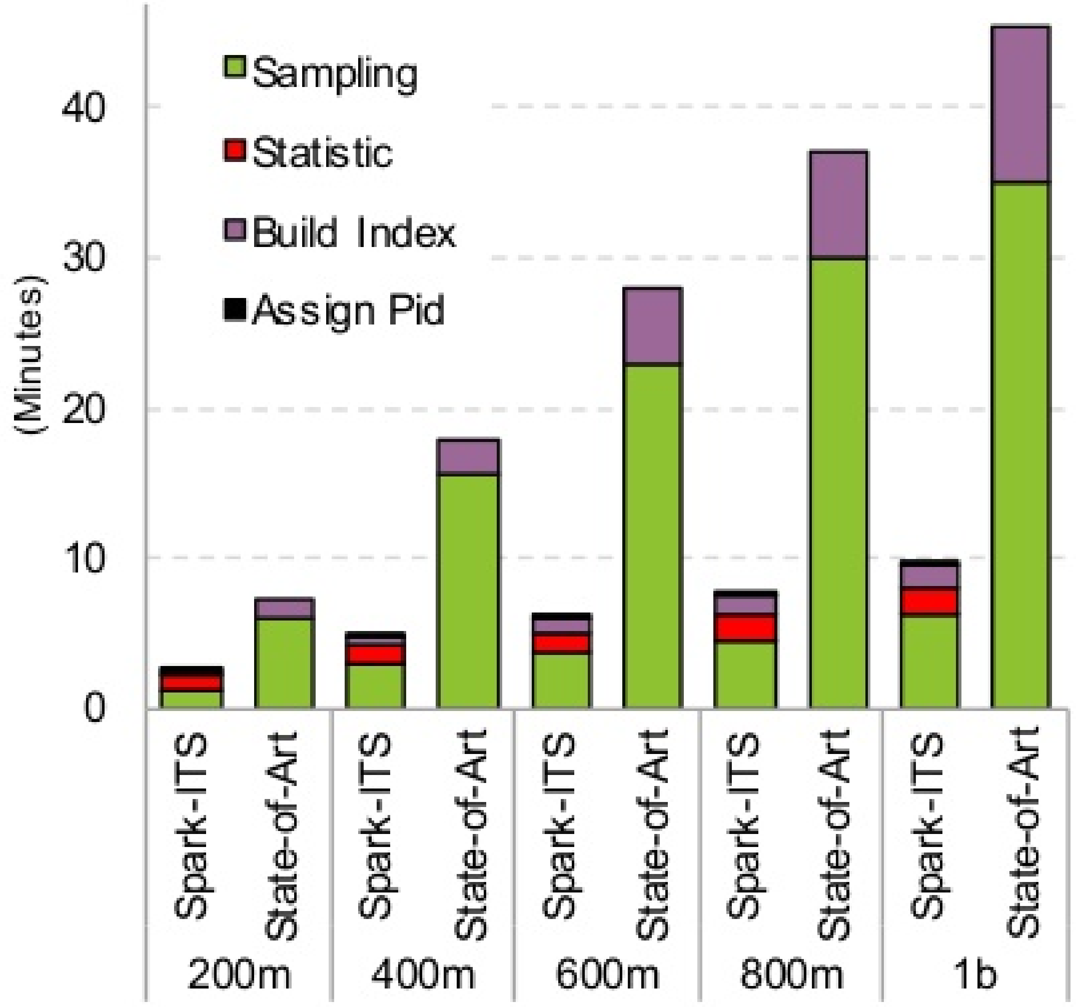
# Index Construction Time



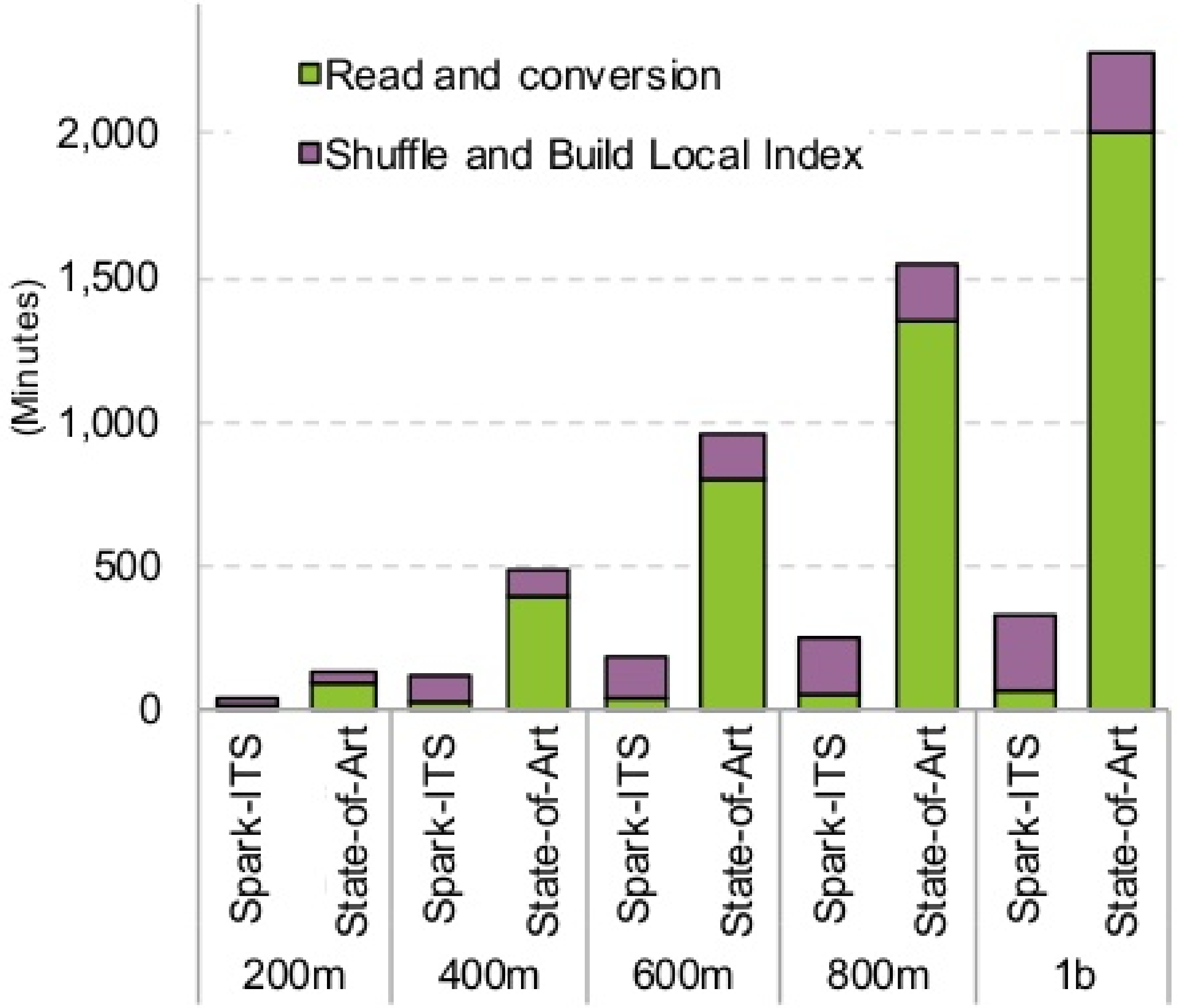
Dataset: Random Walk Benchmark

# Index Construction Time: Breakdown

## Global Index Time Breakdown

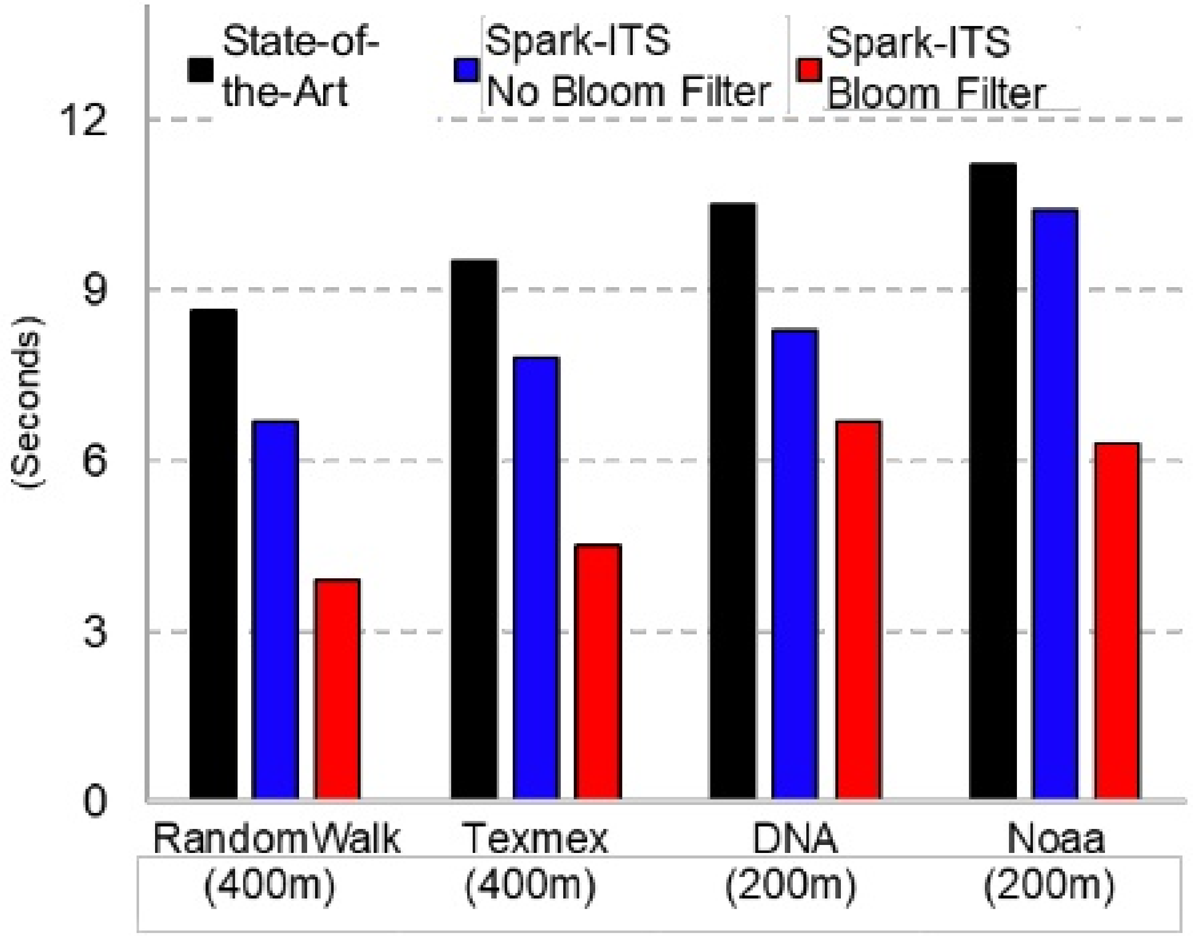


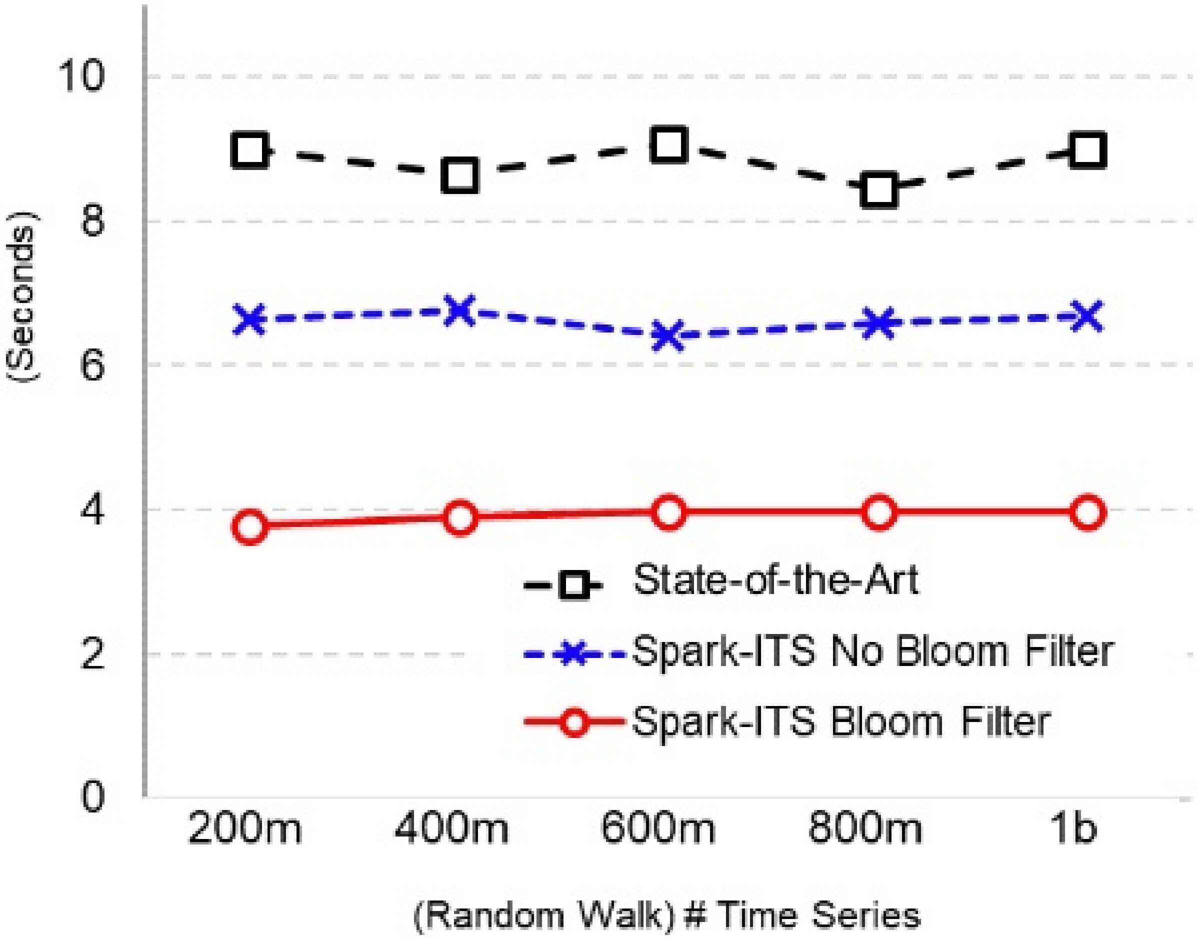
## Repartition and Local Index Time Breakdown



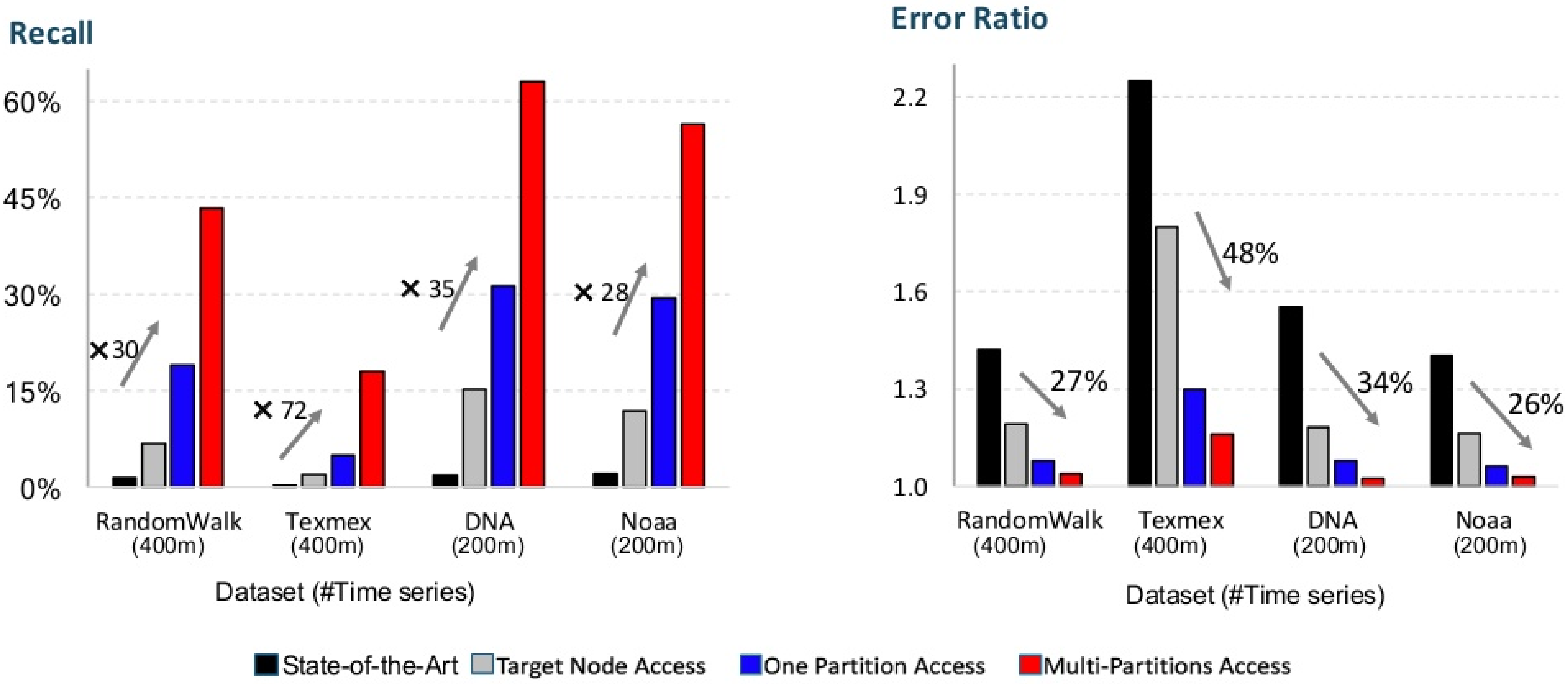
Dataset: Random Walk Benchmark

# Exact Matching Query





# kNN-Approximate Query Performance



# Conclusion

- Index Tree
  - Large fan-out decreases the depth of leaf nodes
  - Keeps better similarity at Word-level
  - The signature simplifies the conversion of cardinality
- Spark-ITS: Index Construction
  - Block-sampling and node statistic collection to fast build global index
  - Synchronously build local indices within a partition
  - Constructs Index faster 80+%.
- Spark-ITS: Query
  - Exact Matching:  the time decreases by 50%.
  - kNN approximate:  the accuracy increases more than 10 fold.

# Acknowledge Funding from...

Xianjin Tech Co., Ltd.

Saudi Arabian Cultural Mission

WPI Computer Science Dept.,

NSF CNS: 305258 II-EN

NSF CRI: 0551584