Dumpy: A Compact and Adaptive Index for Large Data Series Collections

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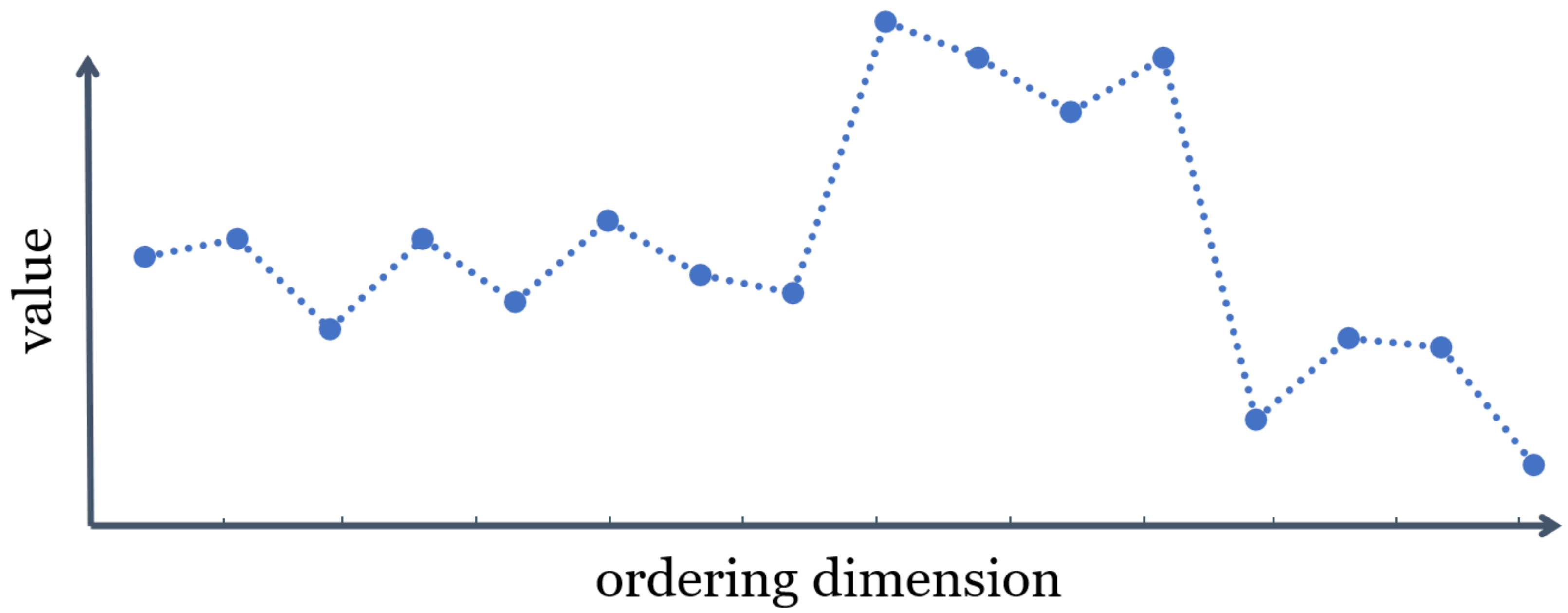
paper: https://helios2.mi.parisdescartes.fr/~themisp/publications/sigmod23-dumpy.pdf
video: https://files.atypon.com/acm/99f6febc21ad6c5a979f504caf188d9a
code: https://github.com/DSM-fudan/Dumpy

1-Data Series

- Sequence of points ordered along some dimension



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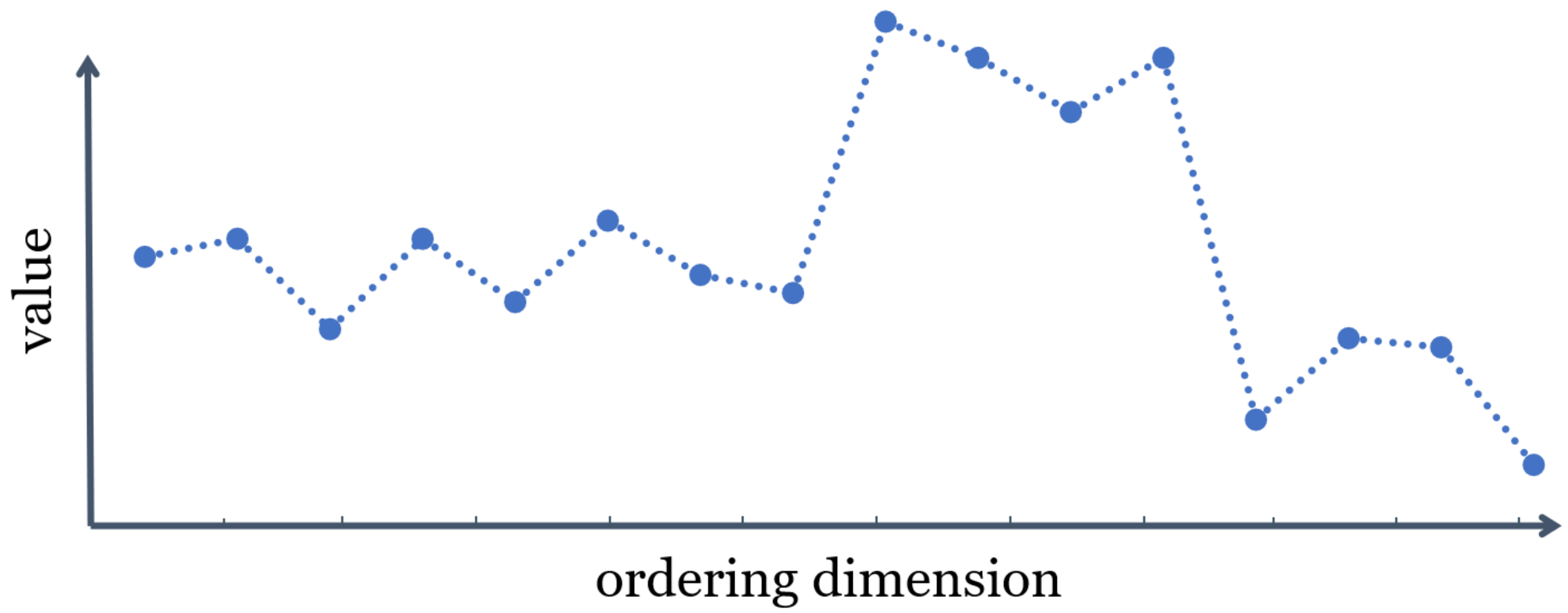
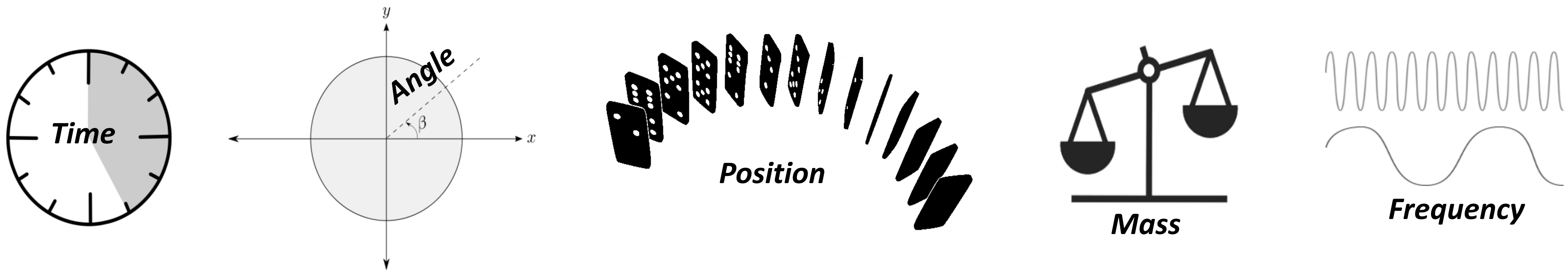
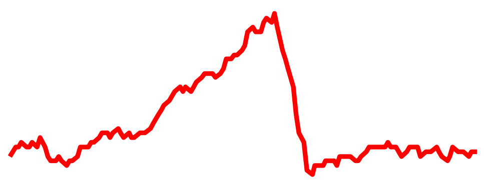




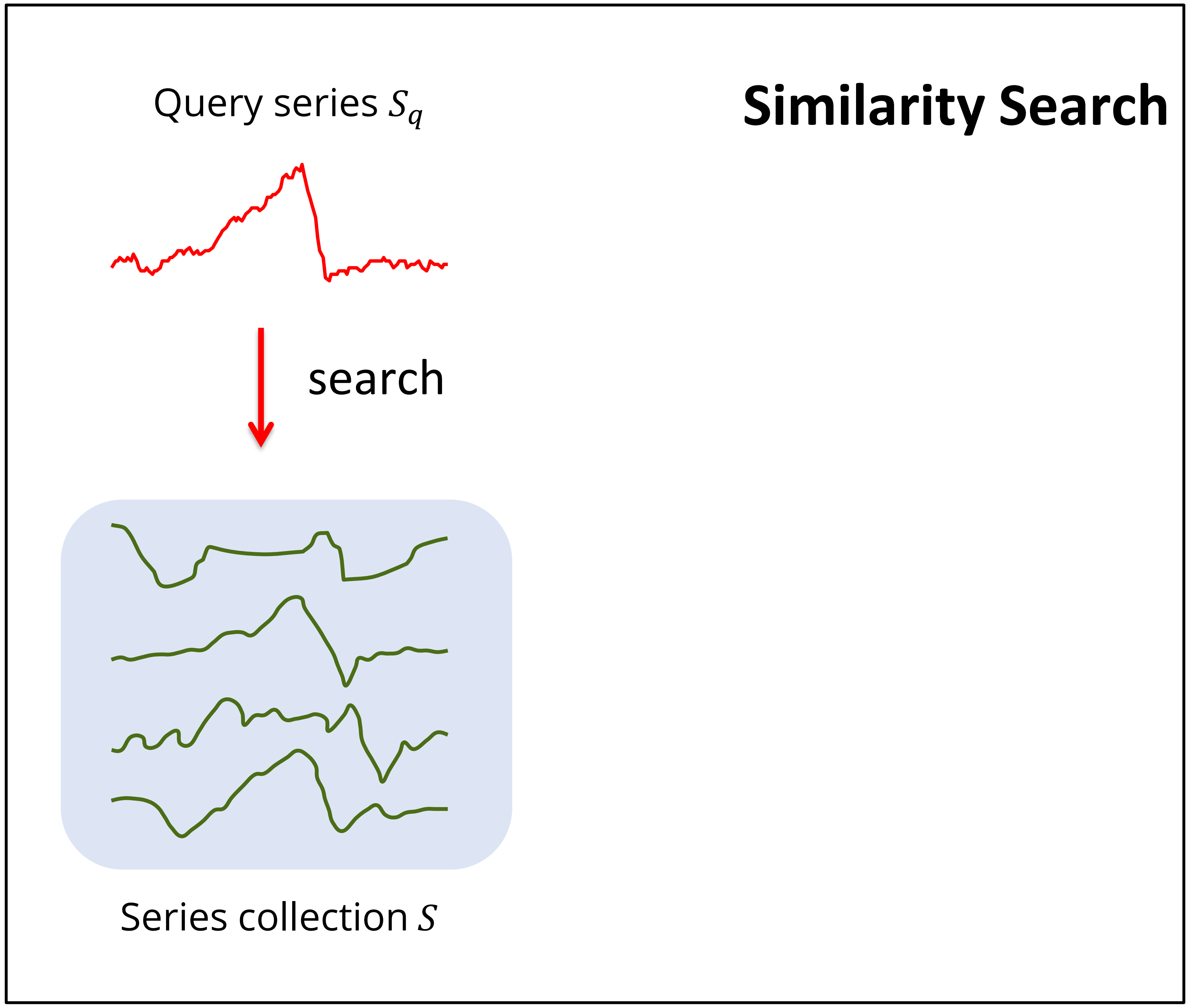
1-Data Series Similarity Search

Query series S_q



Similarity Search

1-Data Series Similarity Search



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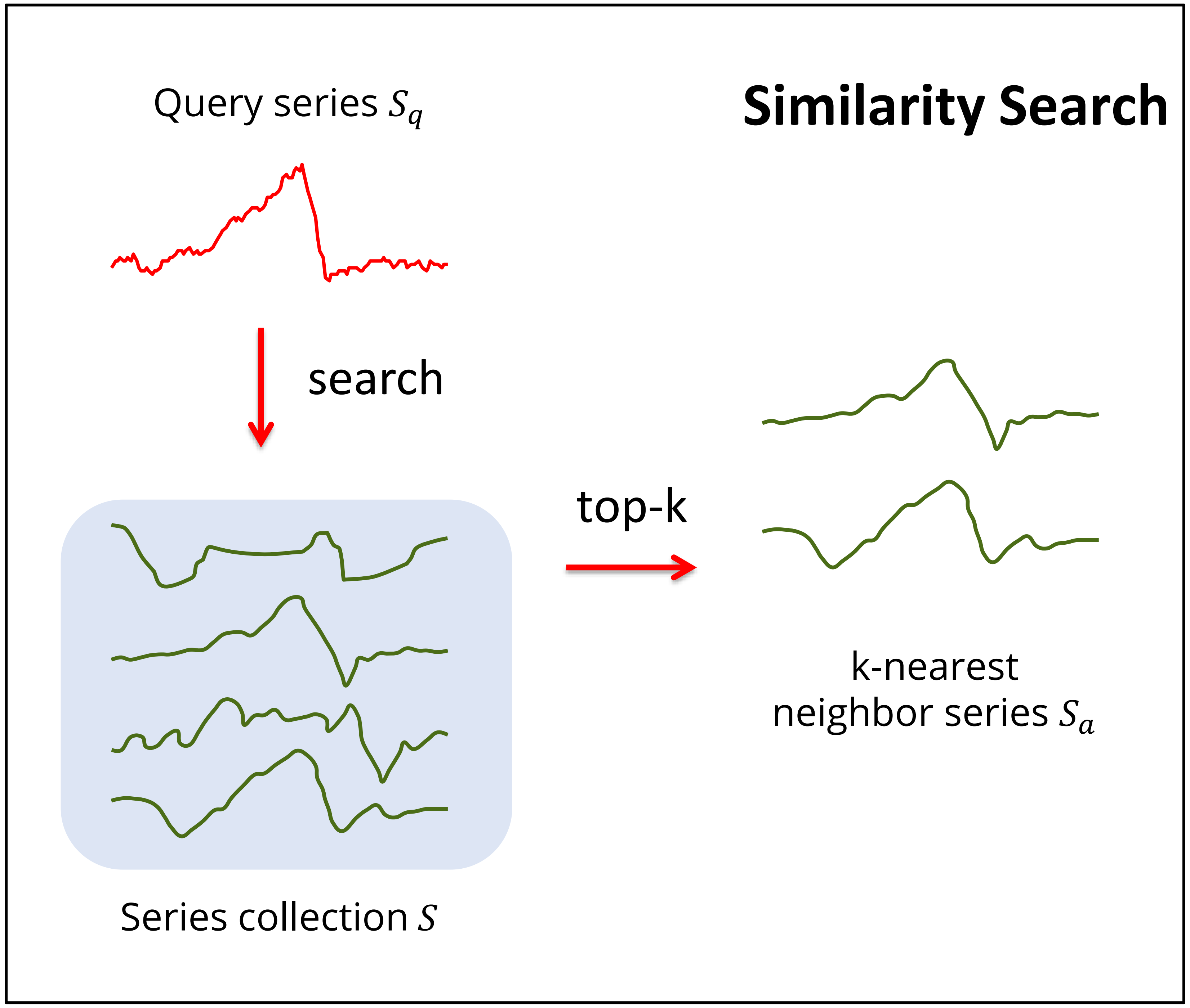

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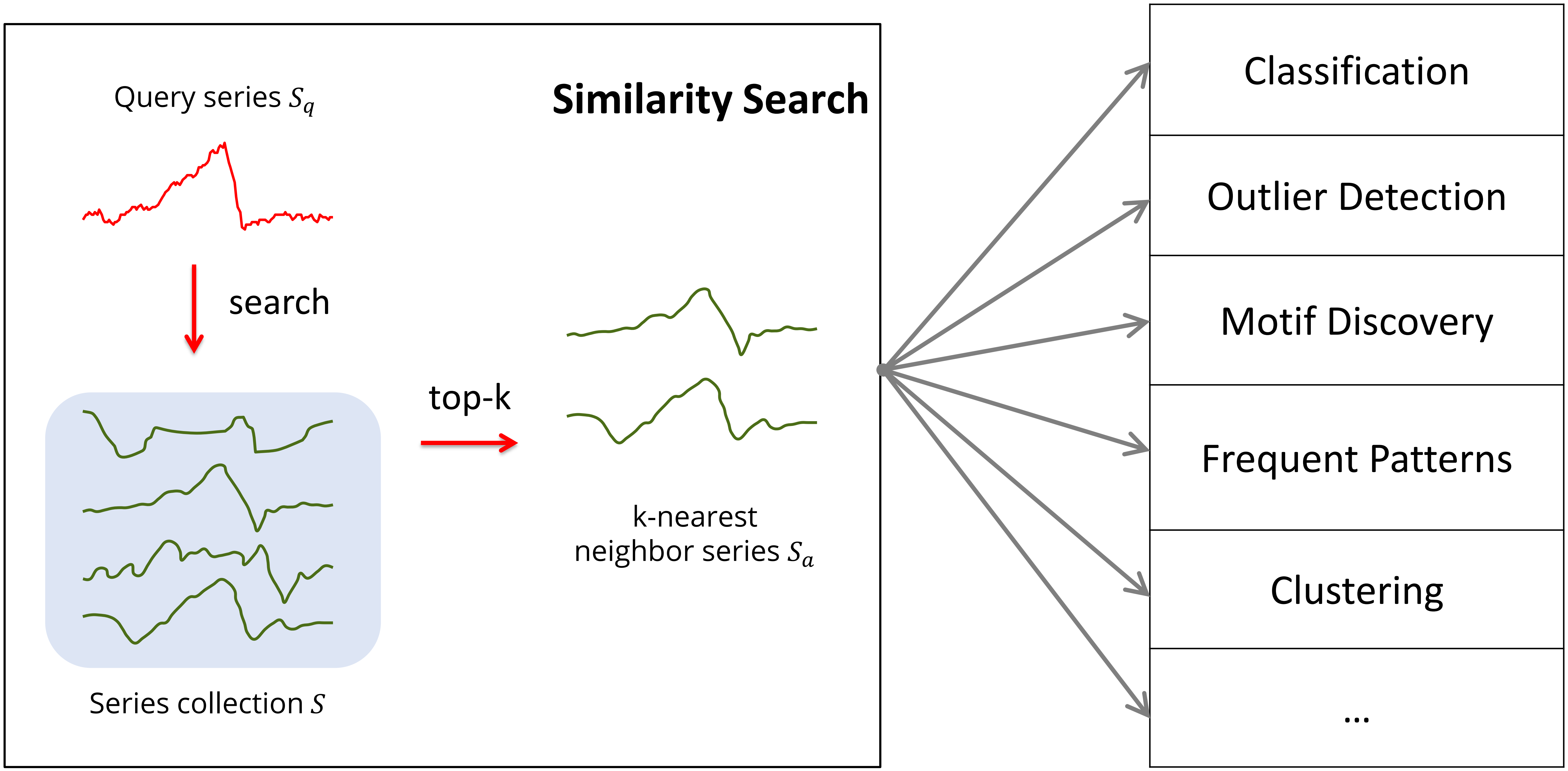


1-Problem Definition

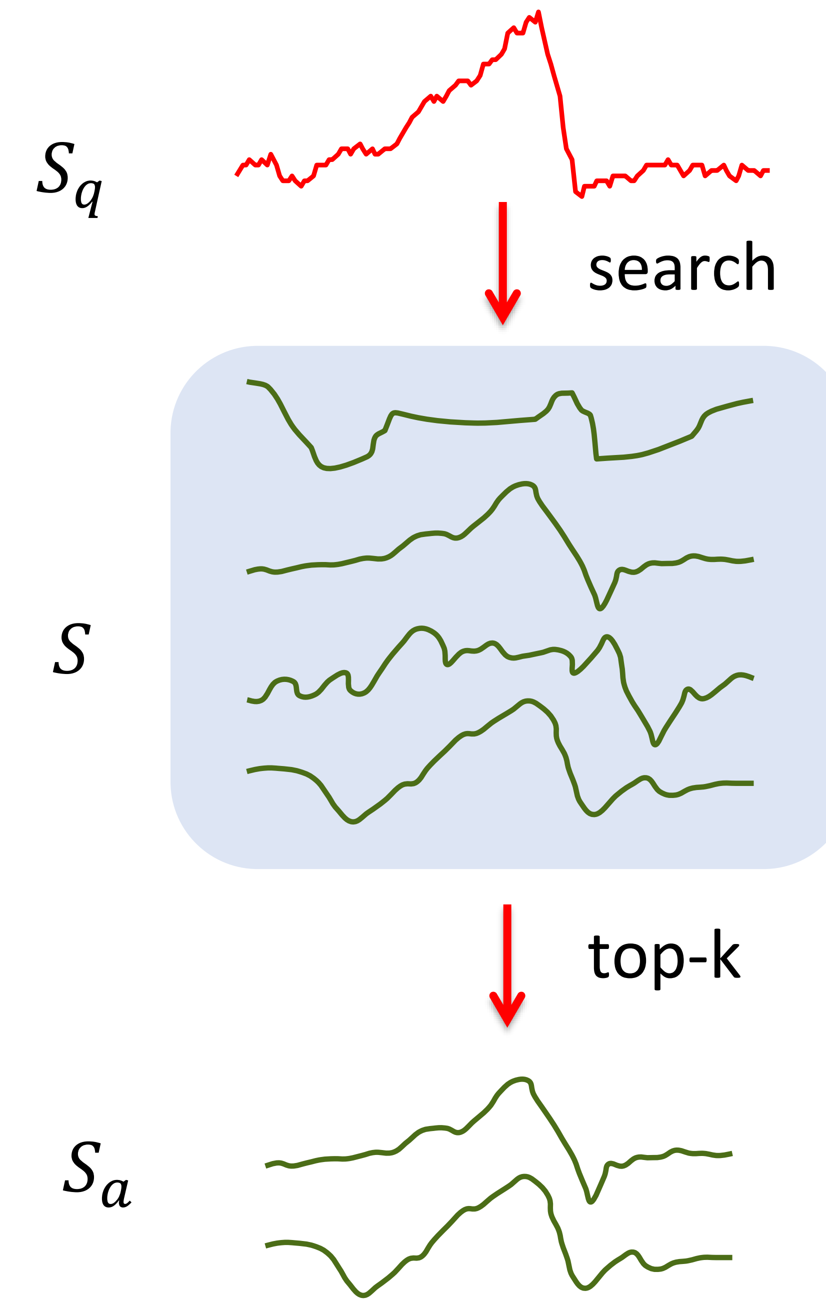
- Similarity search
  - given a series set S, a query series S_q and a similarity measure $d(\cdot,\cdot)$
    - d is commonly the Euclidean distance (ED) or Dynamic Time Warping (DTW)
  - find the closest series in S to s_q, i.e.,

$$s_a = \arg\min_{s_i \in S} d(s_q, s_i)$$

Exact answers sometimes unnecessary

- Approximate similarity search
  - find $s_{a'}$,$d(s_q, s_{a'}) \approx d(s_q, s_a)$
  - core requirements: Accuracy & Scalability

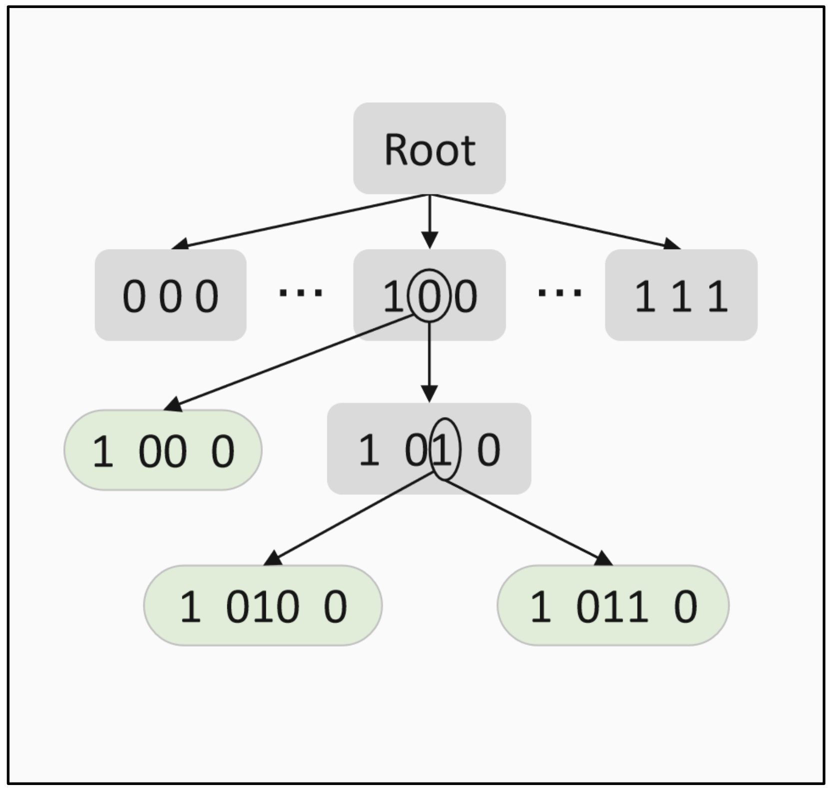
Data Series Index



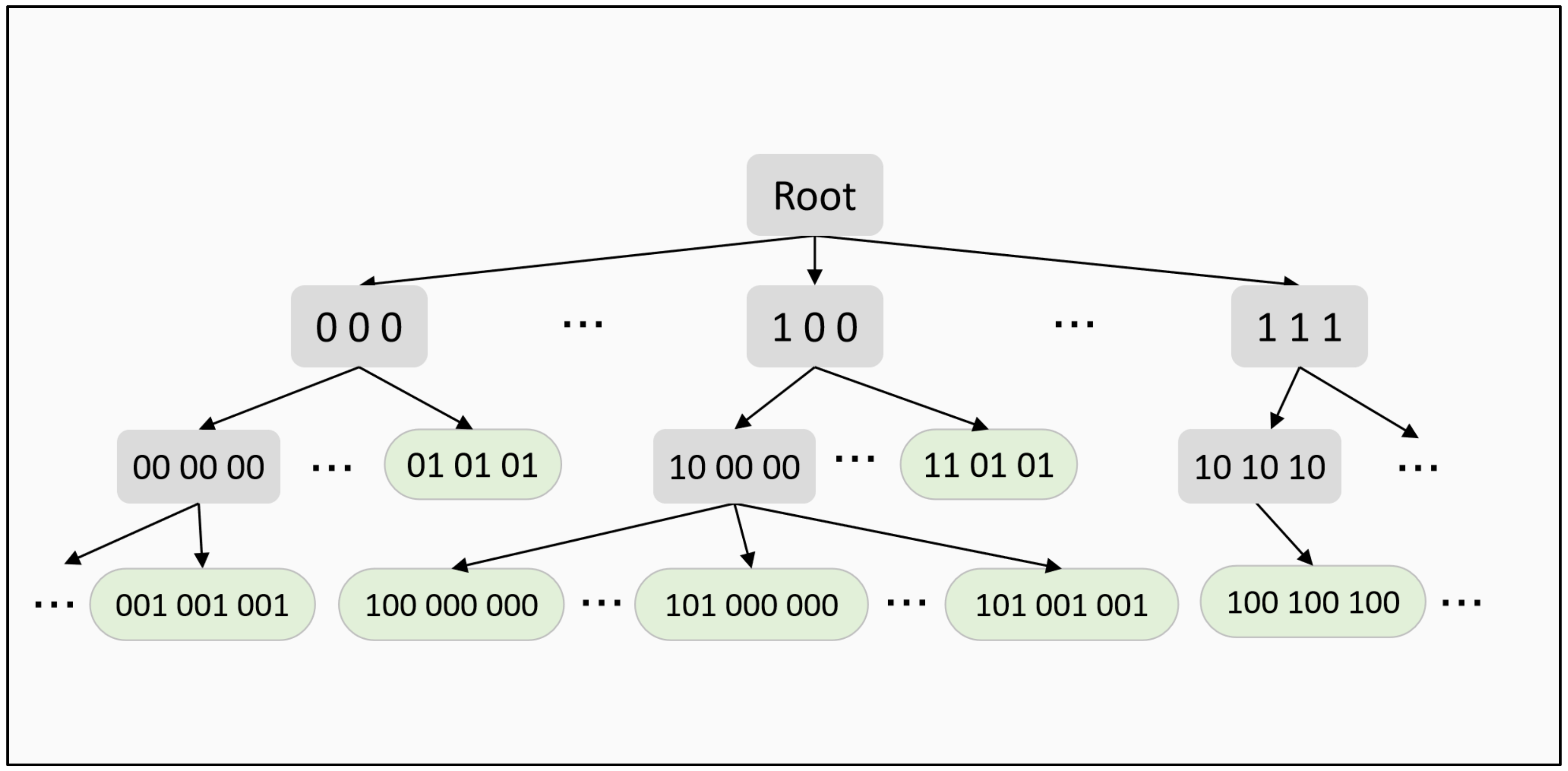
2-Limitations of Existing Solutions

Two structures of iSAX-based index

2-ary[1]



Full-Ary[2]



Splitting Decisions

Not Accurate ↔ **Not Scalable**

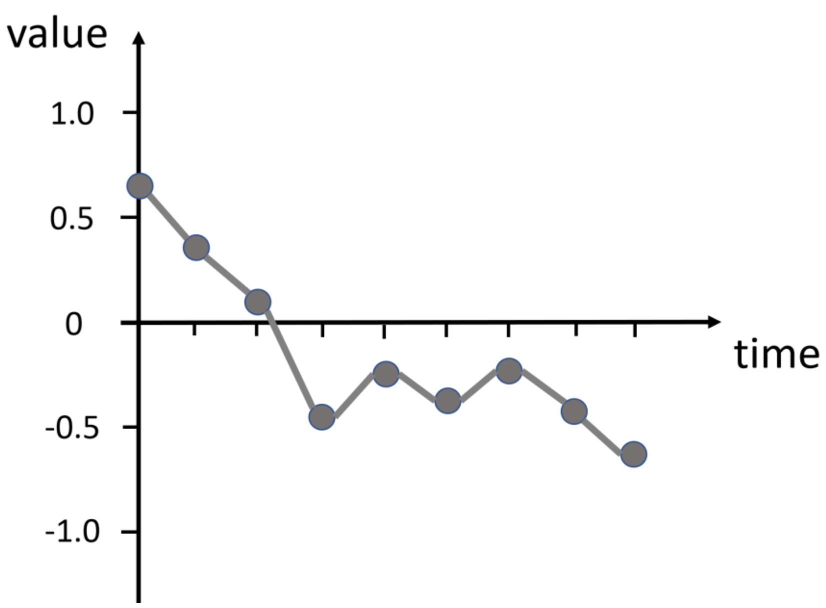
Problem 1: What's the right splitting decision between these two extremes?

Problem 2: How to efficiently implement splitting?

1. Alessandro Camerra, et al. Beyond One Billion Time Series: Indexing and Mining Very Large Time Series Collections with iSAX2+. KAIS 39(1):123-151, 2014.
2. Zhang, L. et al. 2019. TARDIS: Distributed Indexing Framework for Big Time Series Data. 2019 IEEE 35th International Conference on Data Engineering (ICDE)

3-iSAX Index Family

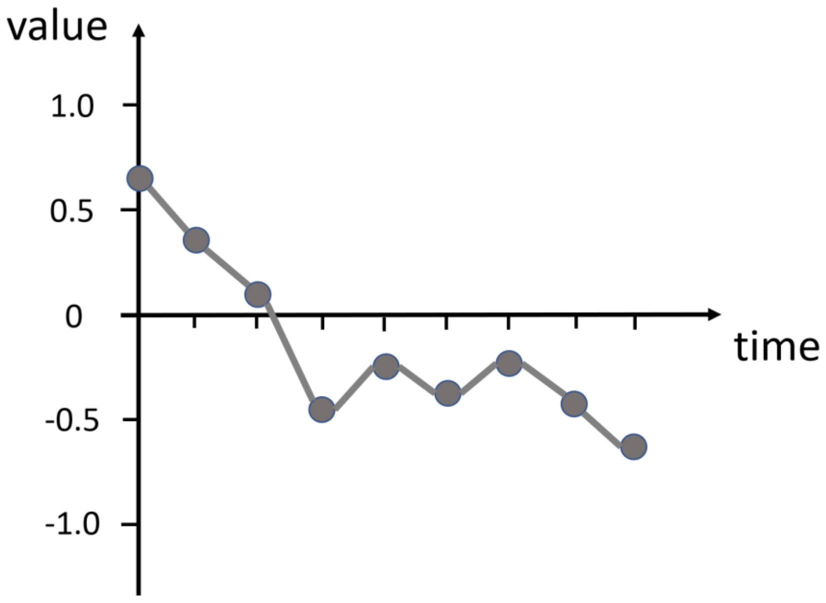
Raw series



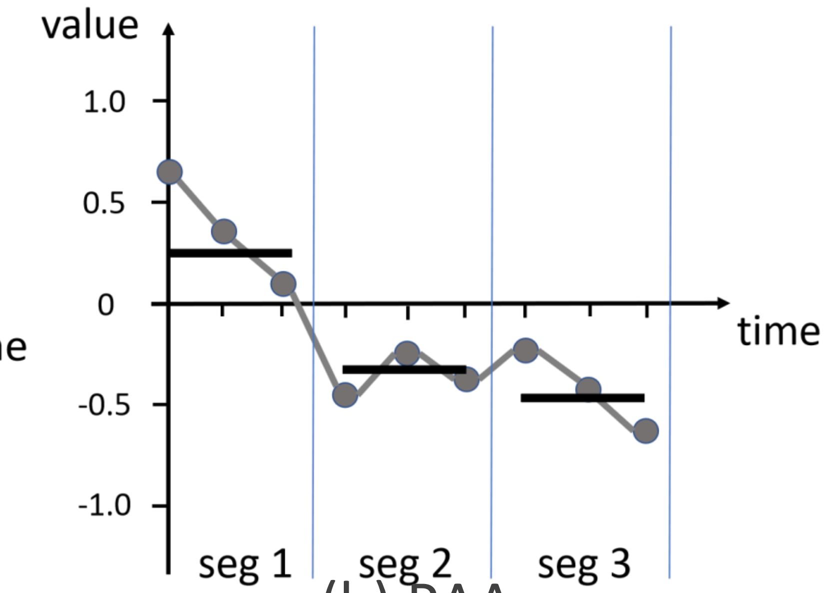
(a) raw series s

3-iSAX Index Family

Raw series → PAA approximation



(a) raw series s

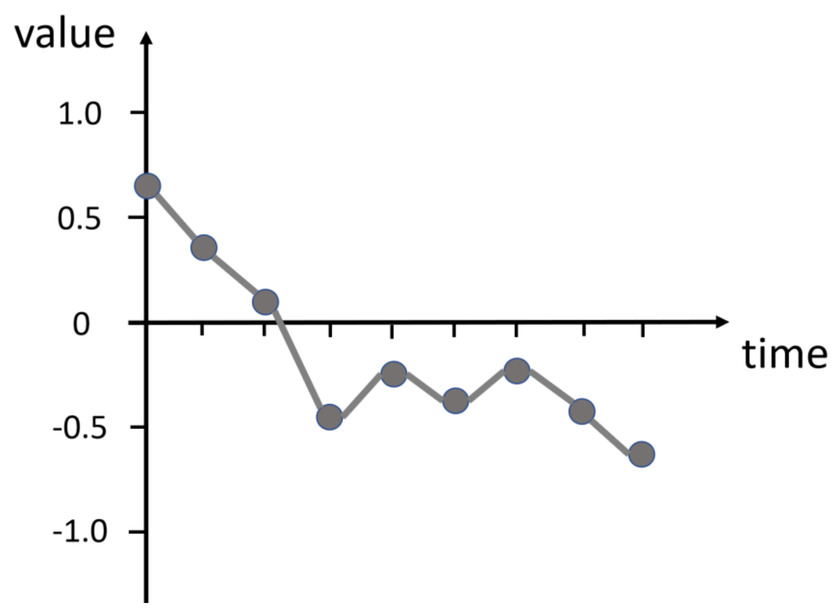


(b) PAA summarization

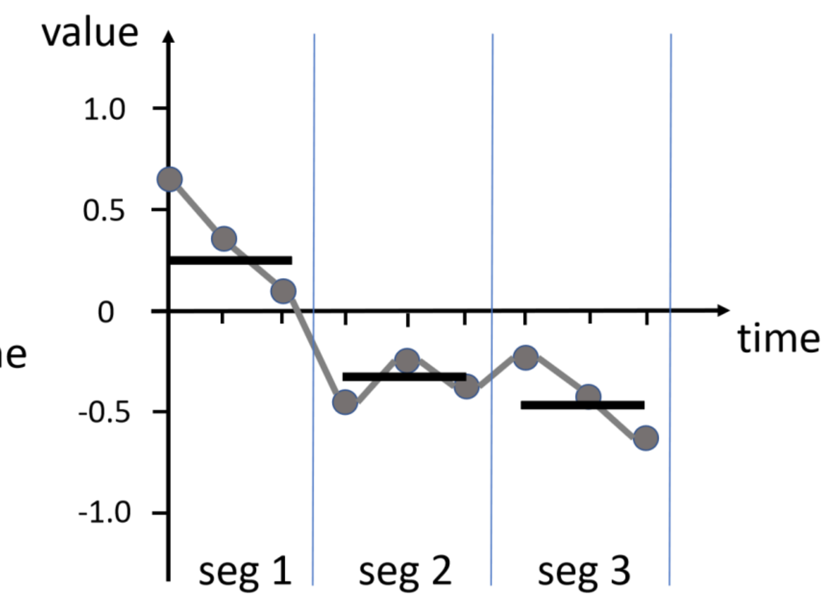
PAA(s)=[0.25, -0.3, -0.55]

3-iSAX Index Family

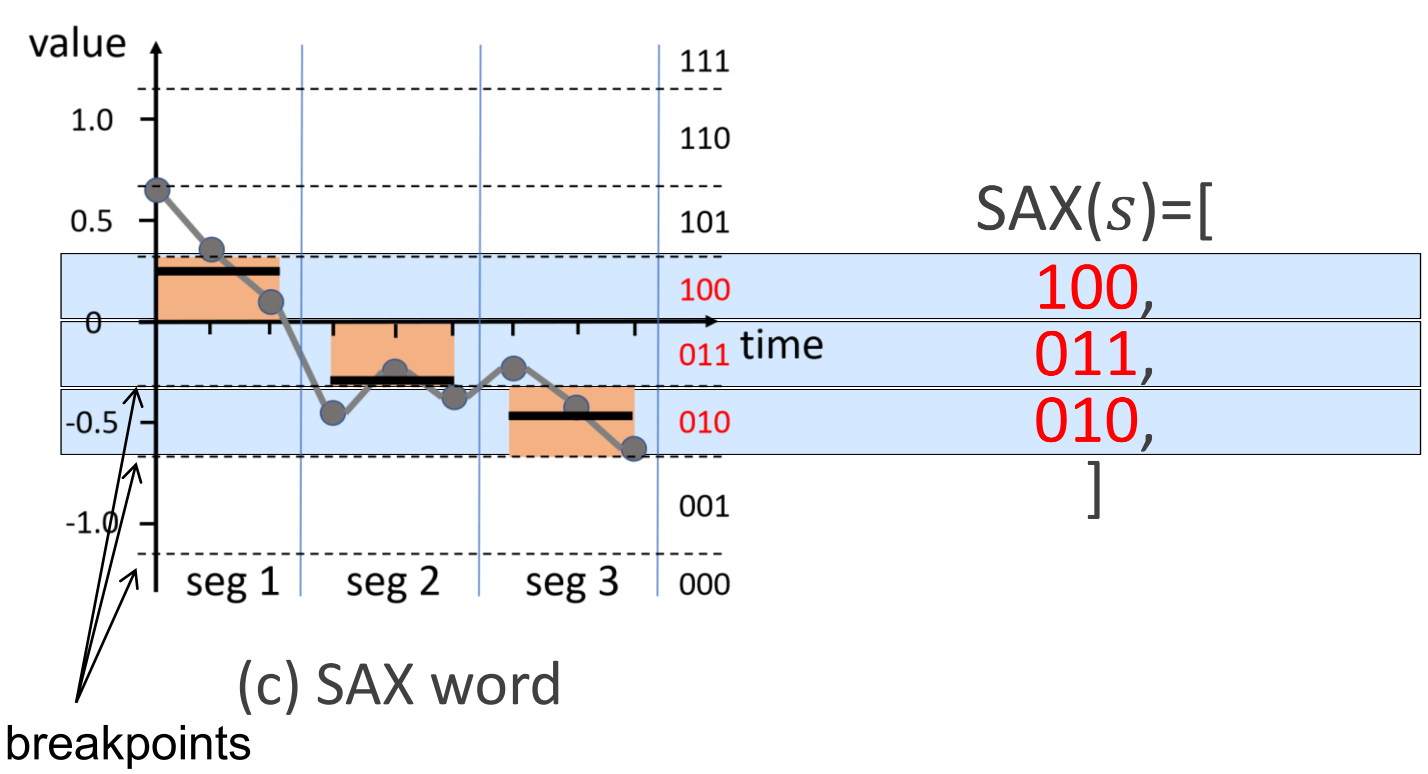
Raw series → PAA approximation → SAX symbolization



(a) raw series



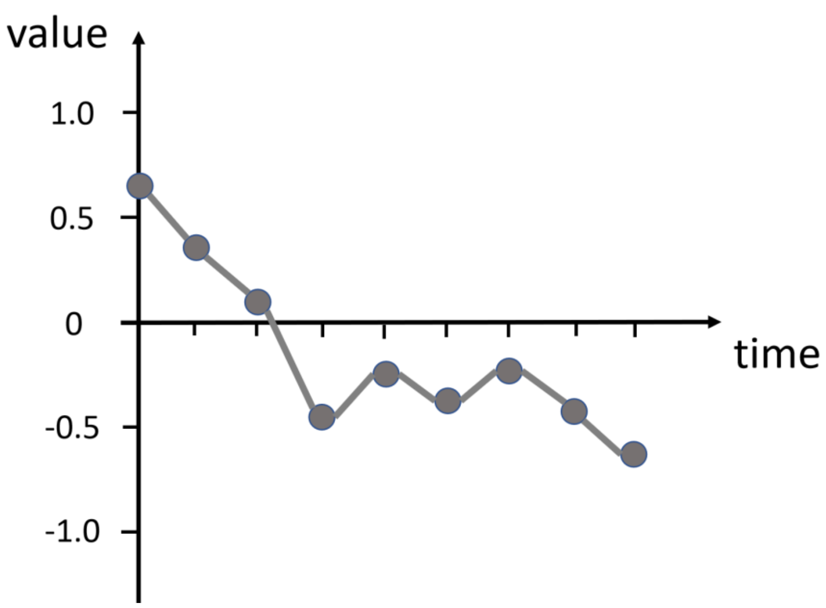
(b) PAA summarization



(c) SAX word

3-iSAX Index Family

Raw series → PAA approximation → SAX symbolization → iSAX index



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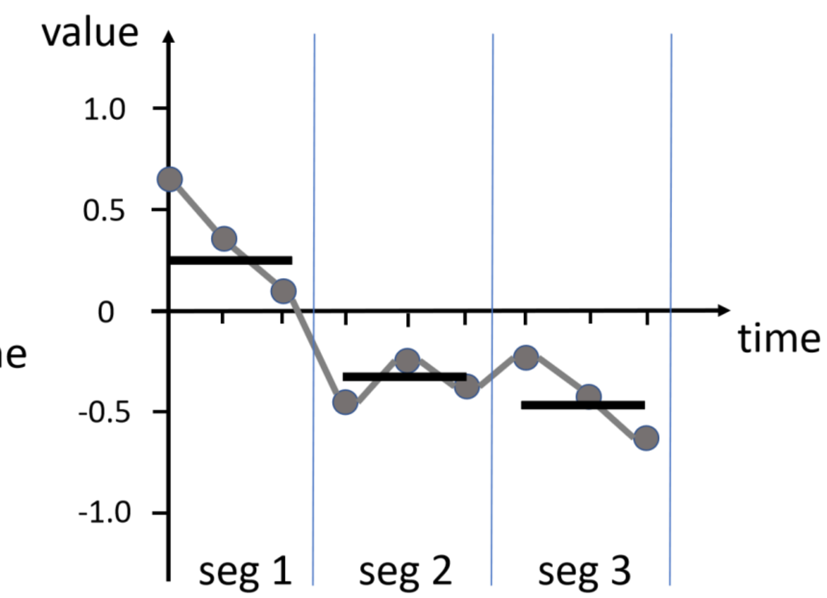
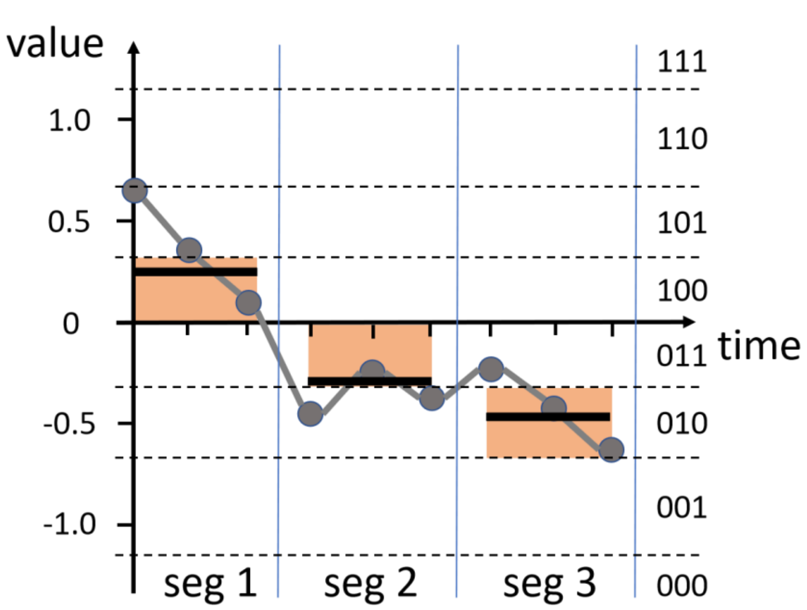
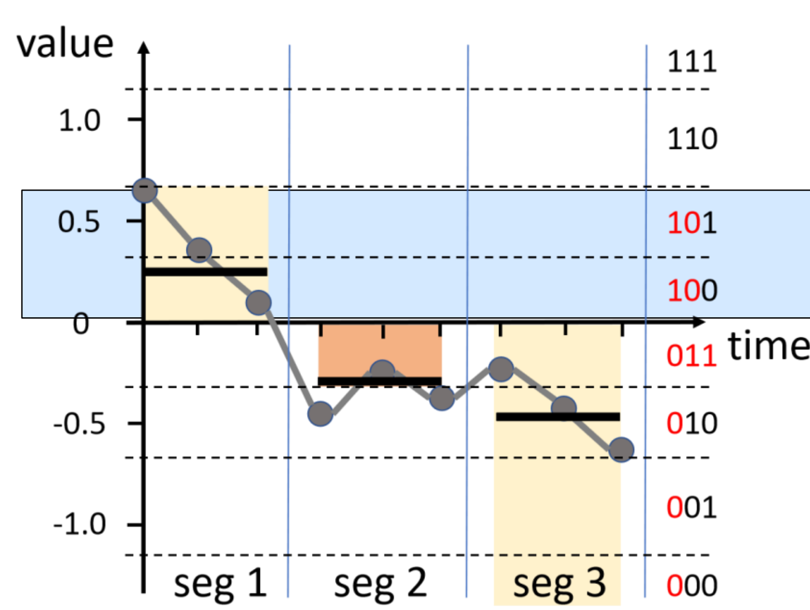


(b) PAA summarization

SAX(s)=[100, 011, 010]



(c) SAX word



(d) iSAX word

One iSAX word of s

iSAX(s)=[

10,

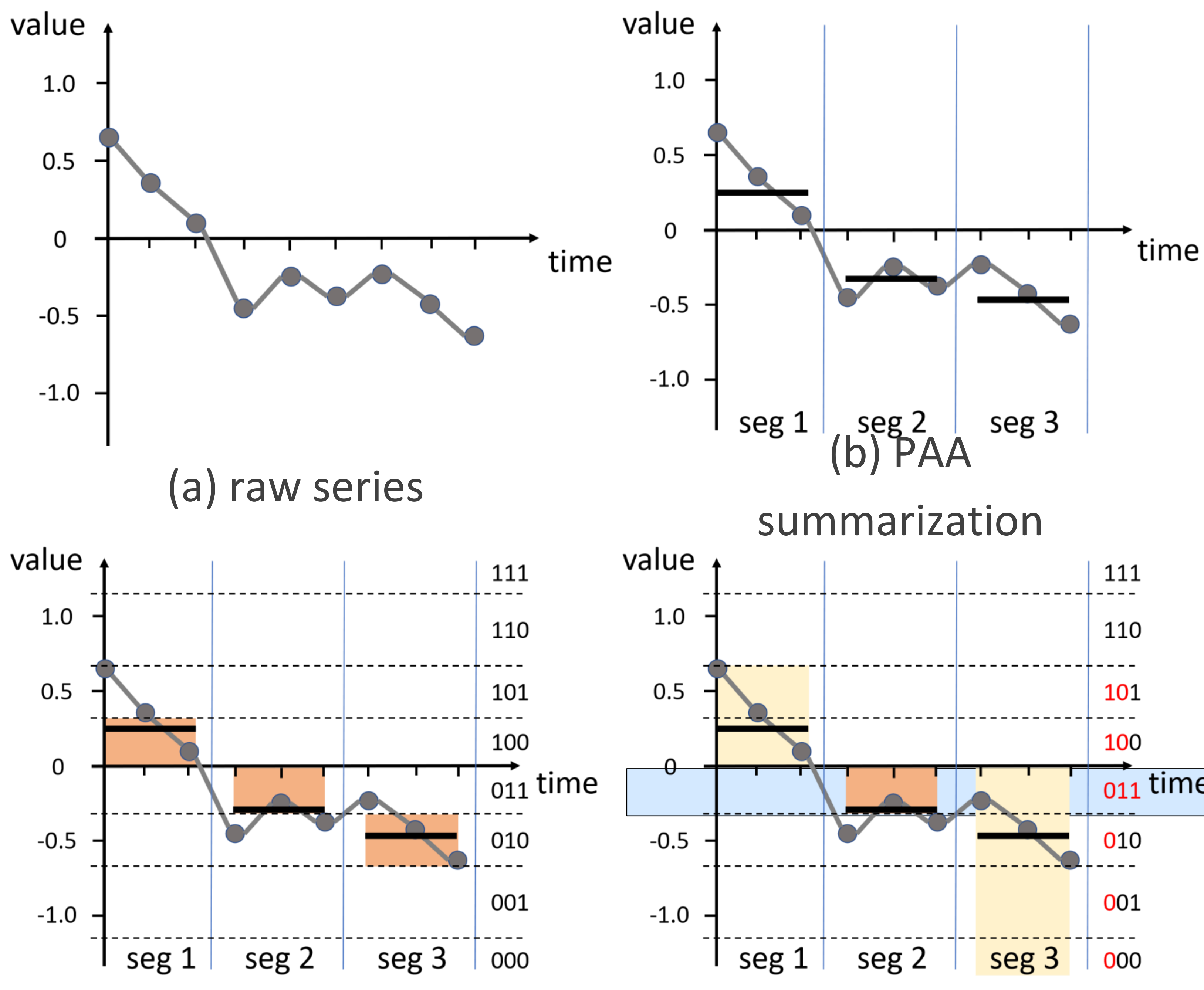
011,

0,

]

3-iSAX Index Family

Raw series → PAA approximation → SAX symbolization → iSAX index



(a) raw series

(b) PAA summarization

(c) SAX word

(d) iSAX word

SAX(s)=[100, 011, 010]

One iSAX word of s

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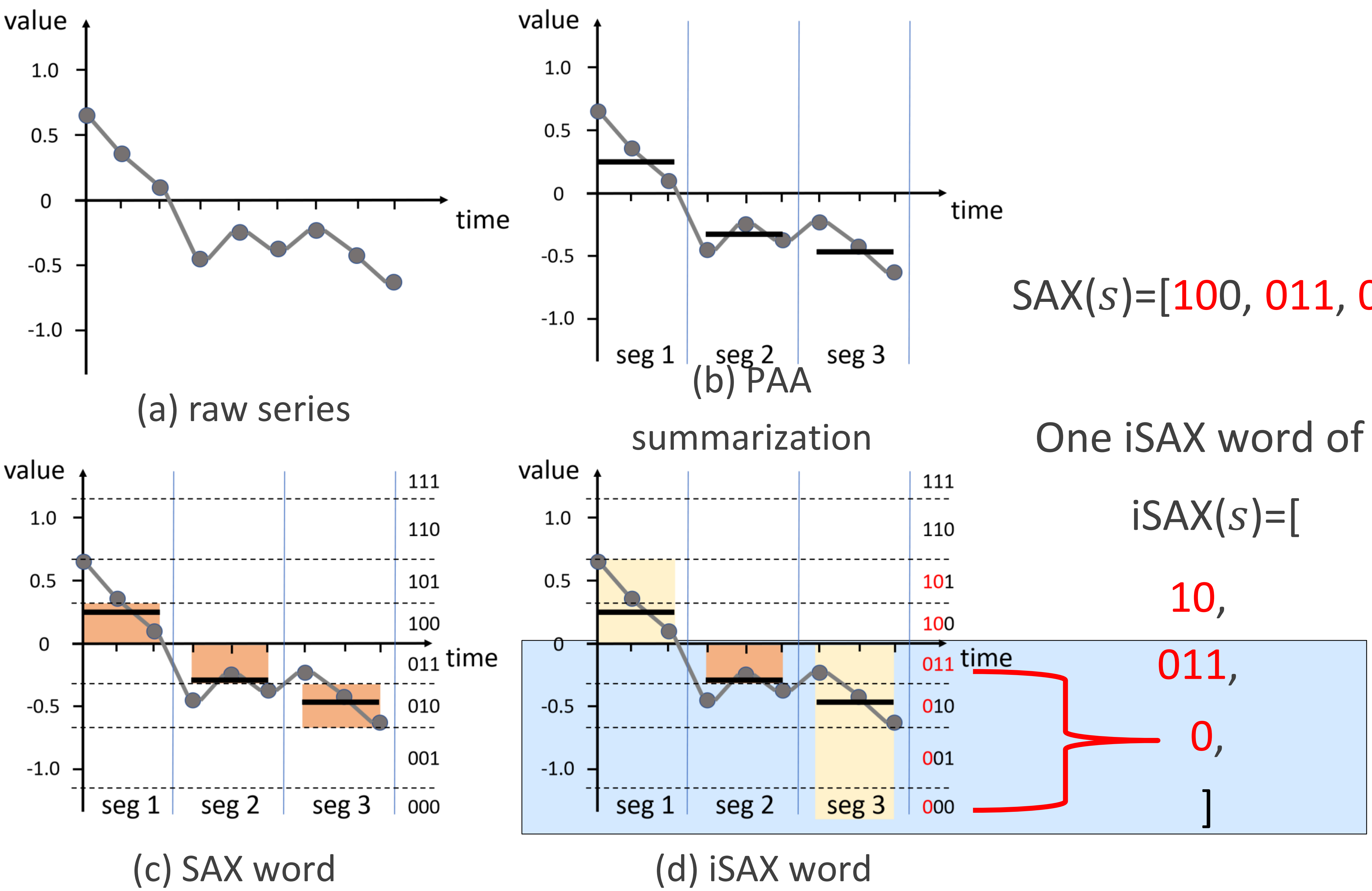

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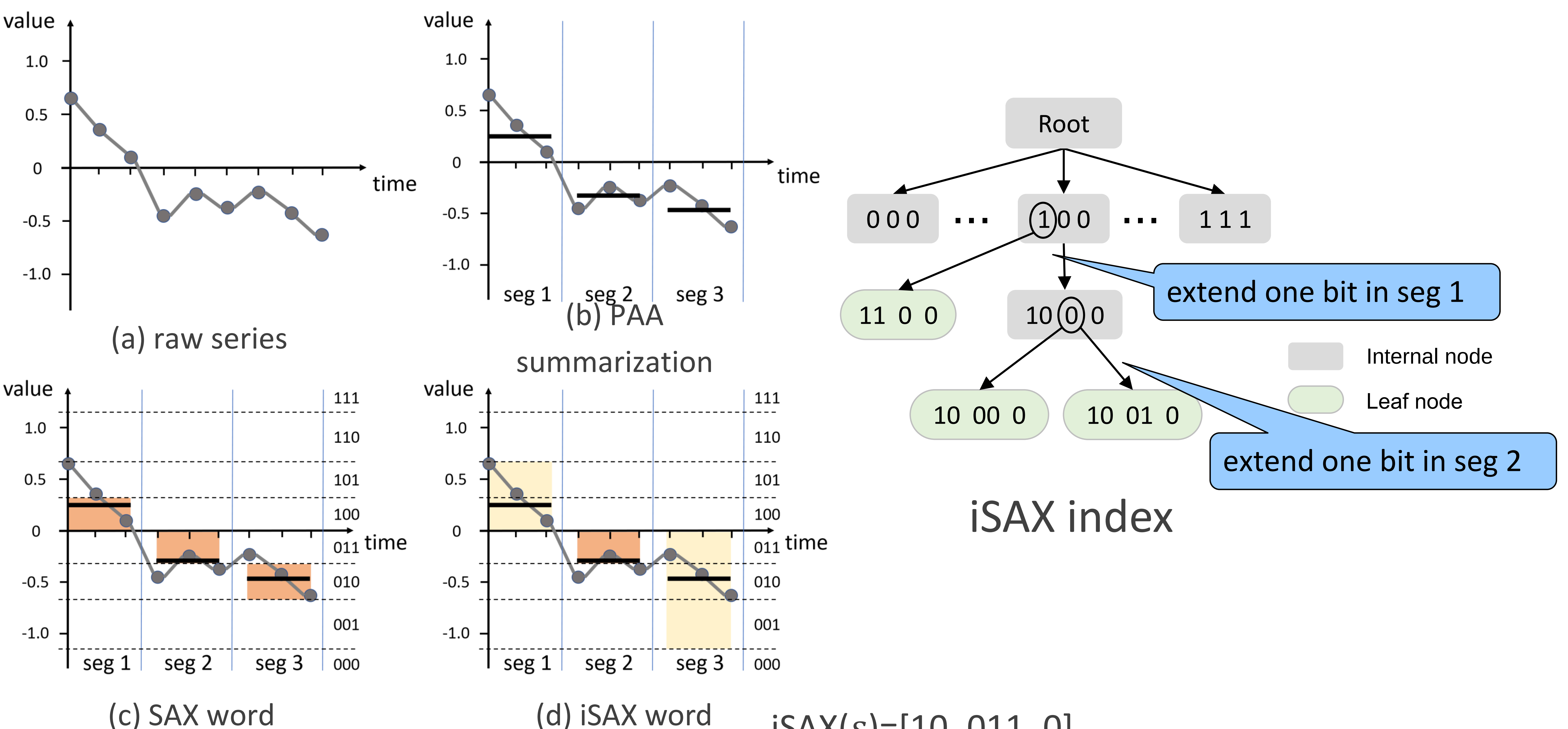
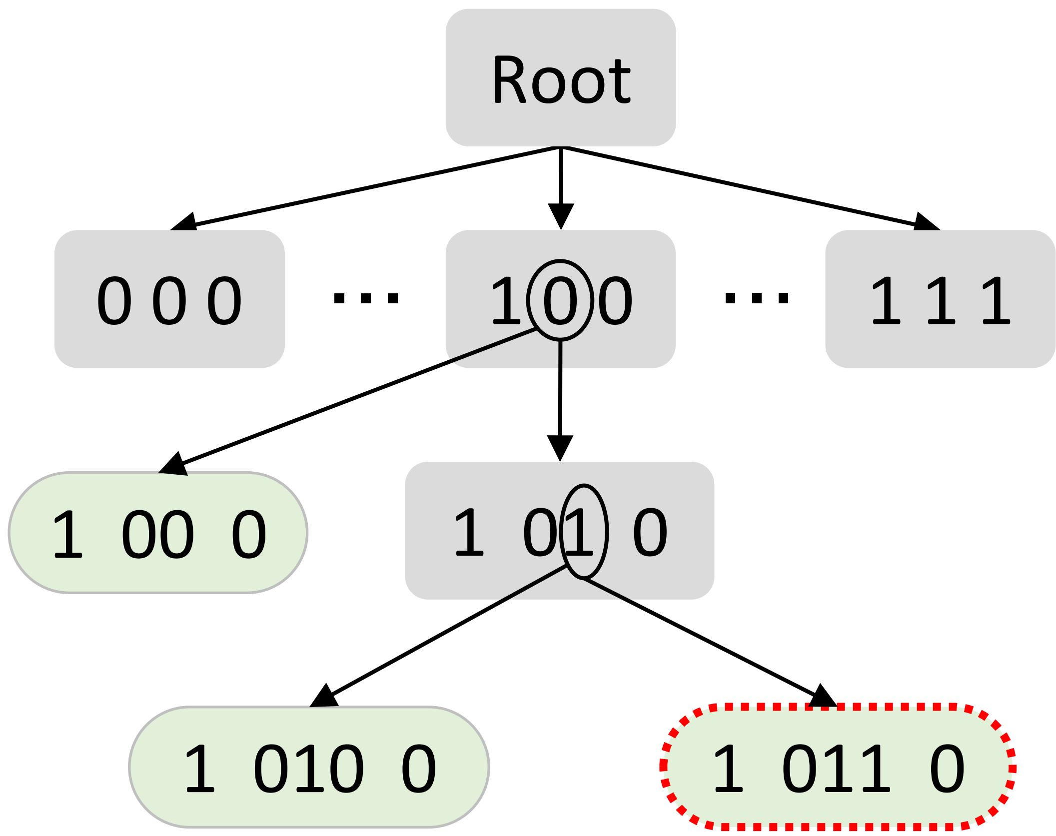


iSAX(s)=[10, 011, 0]

4-Proximity Problem of 2-ary iSAX Index



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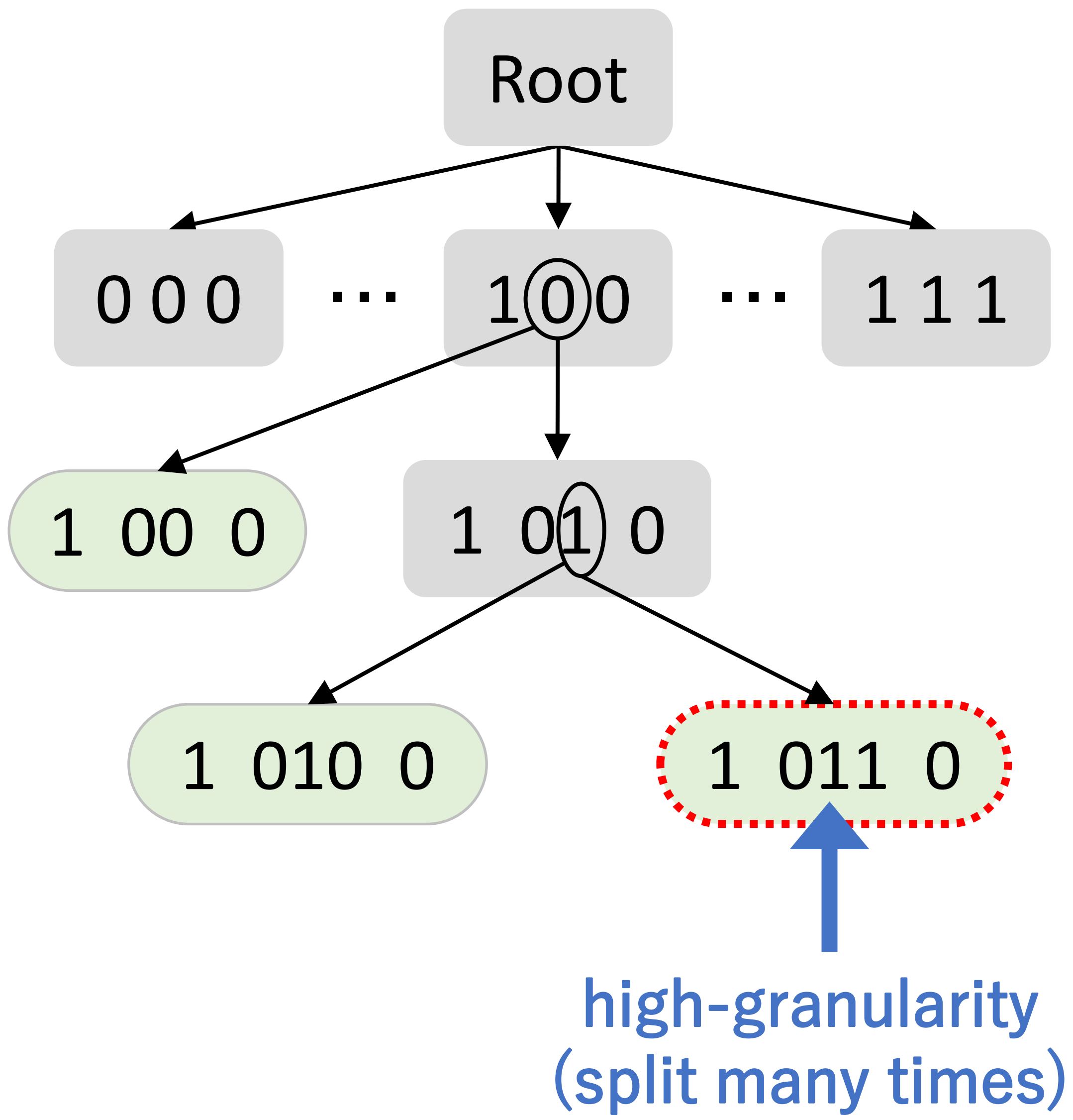

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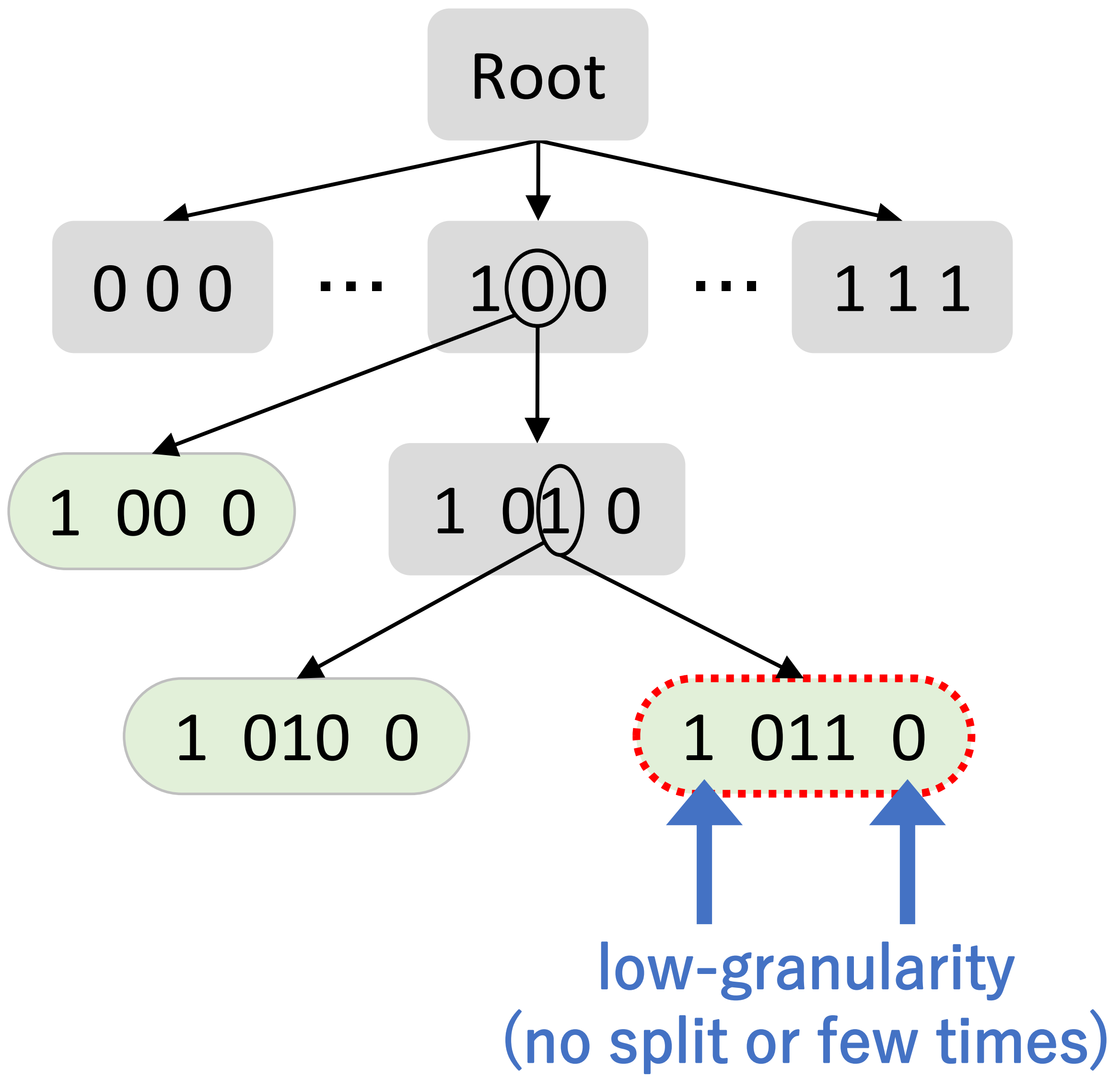

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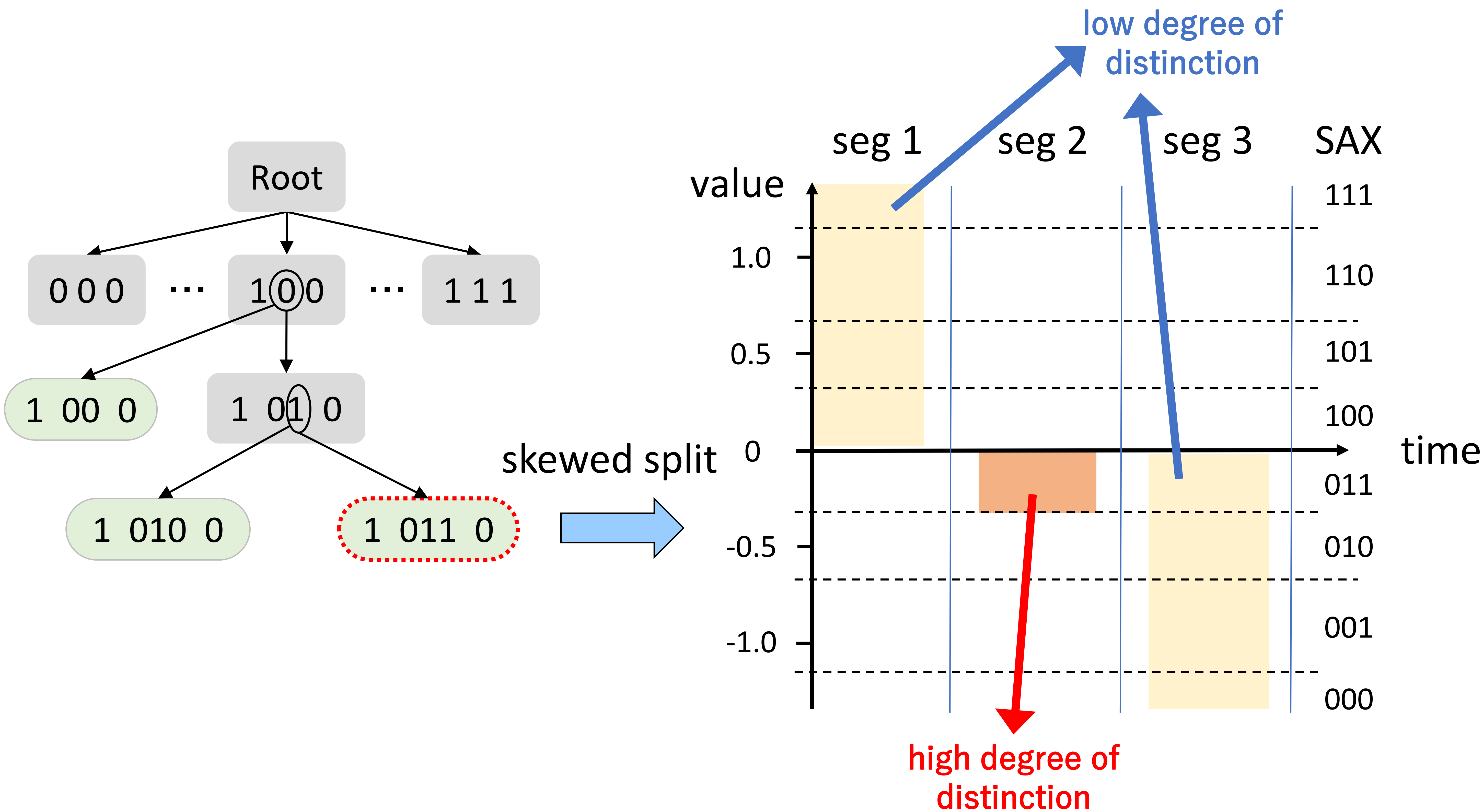

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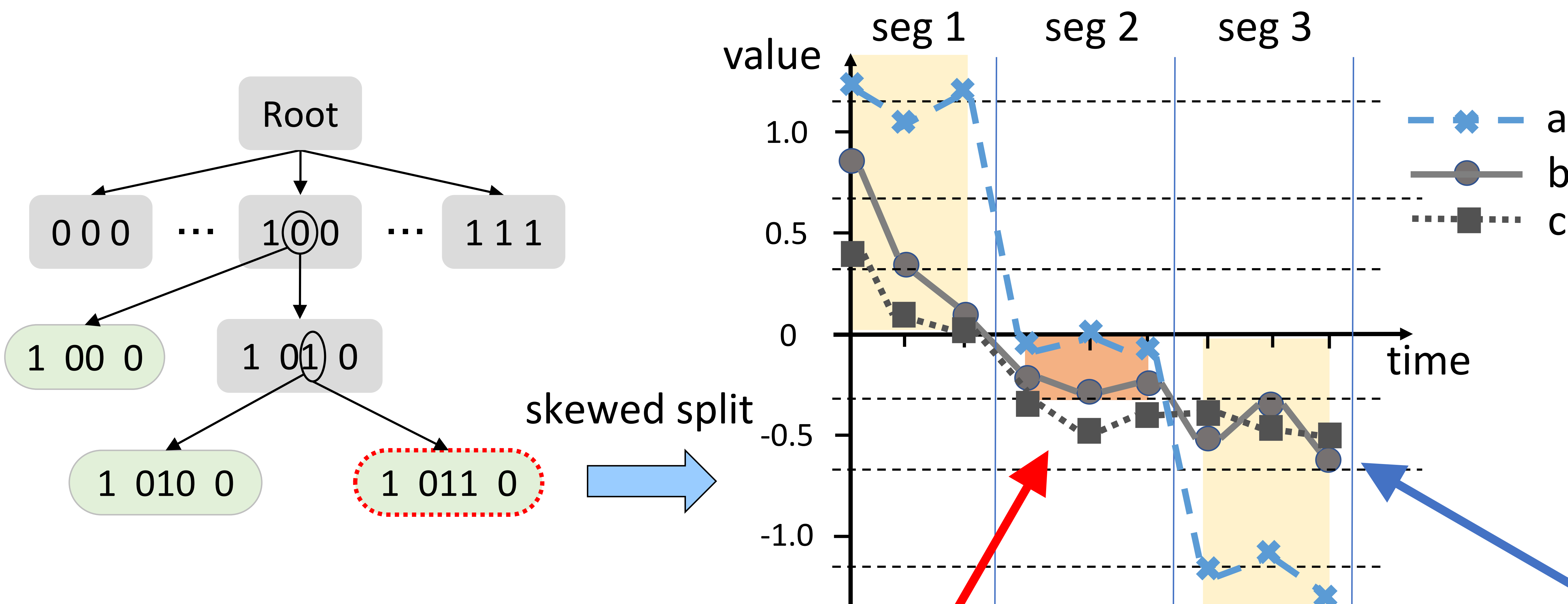
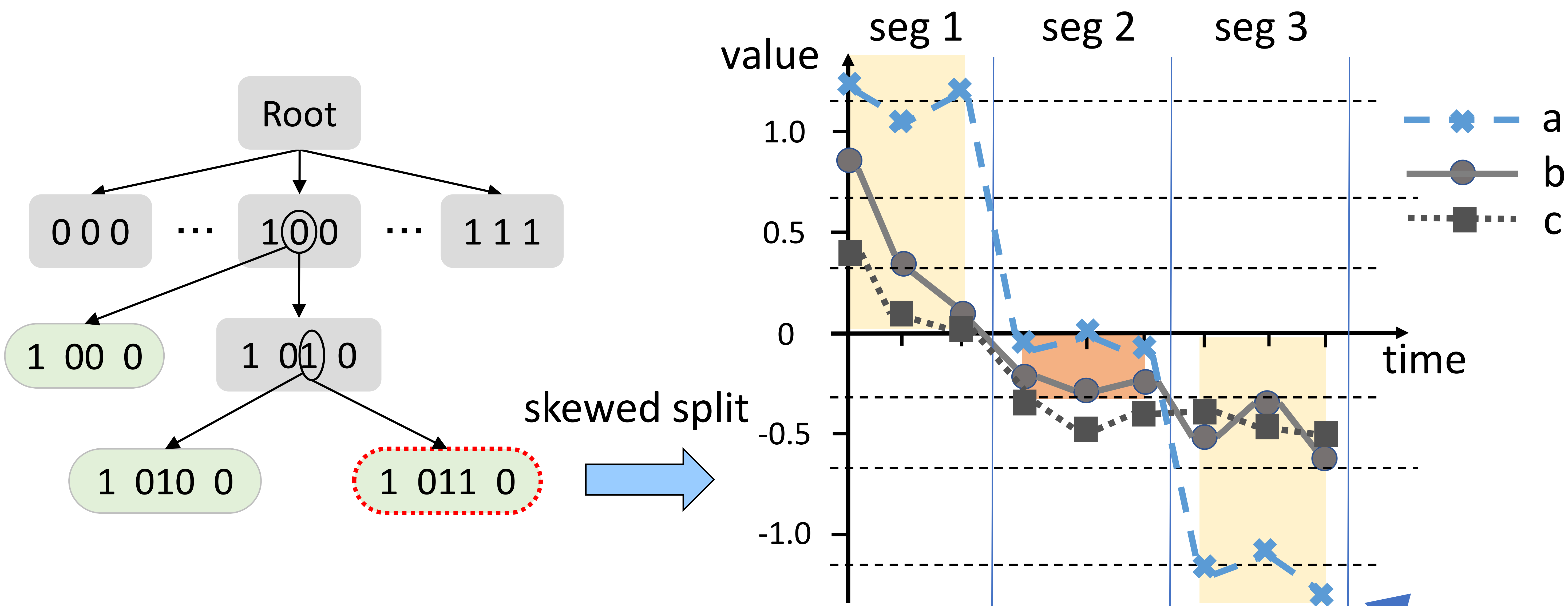


c excluded in this node for seg 2

b and c are very close

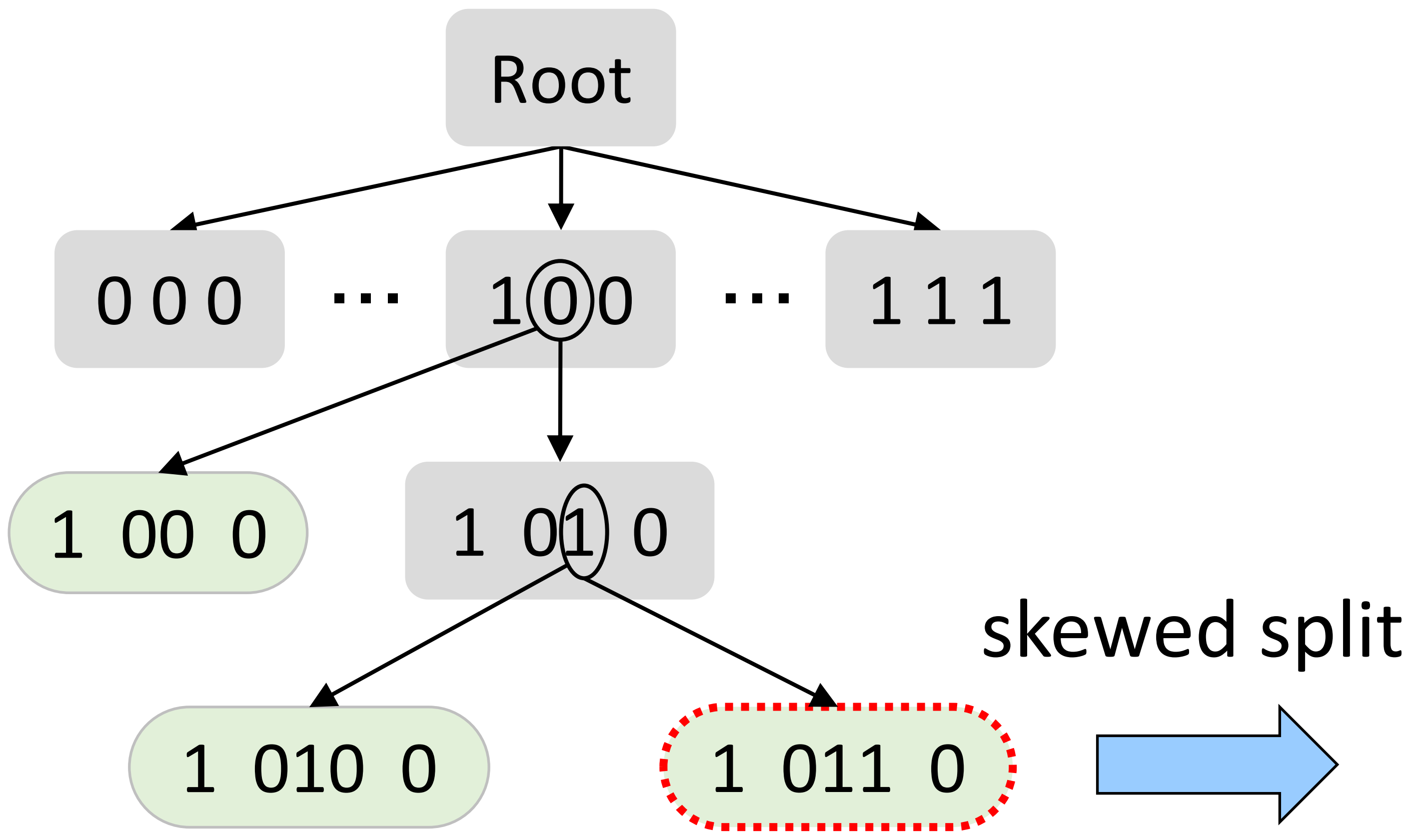
4-Proximity Problem of 2-ary iSAX Index

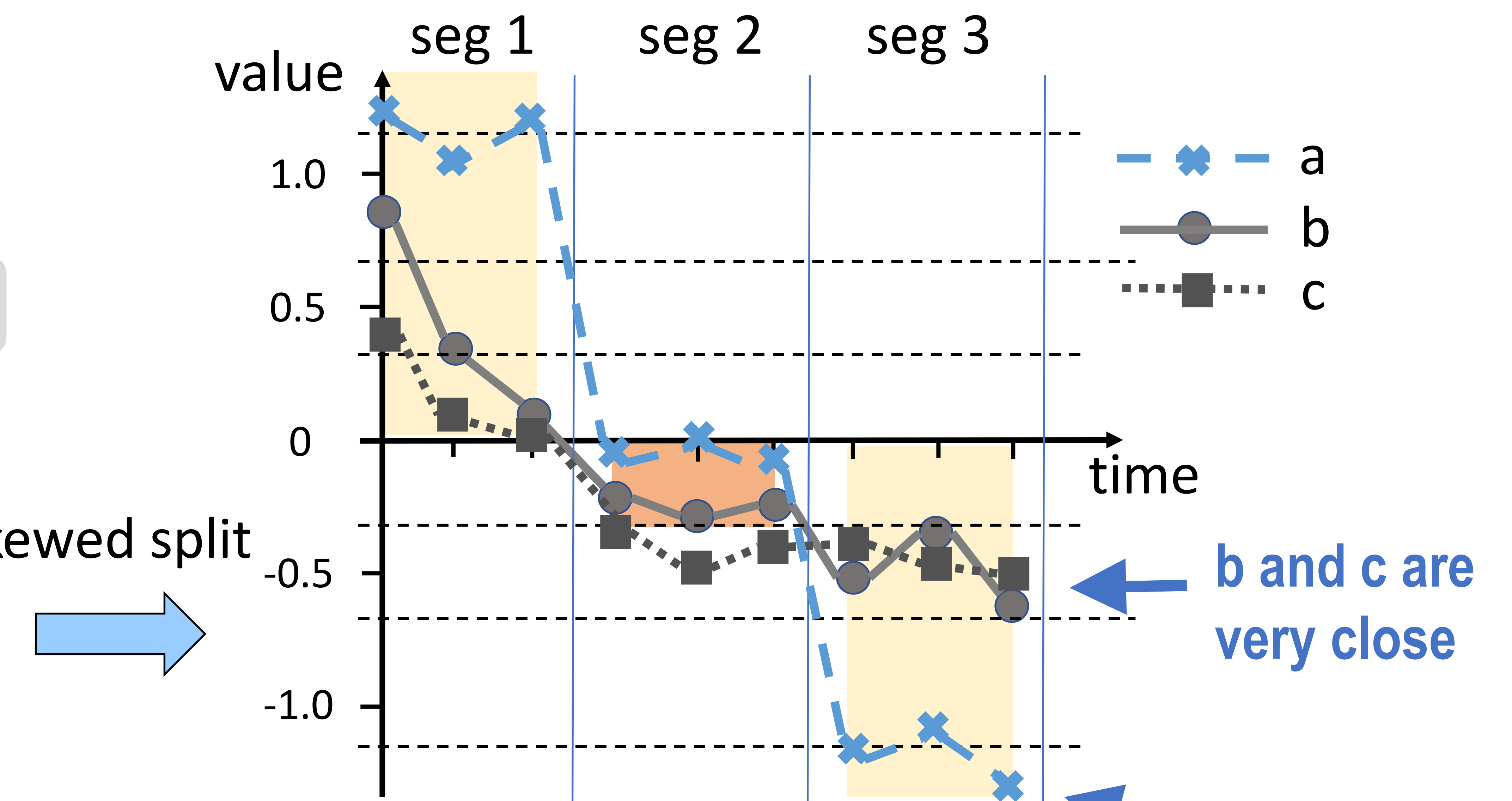


a is far from b and c

a is included in this node together with b

4-Proximity Problem of 2-ary iSAX Index

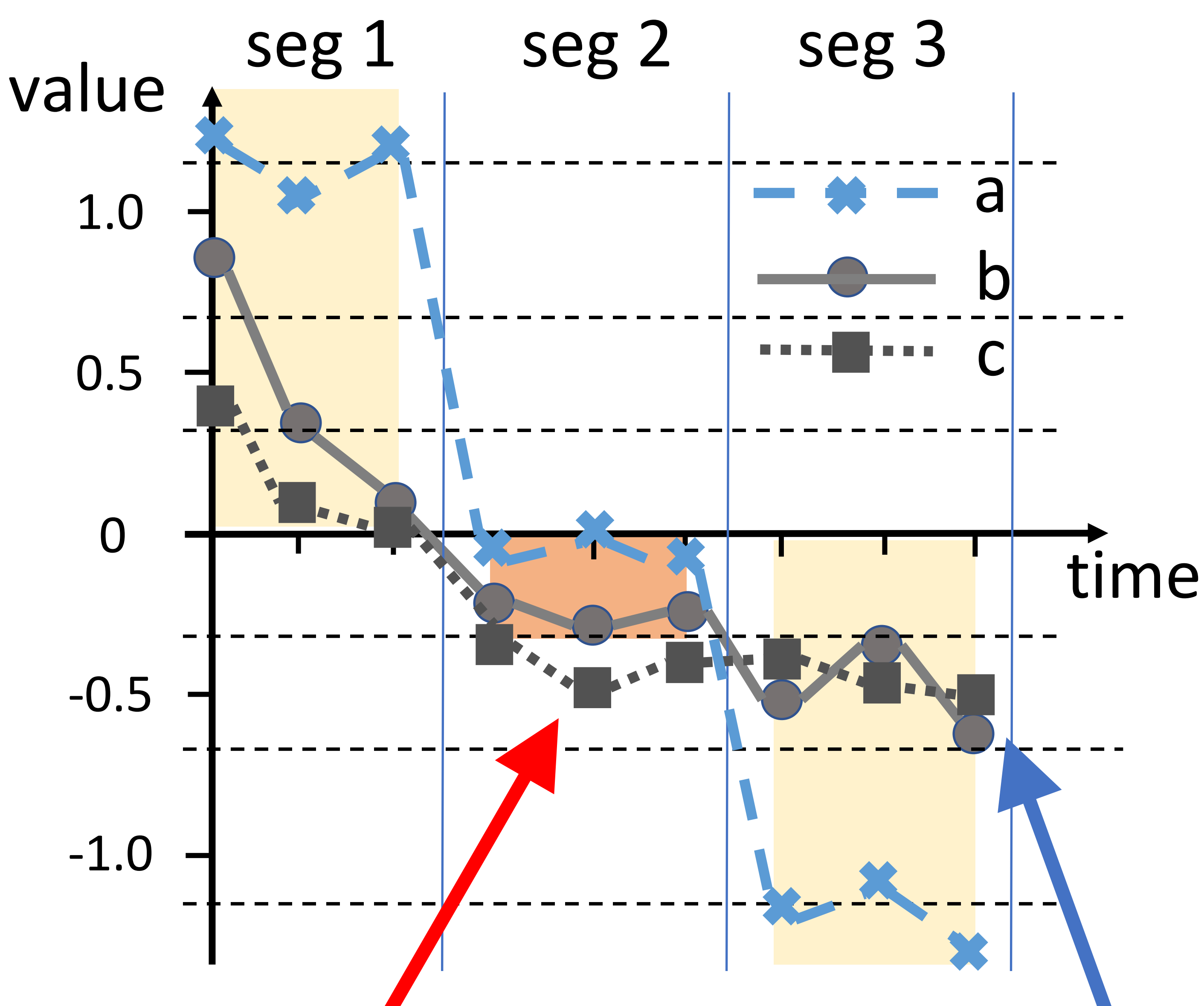




Reason:
<u>over-focus</u> on similarity on seg 2, but final distance equally contributed by all 3 segments

4-Proximity Problem of 2-ary iSAX Index

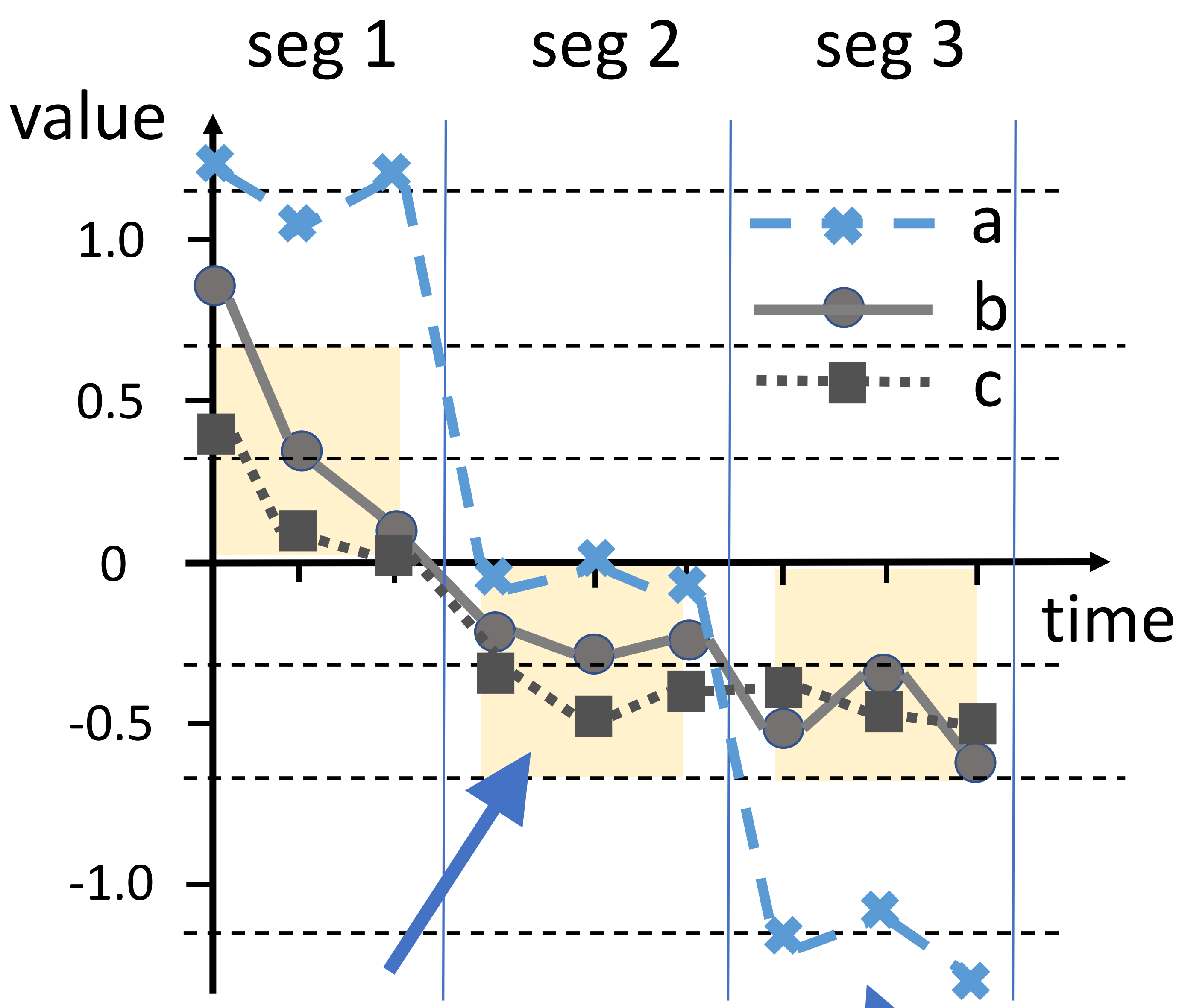
Skewed Split



c excluded in this node for seg 2

b and c are very close

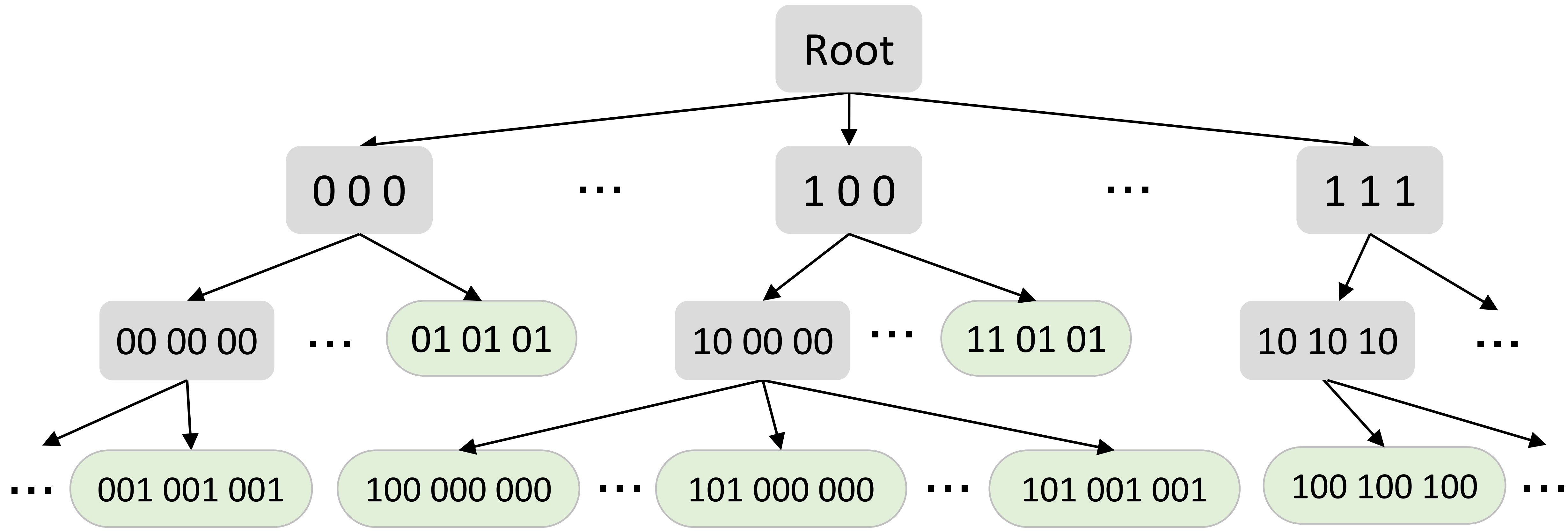
Even Split



a and b are grouped together in this node

c is excluded

5-Compactness Problem of full-ary iSAX Index



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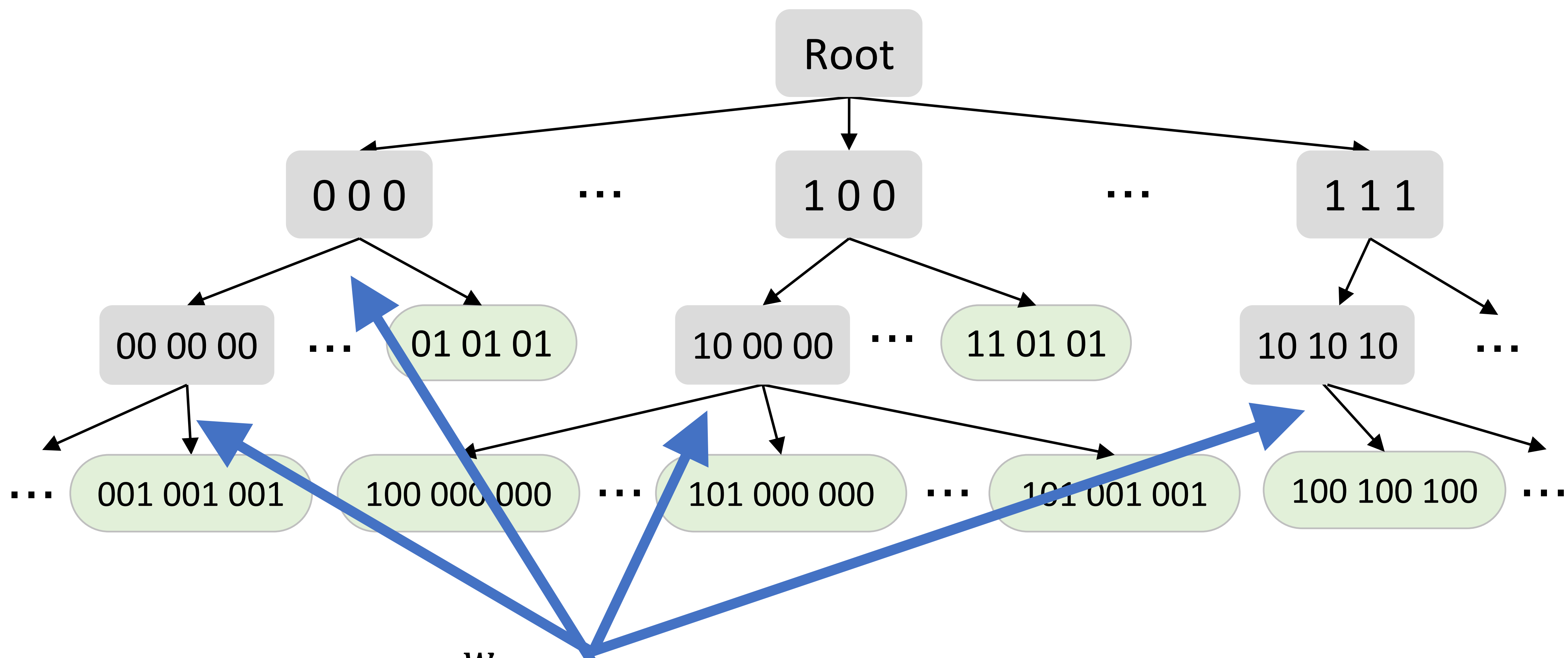


2^w new nodes in each split

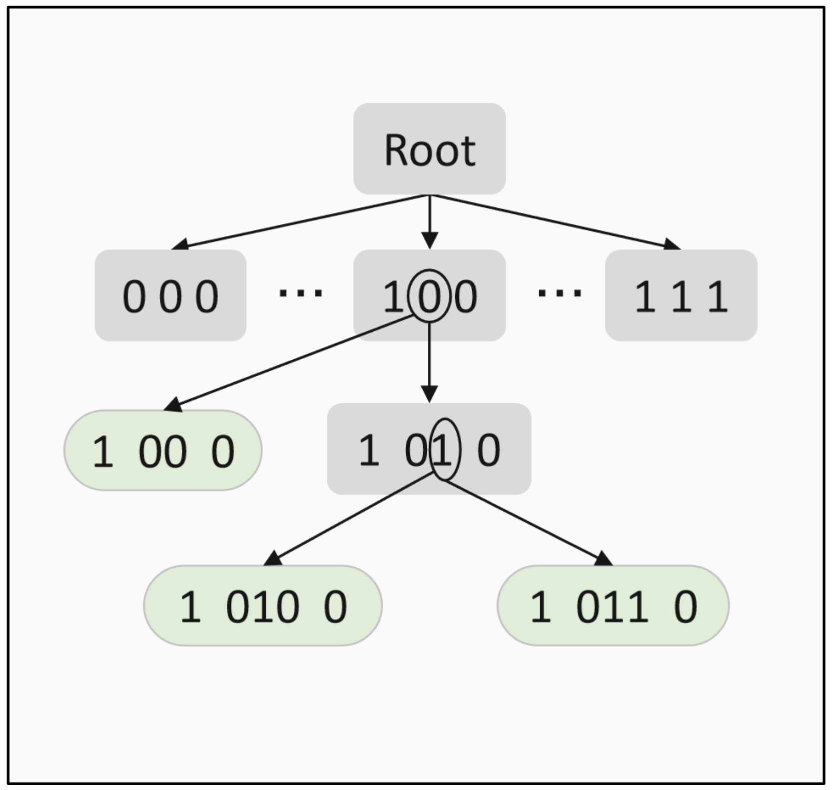
w: number of segments

↓

more random disk accesses in index building and querying!

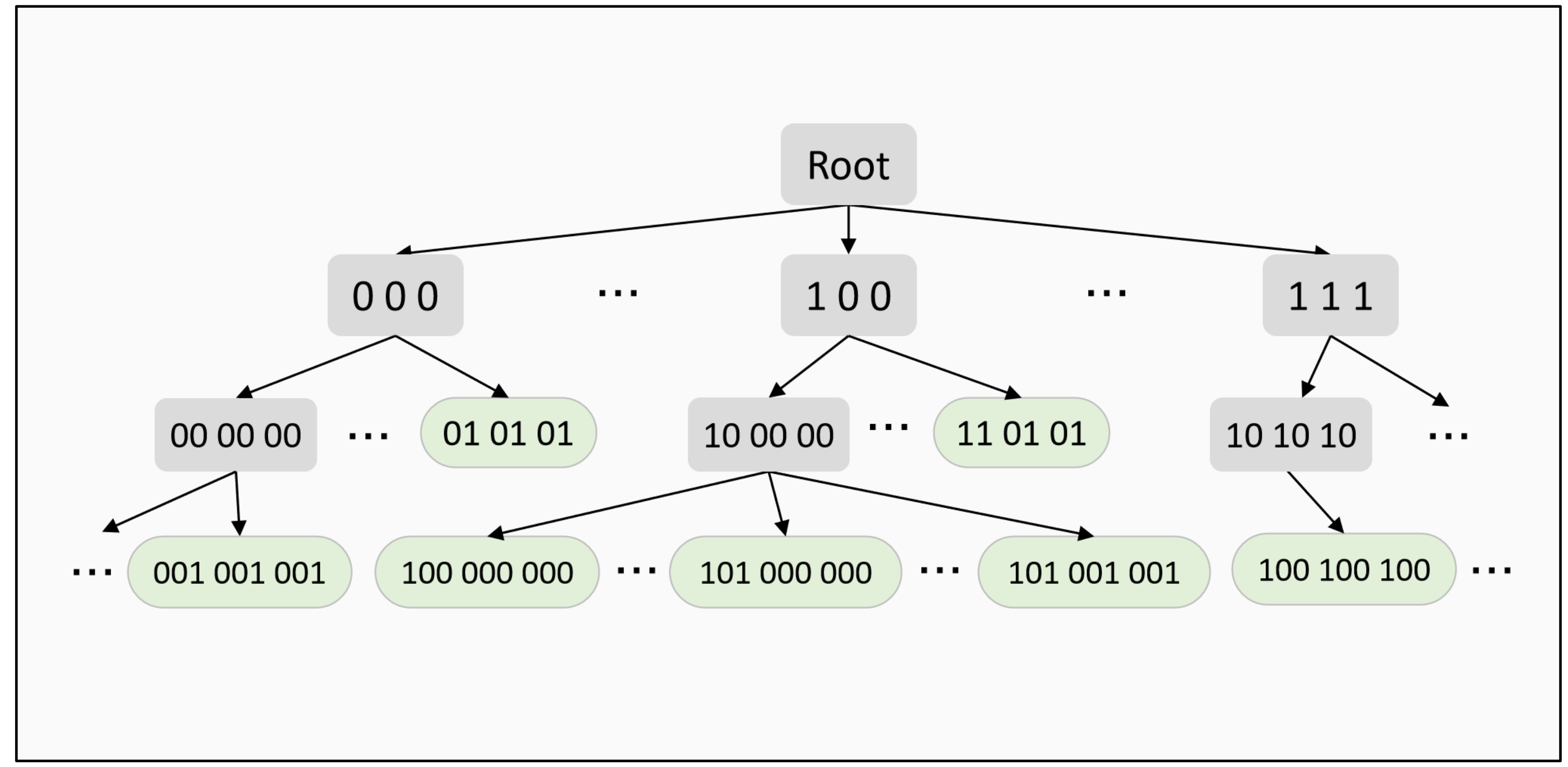
6-Proximity-Compactness Trade-off

2-ary



Splitting Decisions

Full-Ary



Compactness

with proximity problem: skewed split

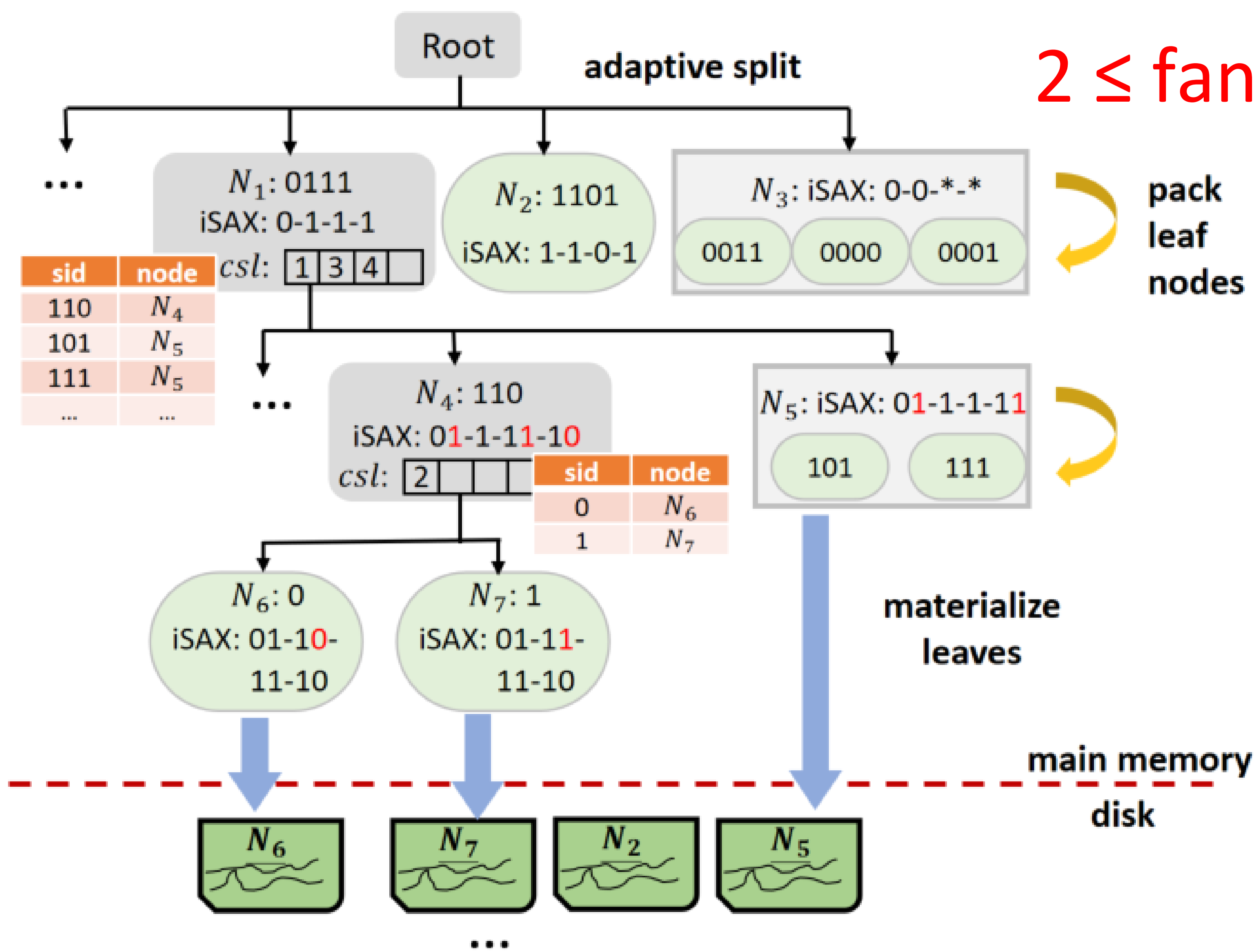
Proximity

with compactness problem: low fill factor

Dumpy dynamically strikes the right balance in this trade-off!

7-Dumpy's Adaptive Split Strategy

Multi-ary Index Structure



$2 \leq \text{fanout} \leq 2^w$

w: number of segments

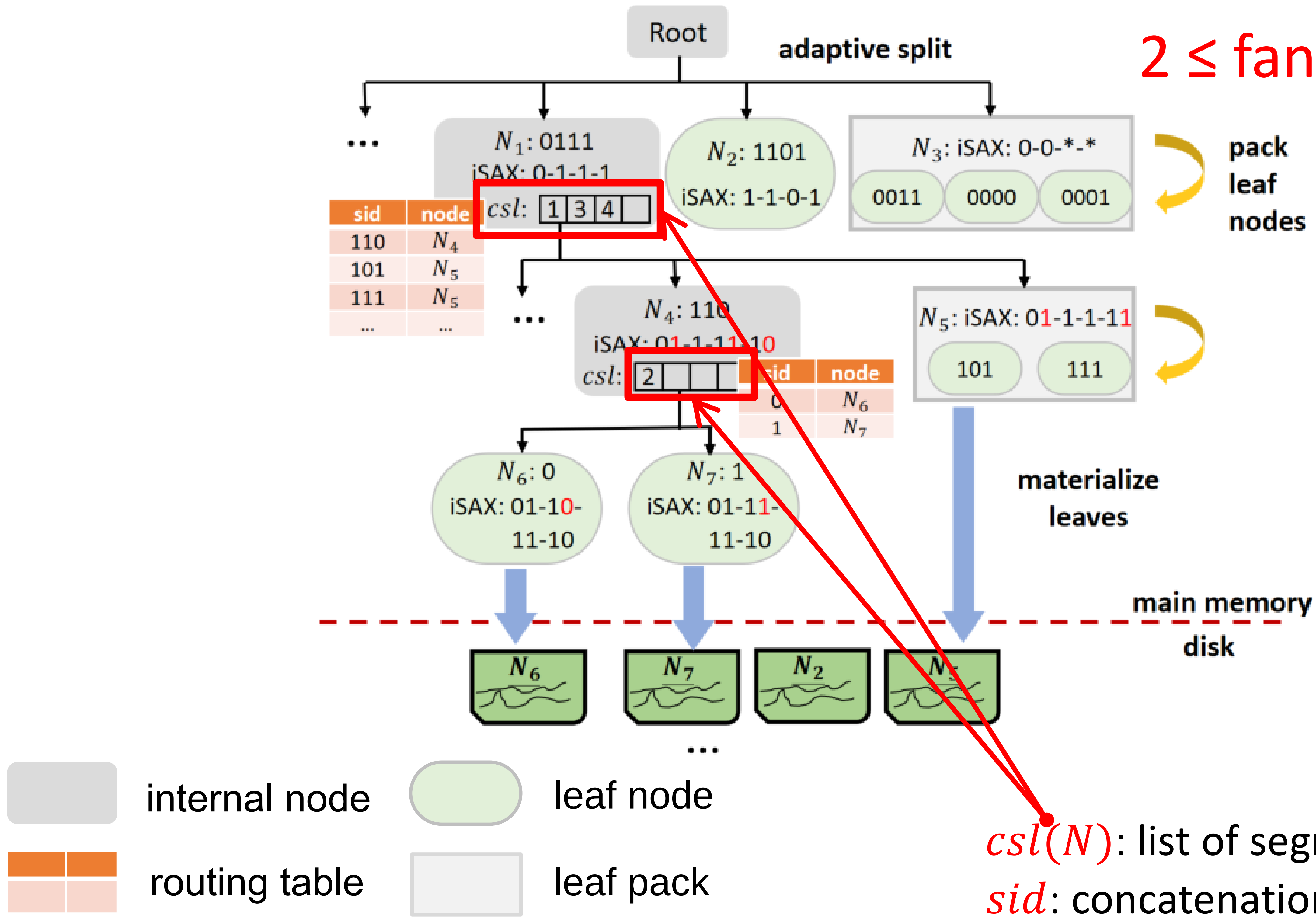
internal node	leaf node
routing table	leaf pack

$csl(N)$: list of segments to be split of node N

sid: concatenation of newly-extended bits compared with parent node

7-Dumpy's Adaptive Split Strategy

Multi-ary Index Structure



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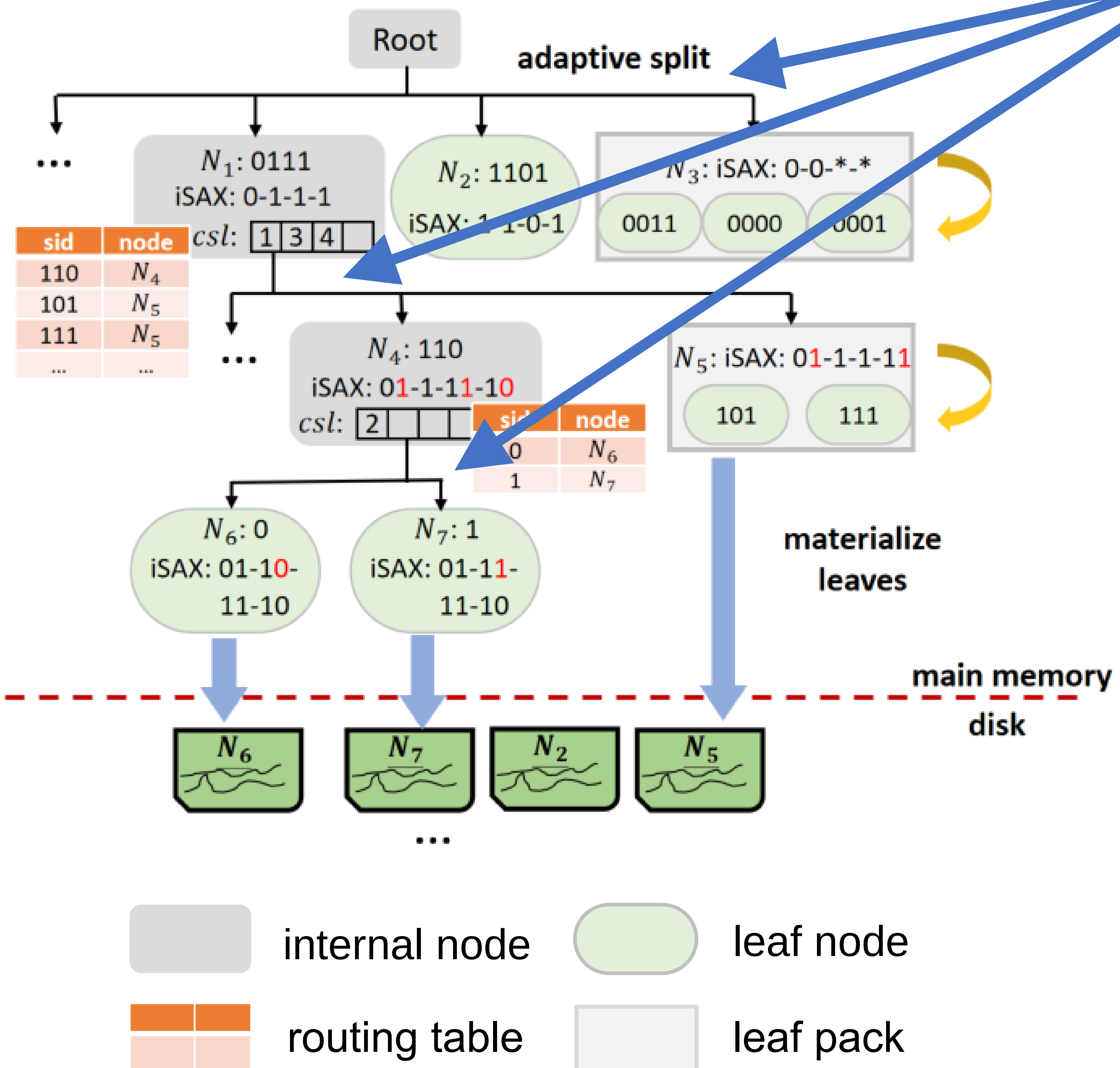


Decide fanout and segments to split on-the-fly

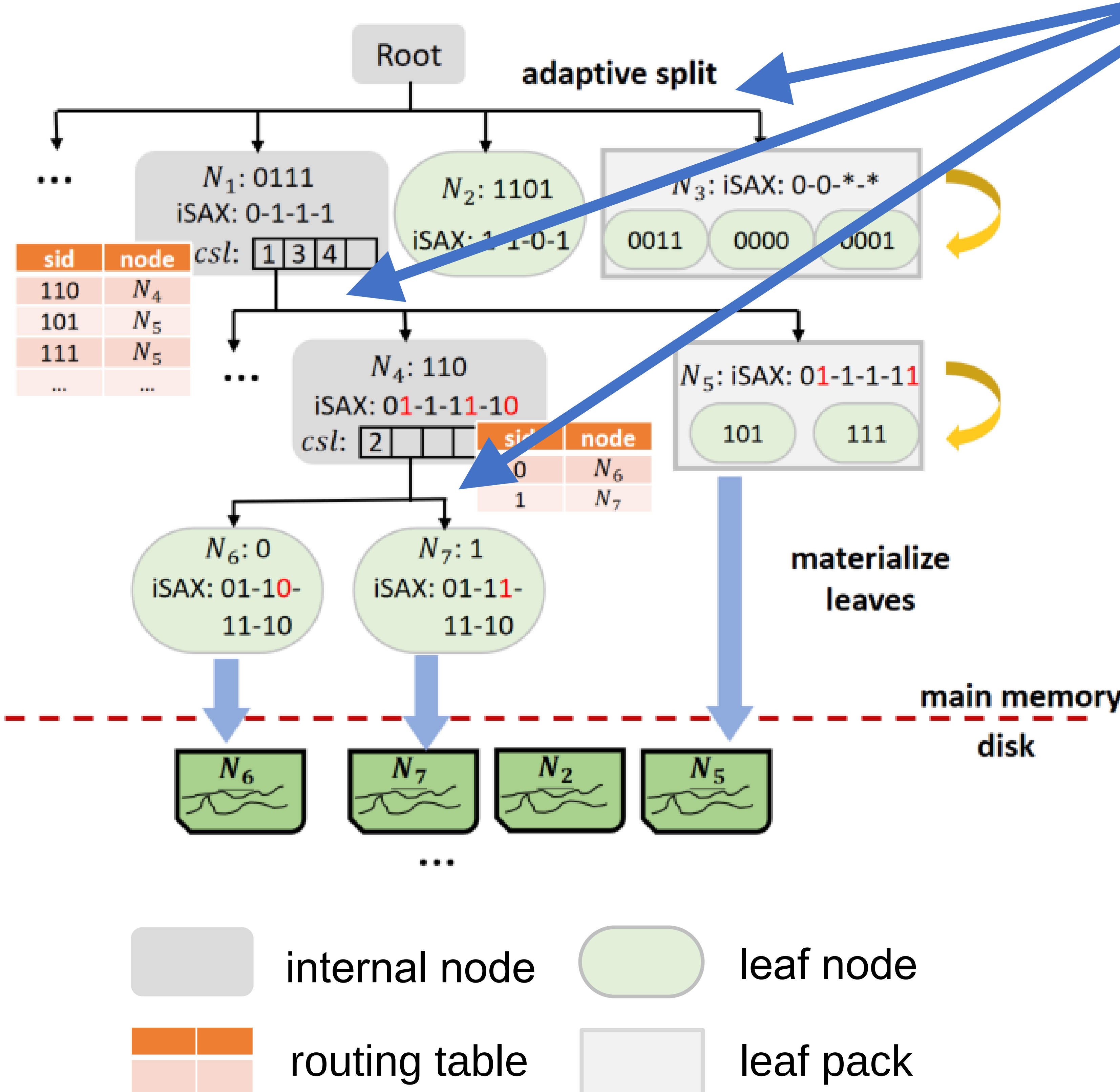
↓

$csl(N)$

$csl(N)$ *can be any non-empty combination of all w segments.*

Totally, $2^w - 1$ *possible ways to split.*
Which one is the optimal?

7-Dumpy's Adaptive Split Strategy



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$\boldsymbol{csl(N)}$

$csl(N)$ can be any non-empty combination of all w segments.

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Proximity-Compactness Trade-off

objective function:

$$\max_{csl(N)} e^{\sqrt{\frac{1}{|csl(N)|} Var(X'_N)}} + \alpha * e^{-(1+o)\sigma_F}$$

Proximity term

weight factor

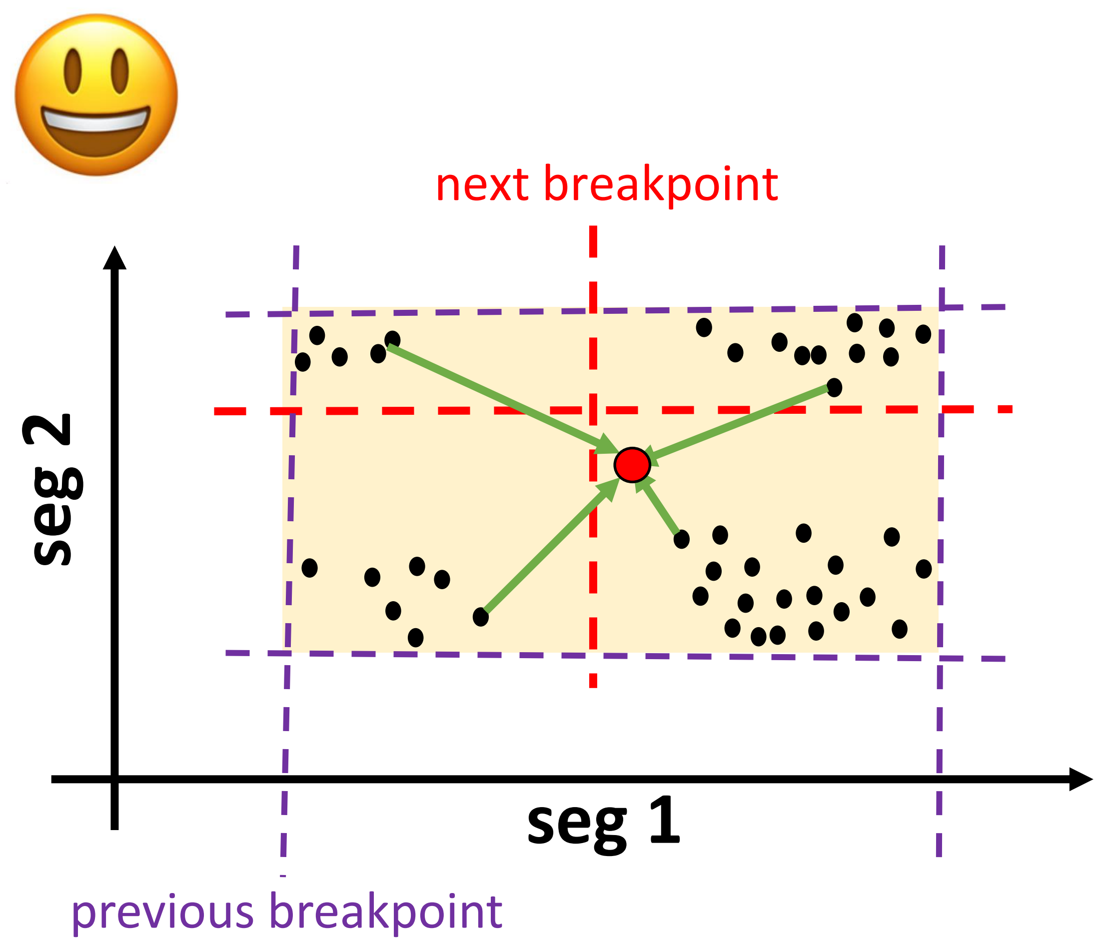
Compactness term

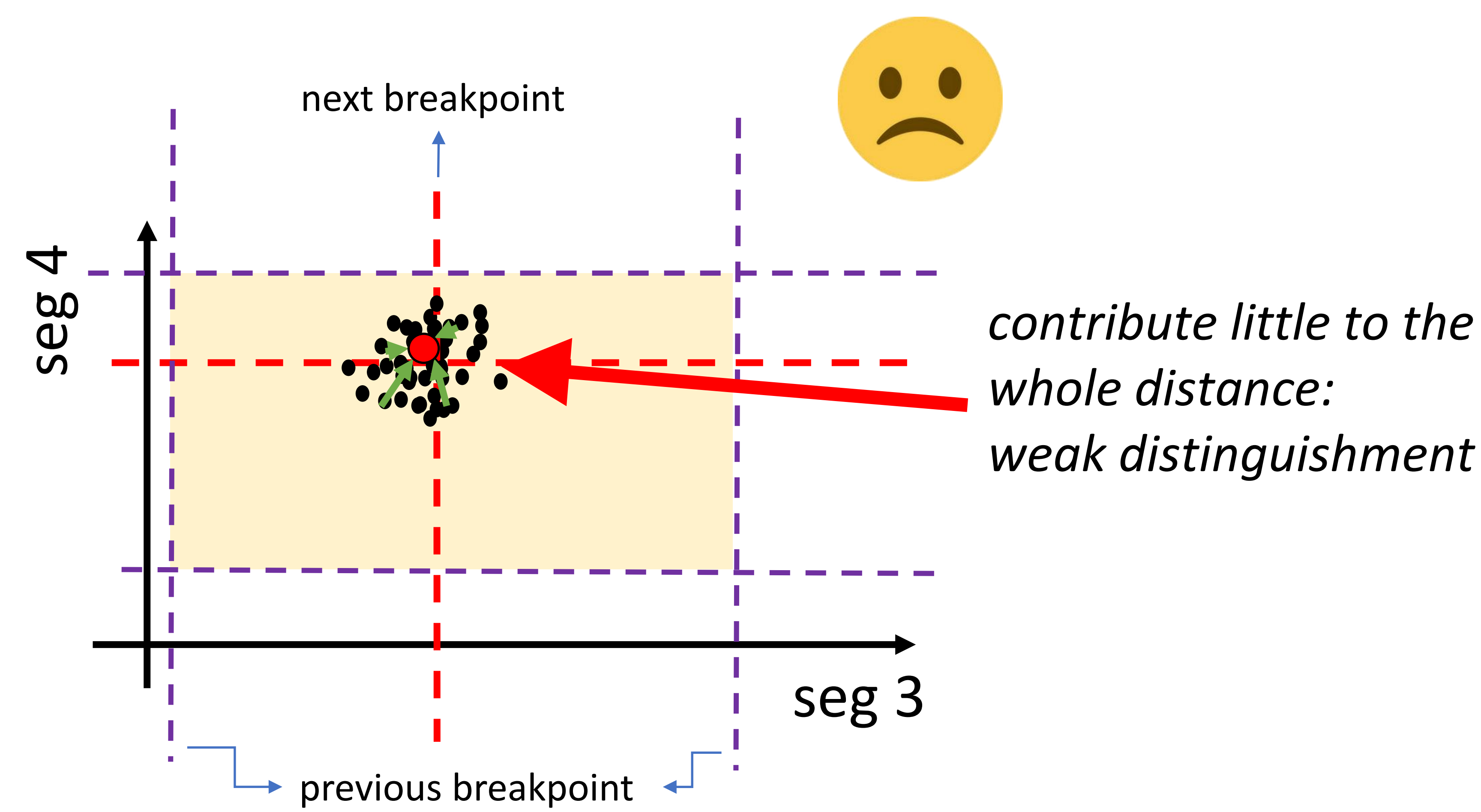
7-Dumpy's Adaptive Split Strategy

Innovation 1: Adaptive split strategy

$$\max_{csl(N)} \boxed{e^{\sqrt{\frac{1}{|csl(N)|}Var(\chi'_N)}}} + \alpha * e^{-(1+o)\sigma_F}$$

Proximity term *avg. distance to the centroid*



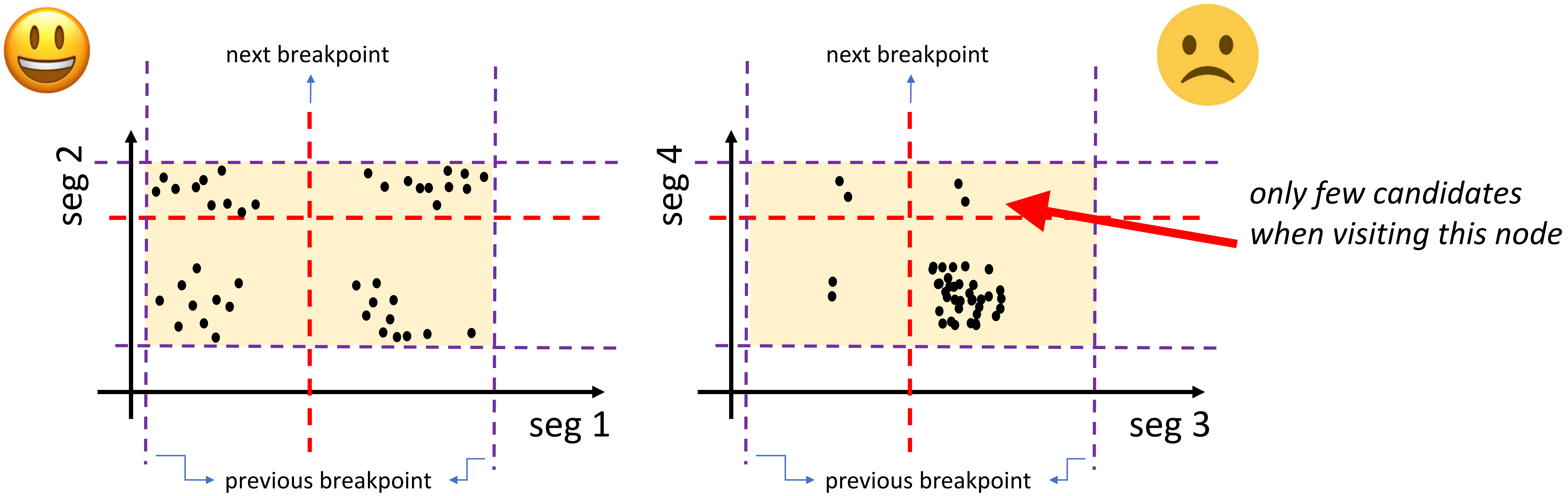


- PAA points projected on the segments of the plan
- $\boldsymbol{\mu}$: centroid of these SAX points

Innovation 1: Adaptive split strategy

$$\max_{csl(N)} e^{\sqrt{\frac{1}{|csl(N)|} Var(\chi'_N)}} + \alpha * \boxed{e^{-(1+o)\sigma_F}}$$

Compactness term *stdev of fill factors of child nodes*



- PAA points projected on the segments of the plan

8-Fast search for optimal split

1. pre-compute variance

$$Var(\mathcal{X}'_N) = \sum_{cs \in csl(N)} Var(\Pi_{cs}(\mathcal{X}_N))$$

ONE time scan for all split plans

8-Fast search for optimal split

1. pre-compute variance

$$Var(\mathcal{X}'_N) = \sum_{cs \in csl(N)} Var(\Pi_{cs}(\mathcal{X}_N))$$

ONE time scan for all split plans

2. restrict the search space

$$\max(1, \log \frac{c_N}{F_r * th}) \leq |csl(N)| \leq \min(w, \log \frac{c_N}{F_l * th})$$

skip the split plan whose fanout is too large or small

8-Fast search for optimal split

1. pre-compute variance

$$Var(X'_N) = \sum_{cs \in csl(N)} Var(\Pi_{cs}(X_N))$$

ONE time scan for all split plans

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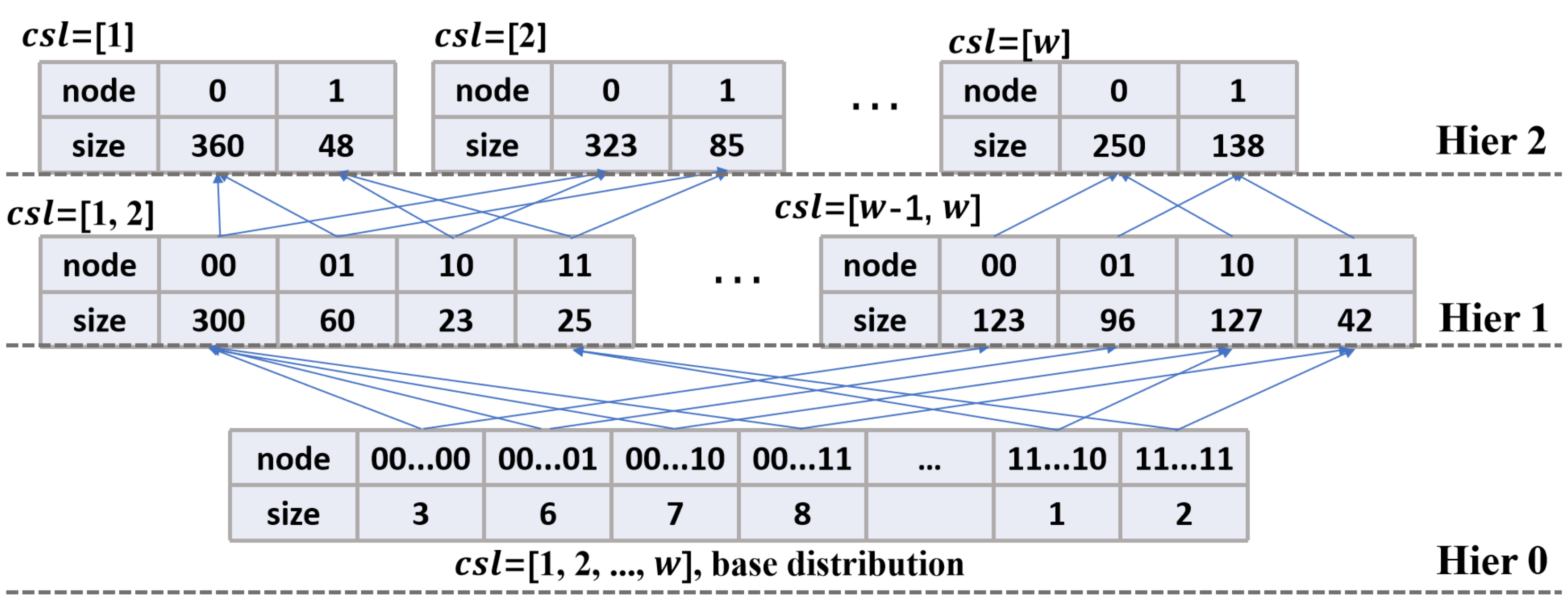
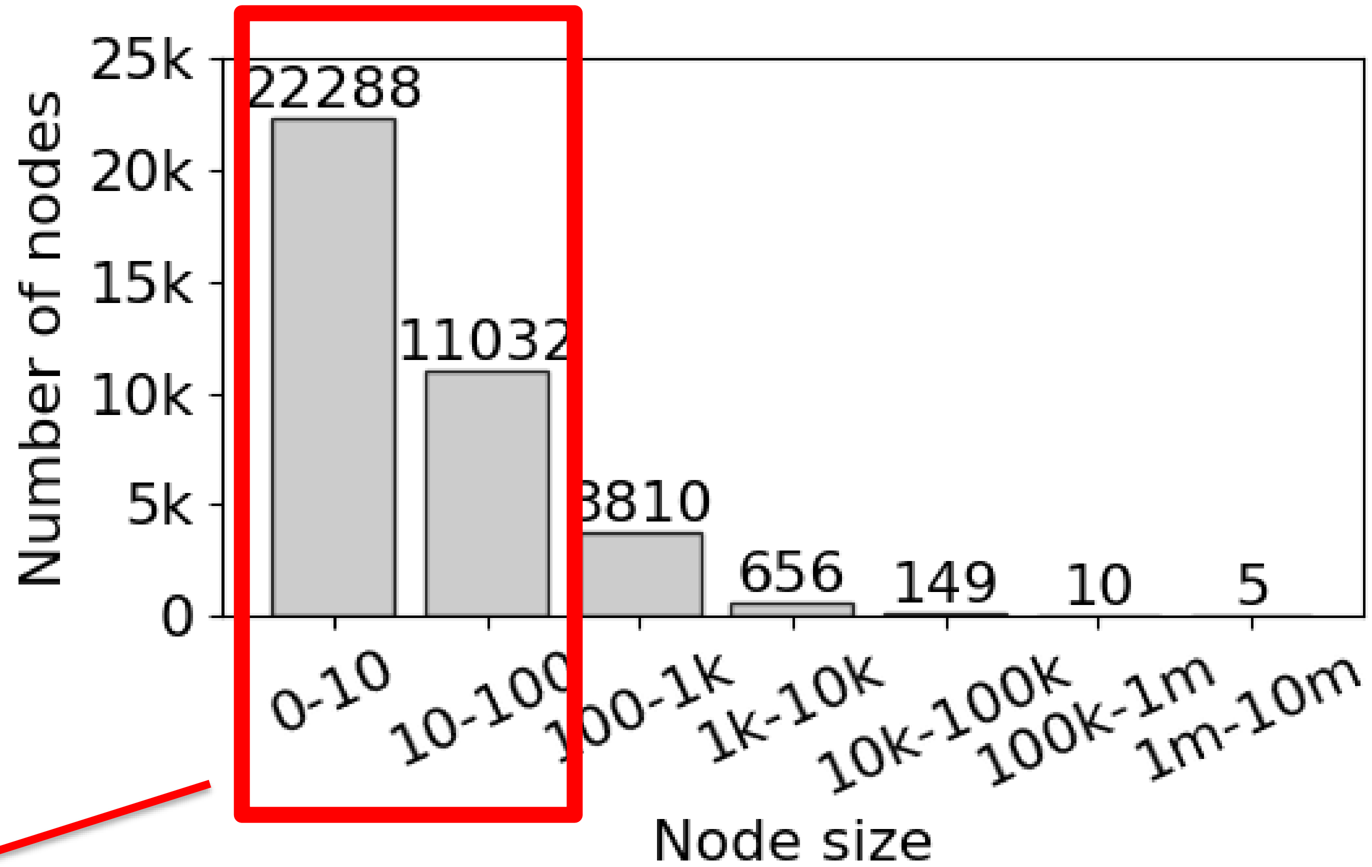
skip the split plan whose fanout is too large or small

3. hierarchically compute sizes of child nodes



recursive computing:
CONSTANT complexity for most split plans

9-Data Skewness of iSAX Index

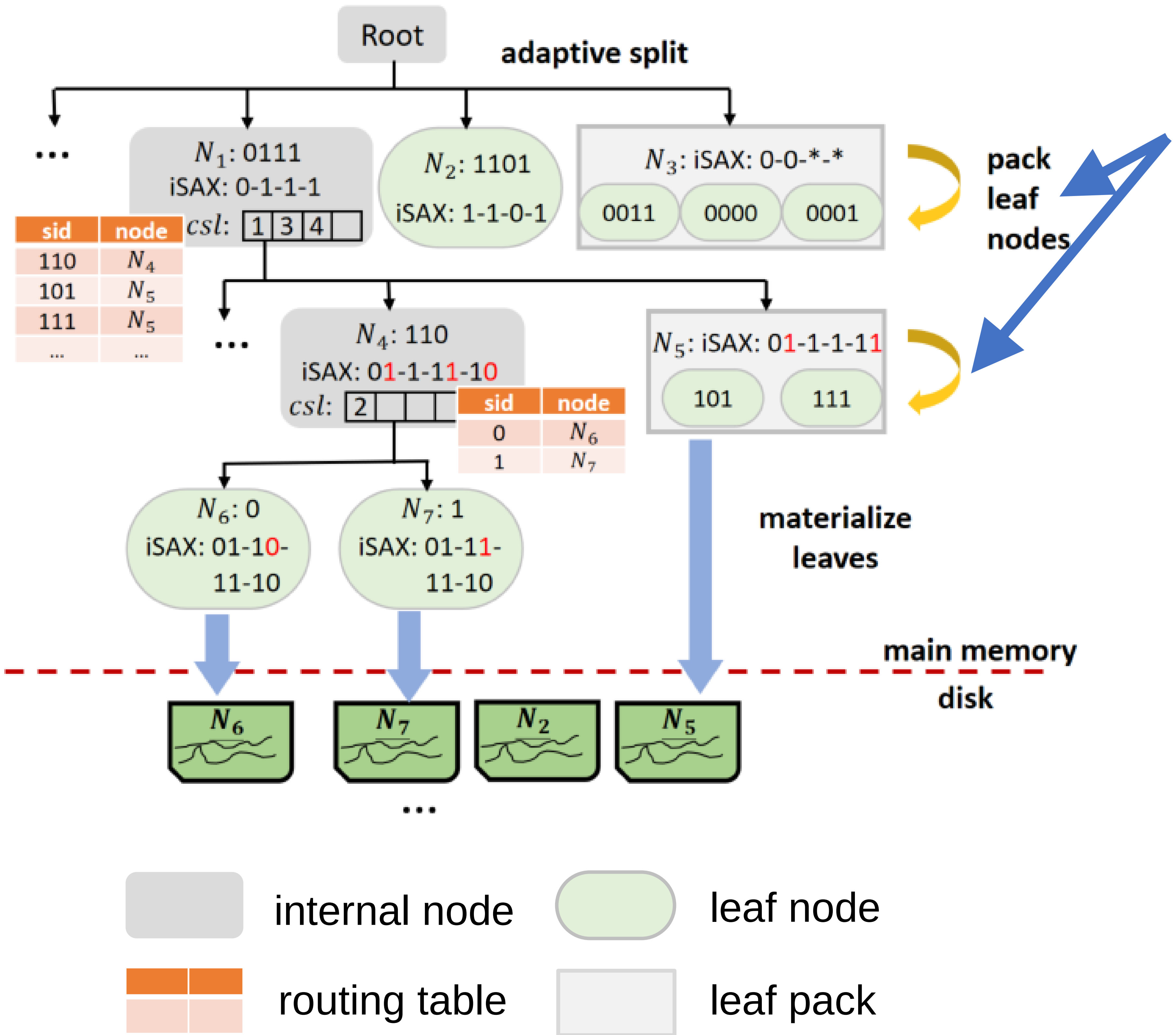


Most leaves are very small!

Node size distribution on the 1st layer of iSAX (w=16)

w: number of segments

10-Dumpy's Leaf Node Packing

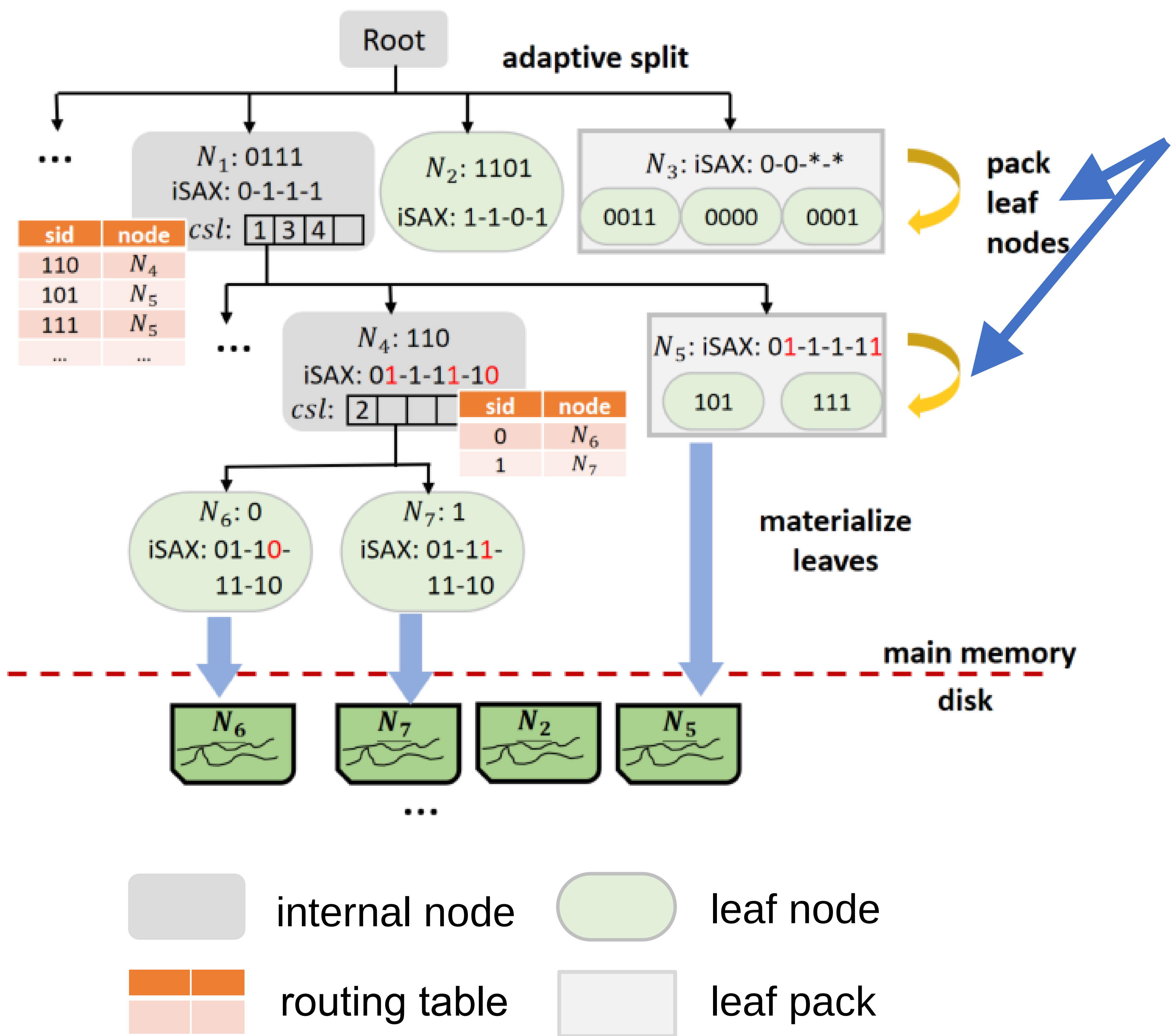


Group small similar leaf nodes into a pack

Input: small leaf nodes under the same parent (siblings)

Output: A group of leaf packs within the size constraints

10-Dumpy's Leaf Node Packing



Group small close leaf nodes into a pack

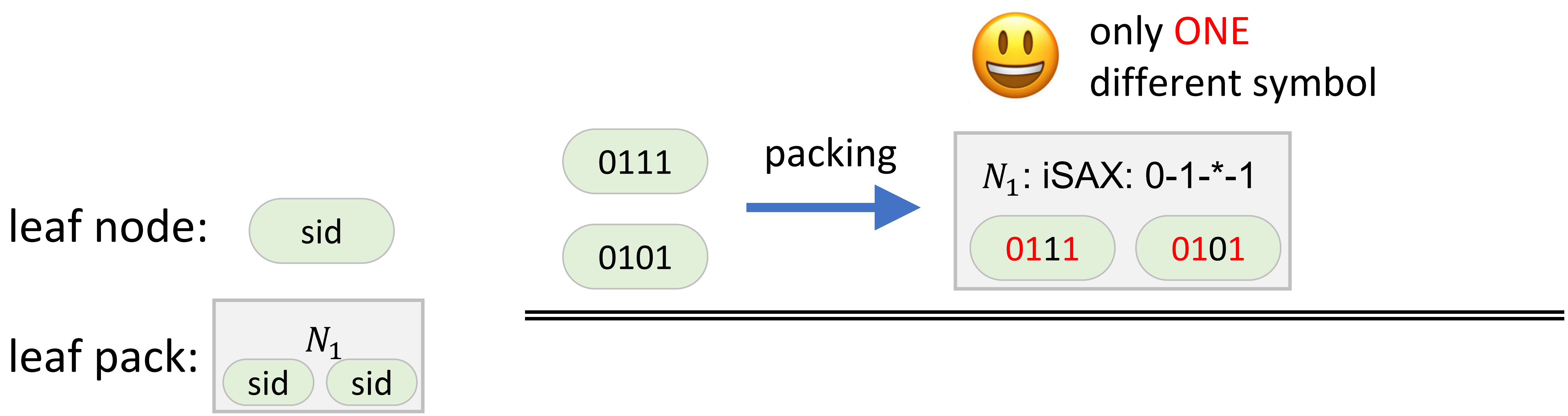
How to measure?

Input: small leaf nodes under the same parent (siblings)

Output: A group of leaf packs within the size constraints

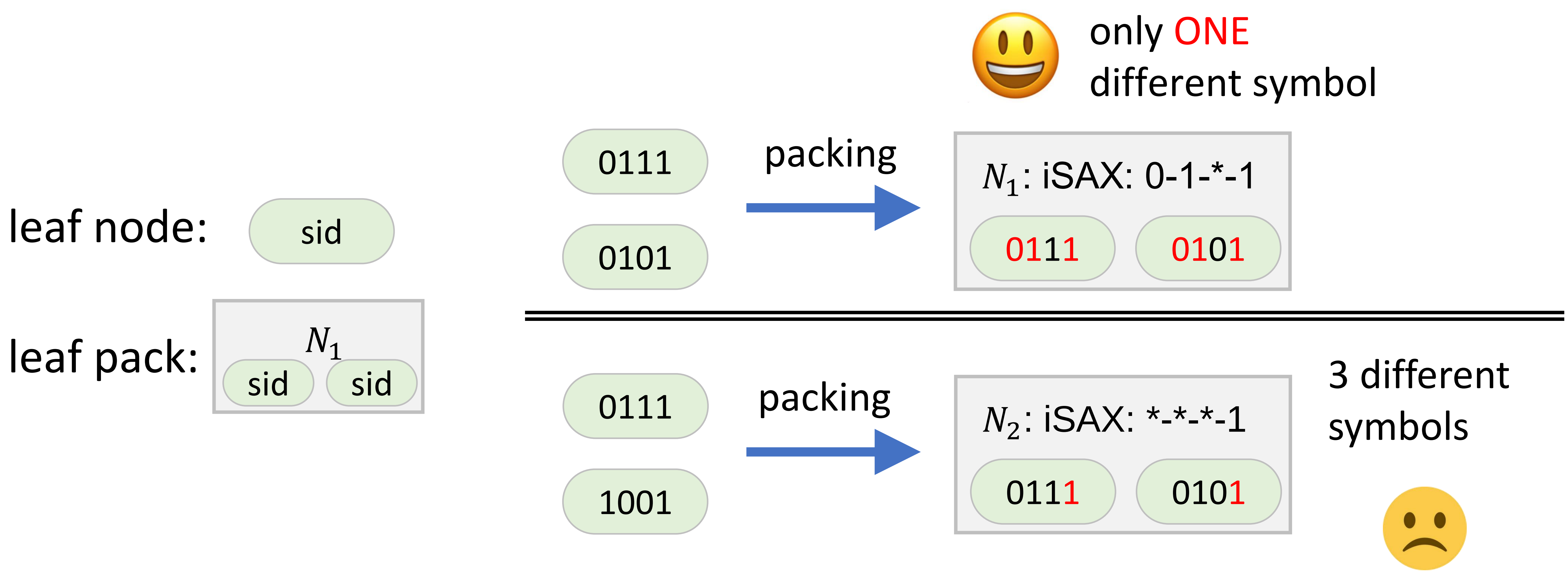
10-Dumpy's Leaf Node Packing

- Input: <u>Small</u> leaf nodes under the same parent (siblings)
- Output: A group of leaf node packs within the size constriant



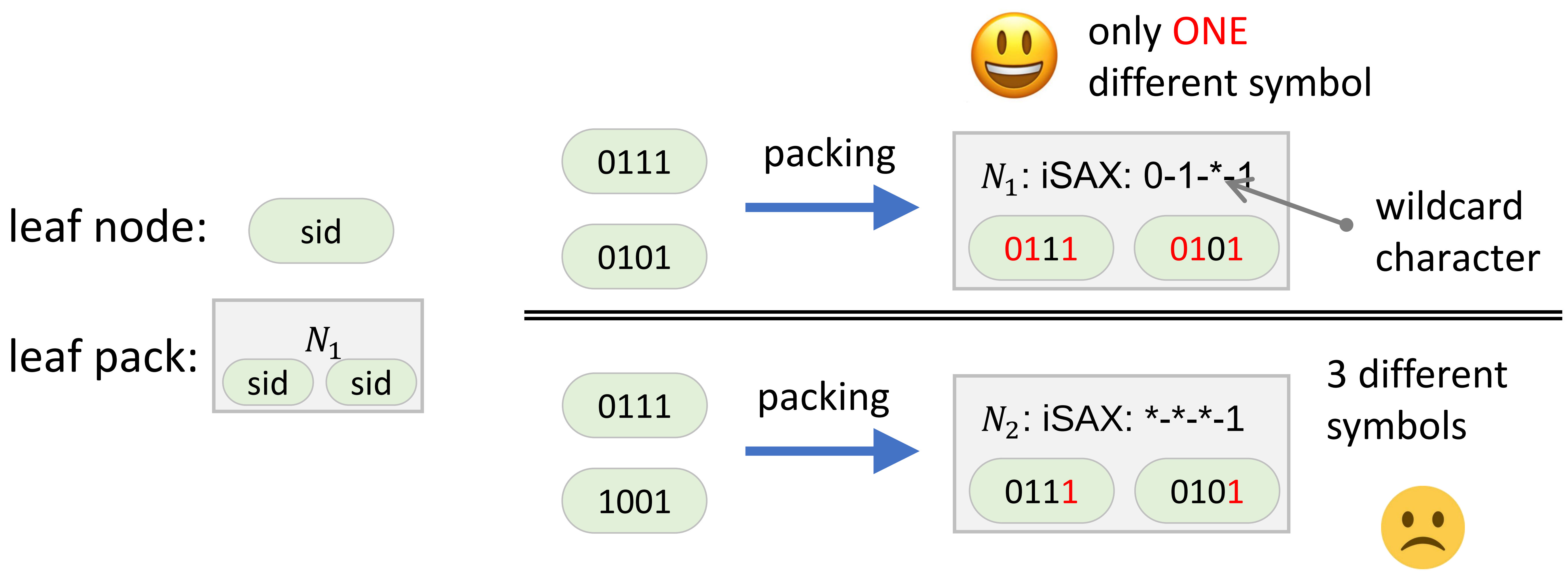
10-Dumpy's Leaf Node Packing

- Input: Small leaf nodes under the same parent (siblings)
- Output: A group of leaf node packs within the size constriant



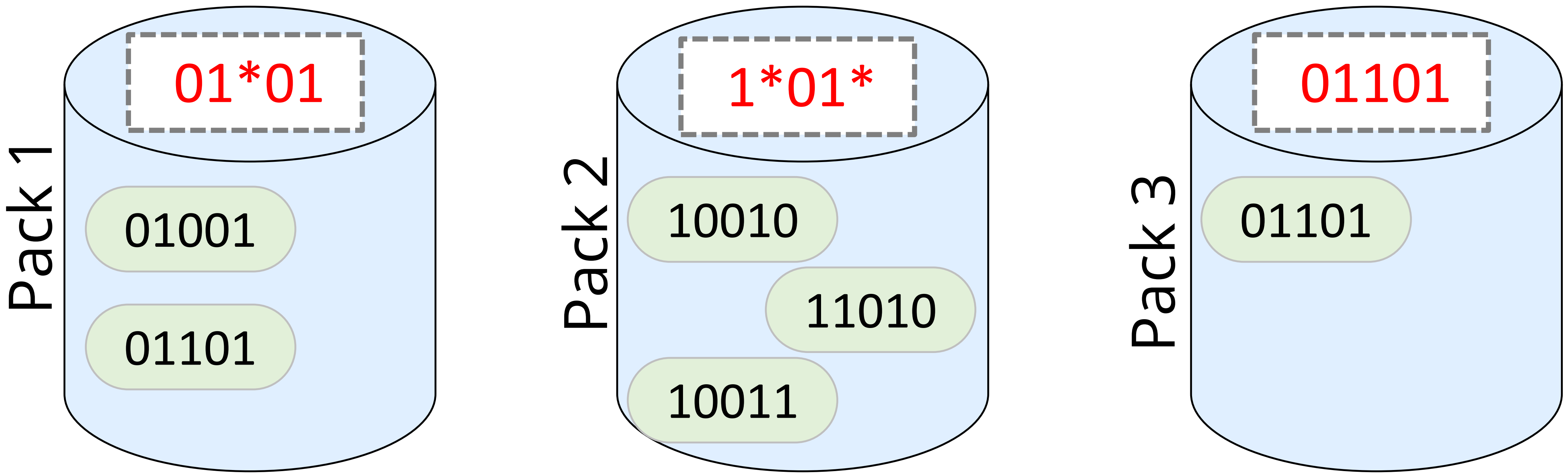
10-Dumpy's Leaf Node Packing

- Input: Small leaf nodes under the same parent (siblings)
- Output: A group of leaf node packs within the size constriant
- Core idea: **limit the number of different symbols (#(*)) in the leaf pack.**



10-Dumpy's Leaf Node Packing

Greedily select the best pack or create a new one

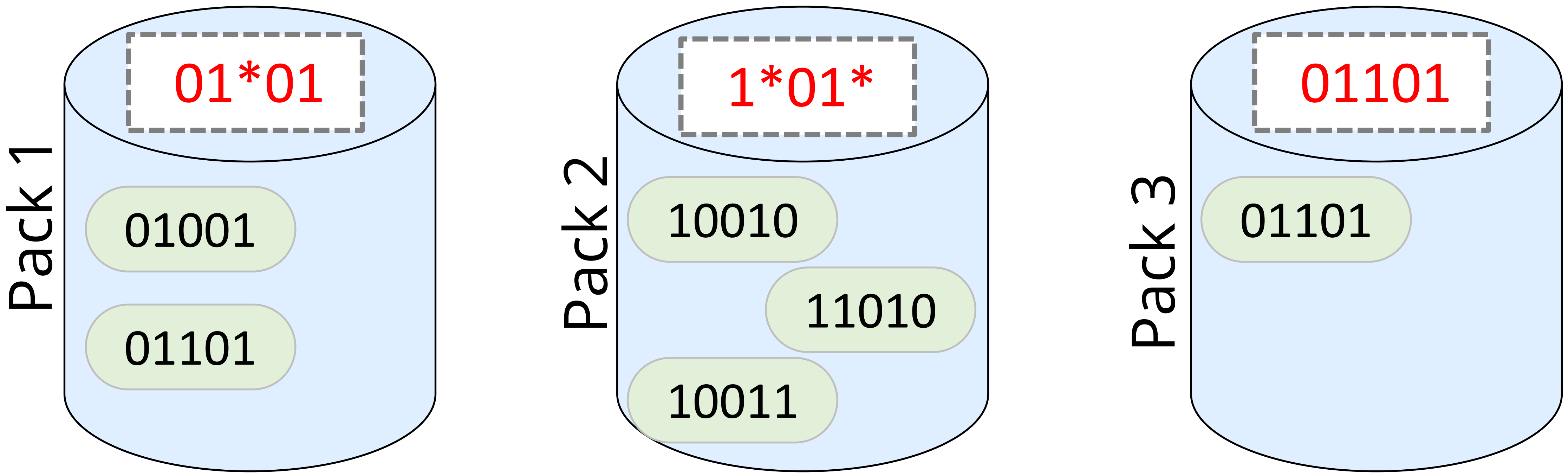


10-Dumpy's Leaf Node Packing

Greedily select the best pack or create a new one

find a pack for this leaf

11101



10-Dumpy's Leaf Node Packing

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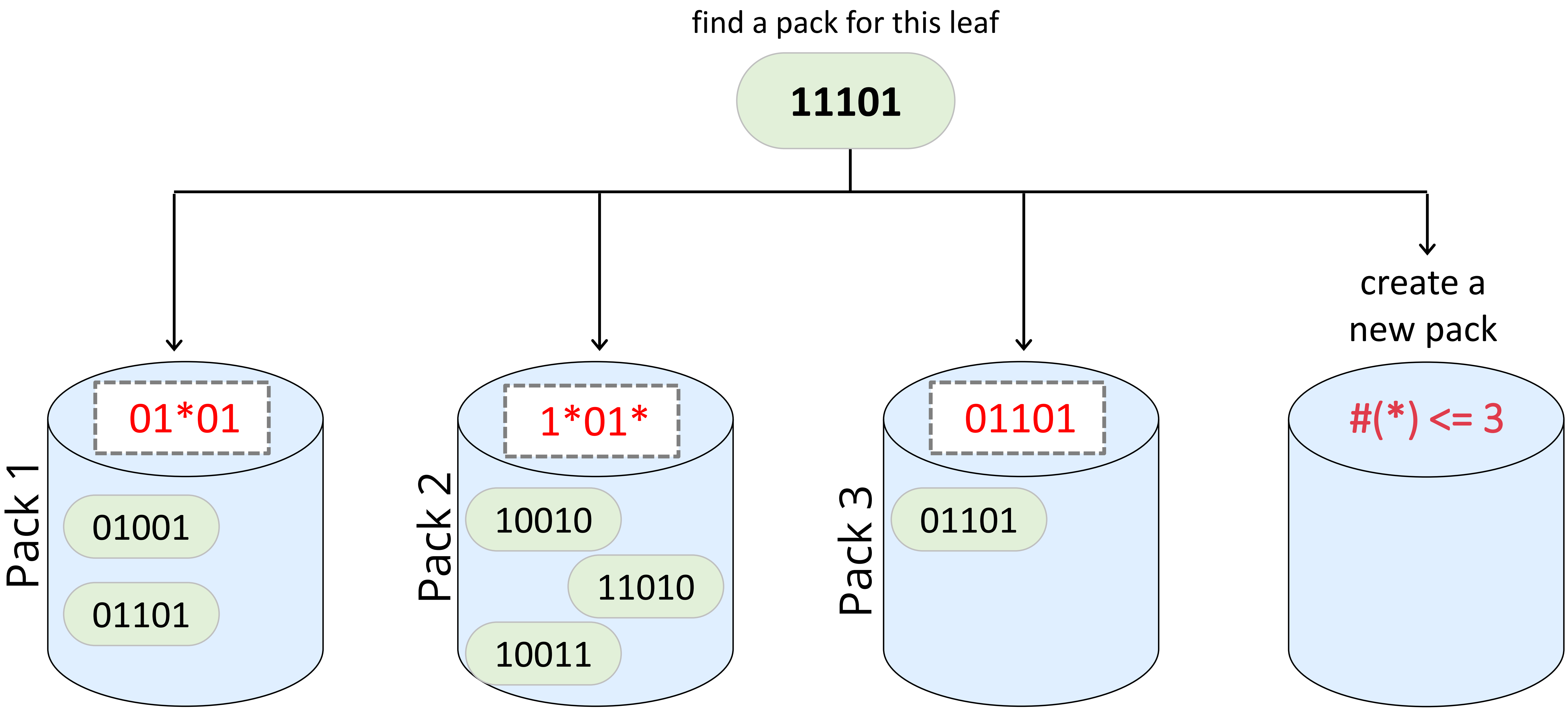
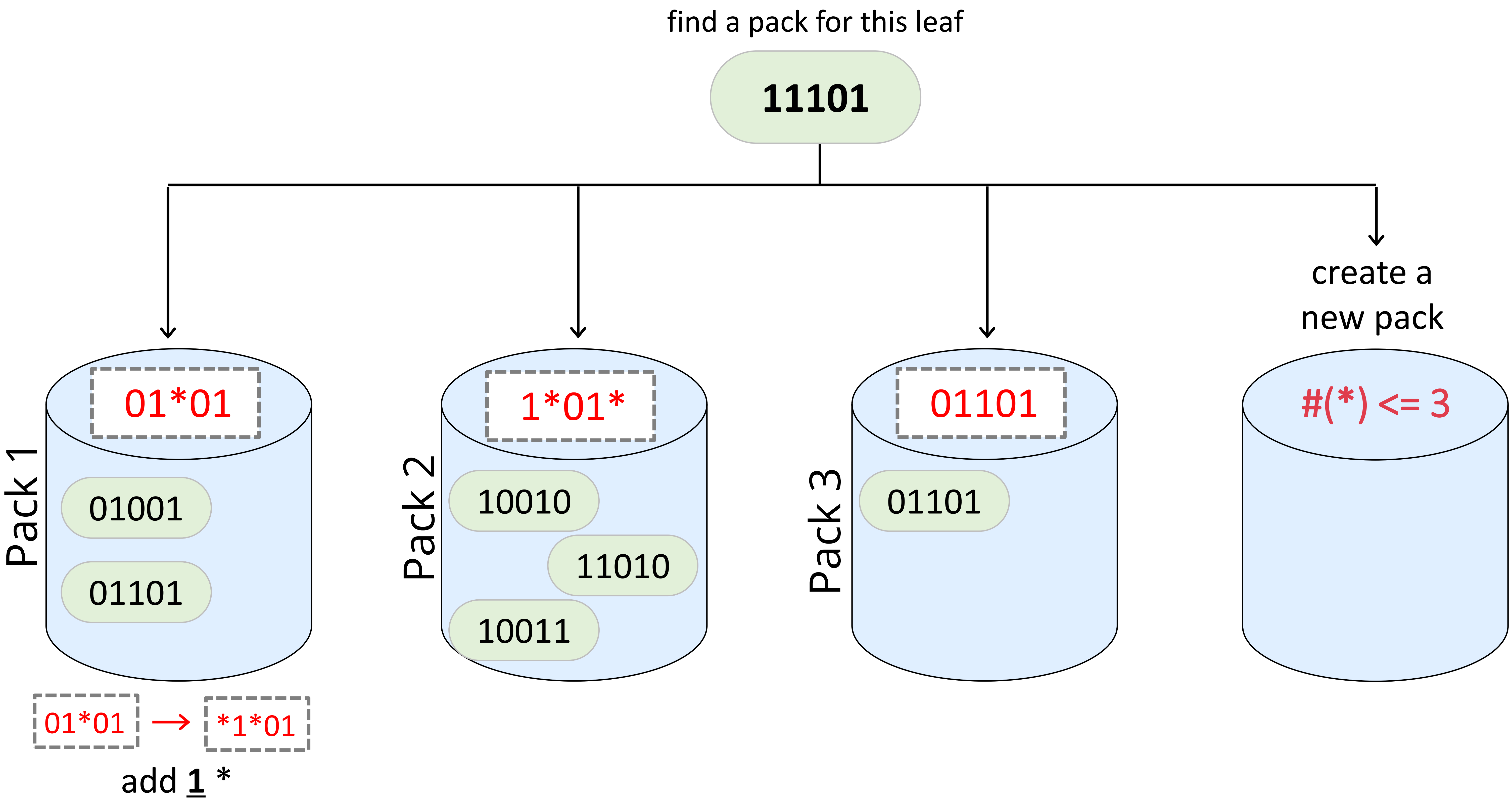


10-Dumpy's Leaf Node Packing

Greedily select the best pack or create a new one



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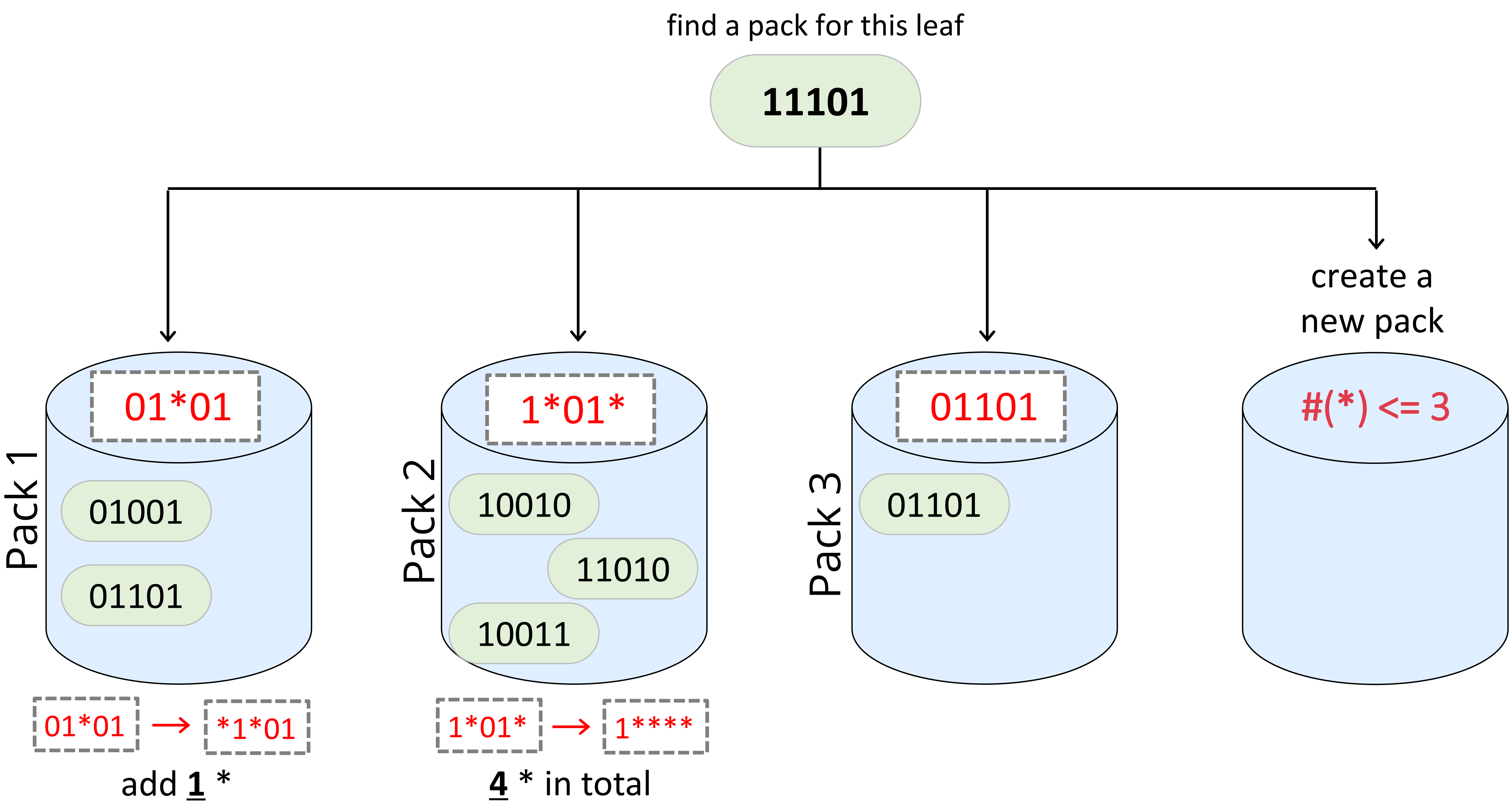

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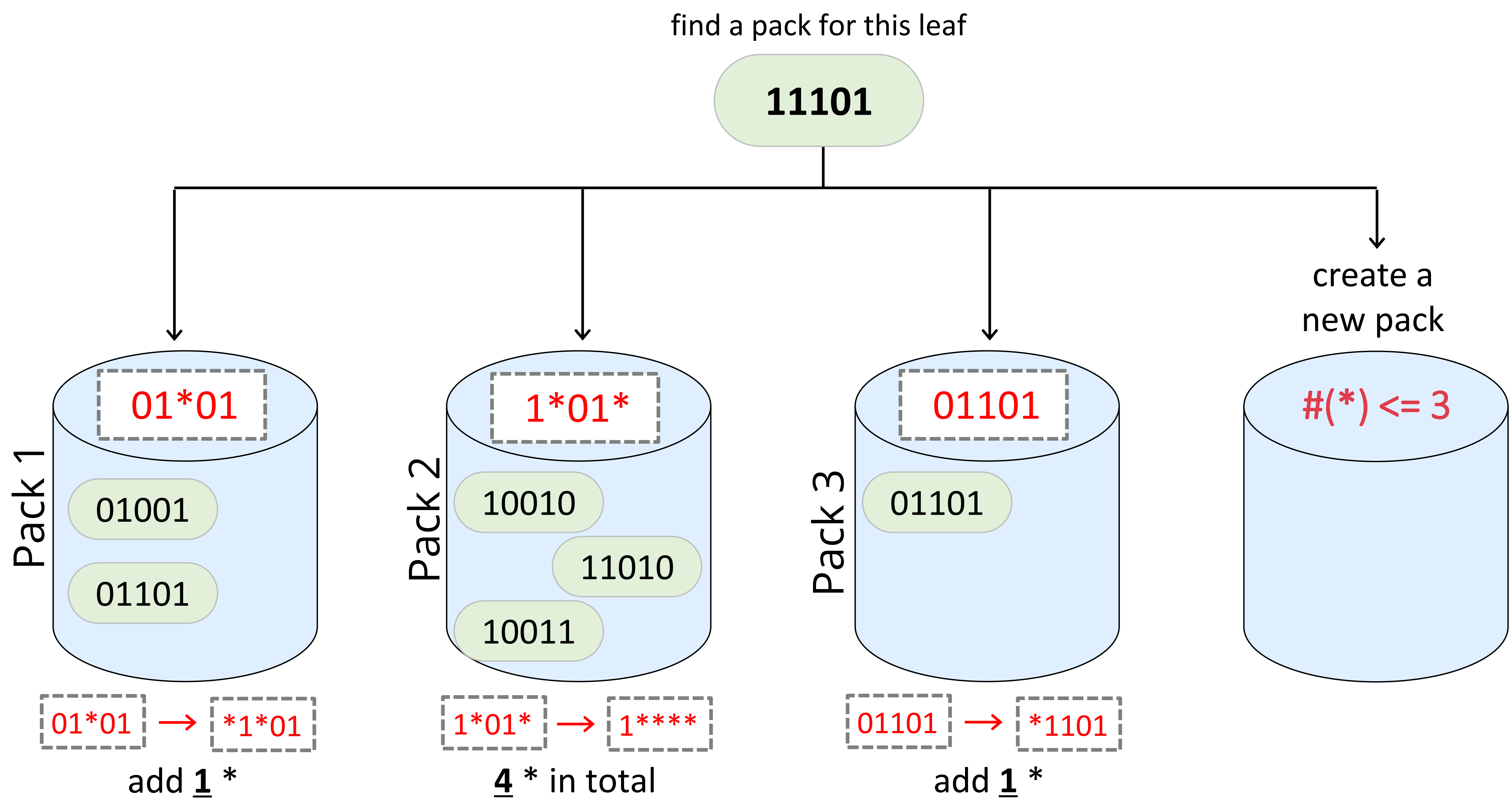

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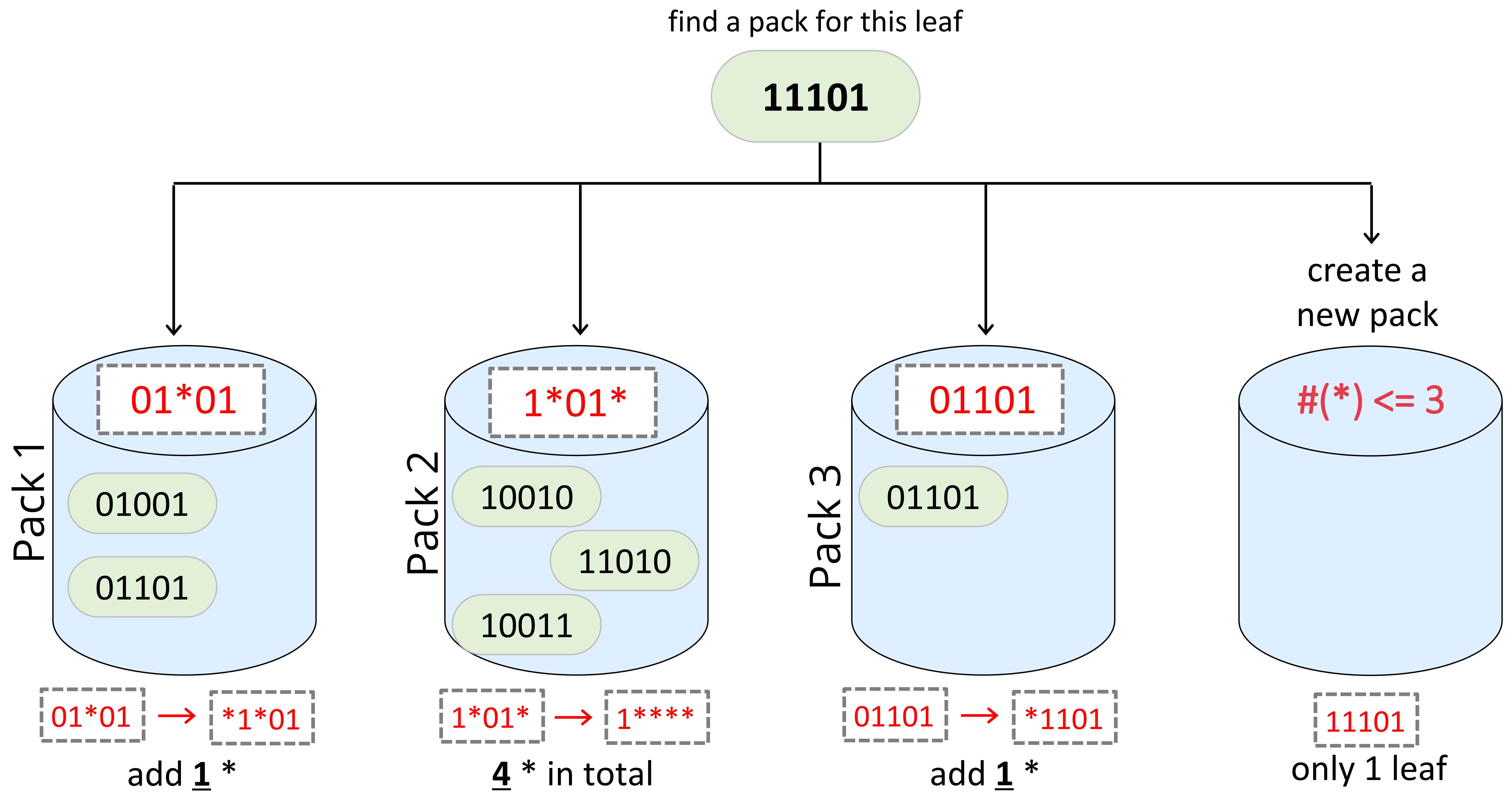

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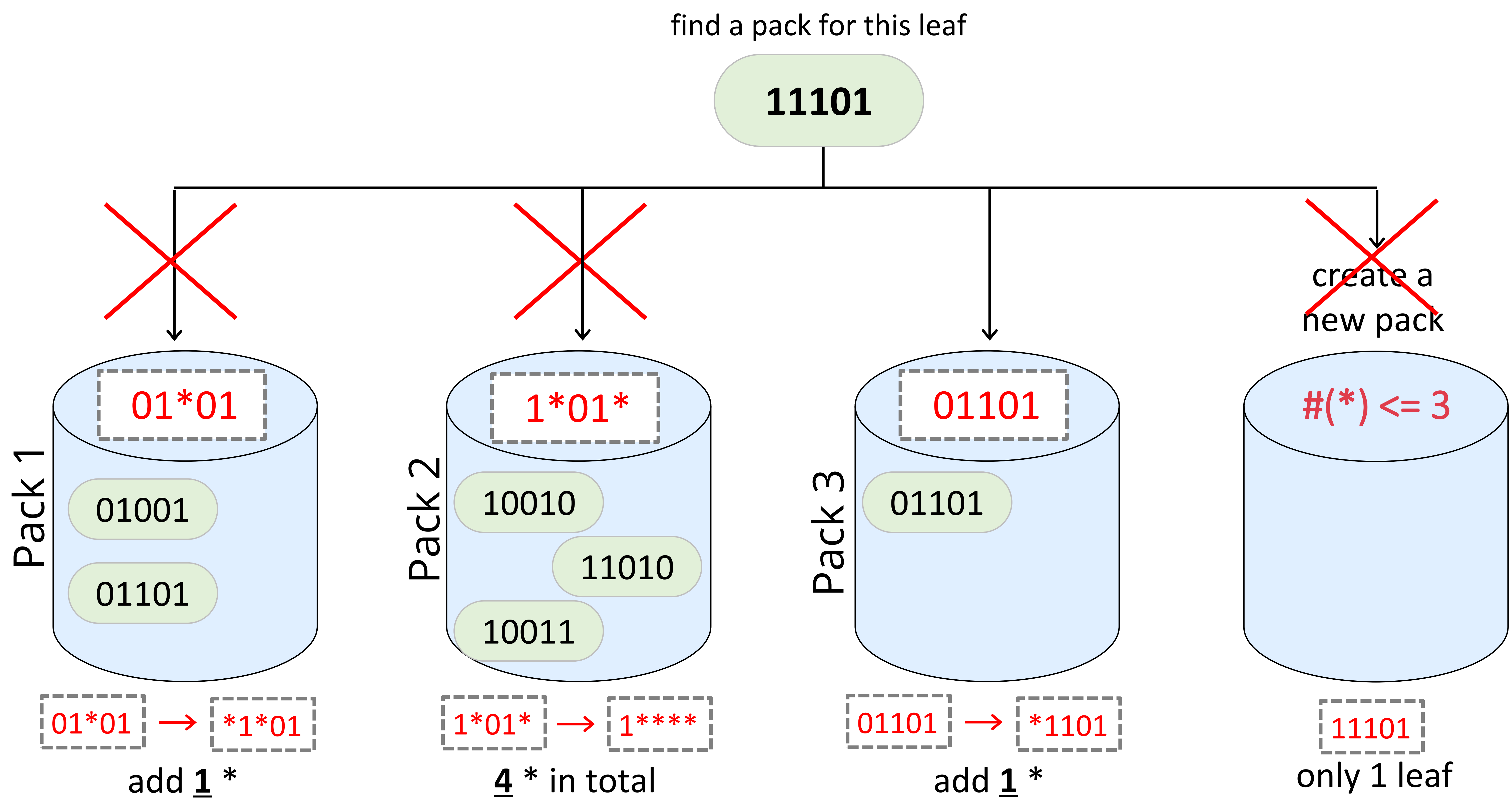

10-Dumpy's Leaf Node Packing

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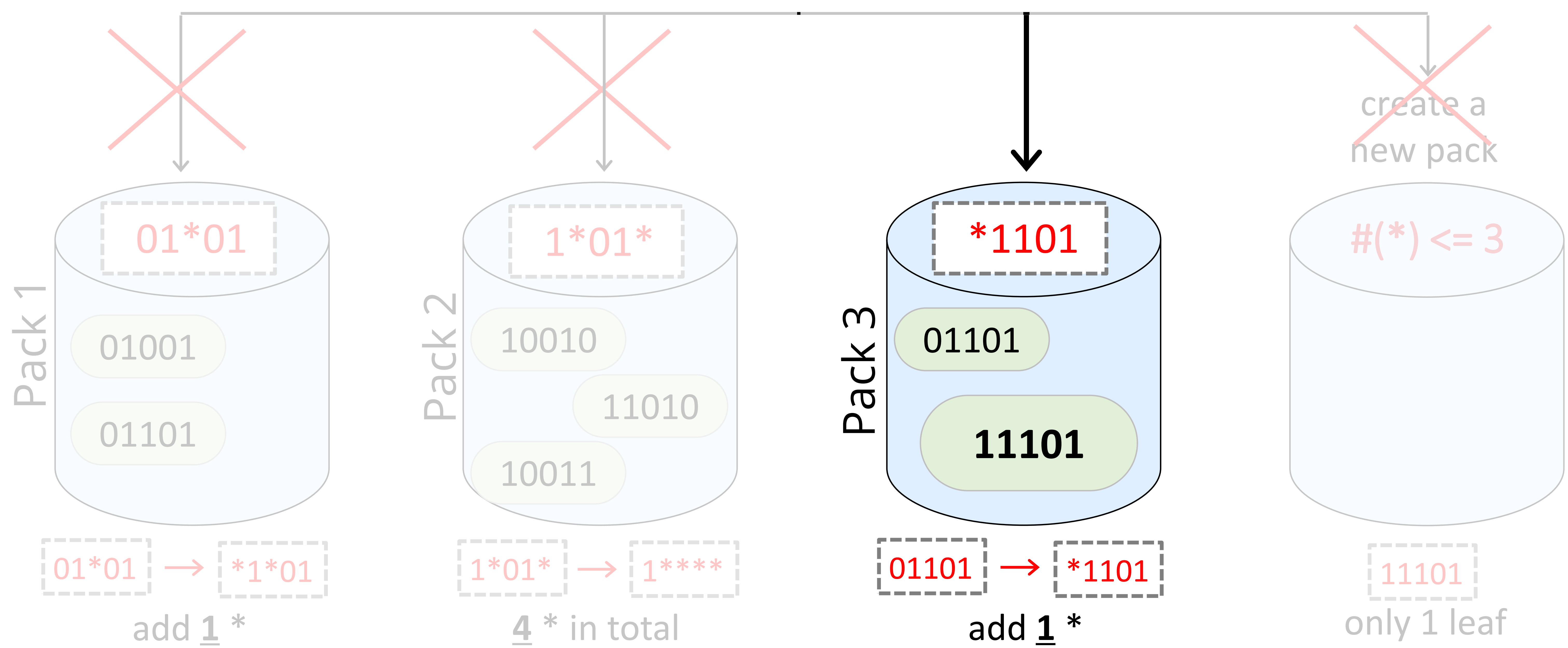
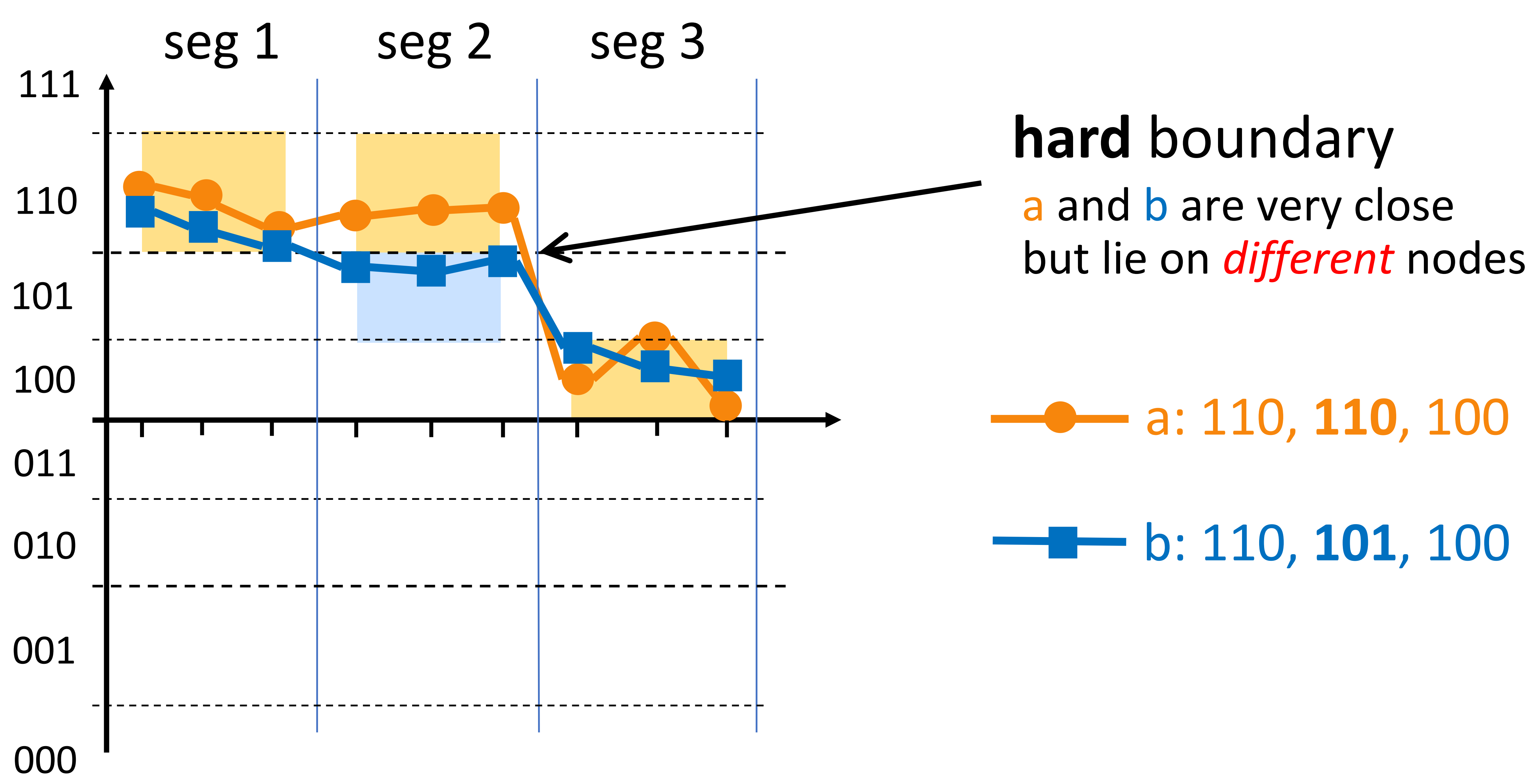


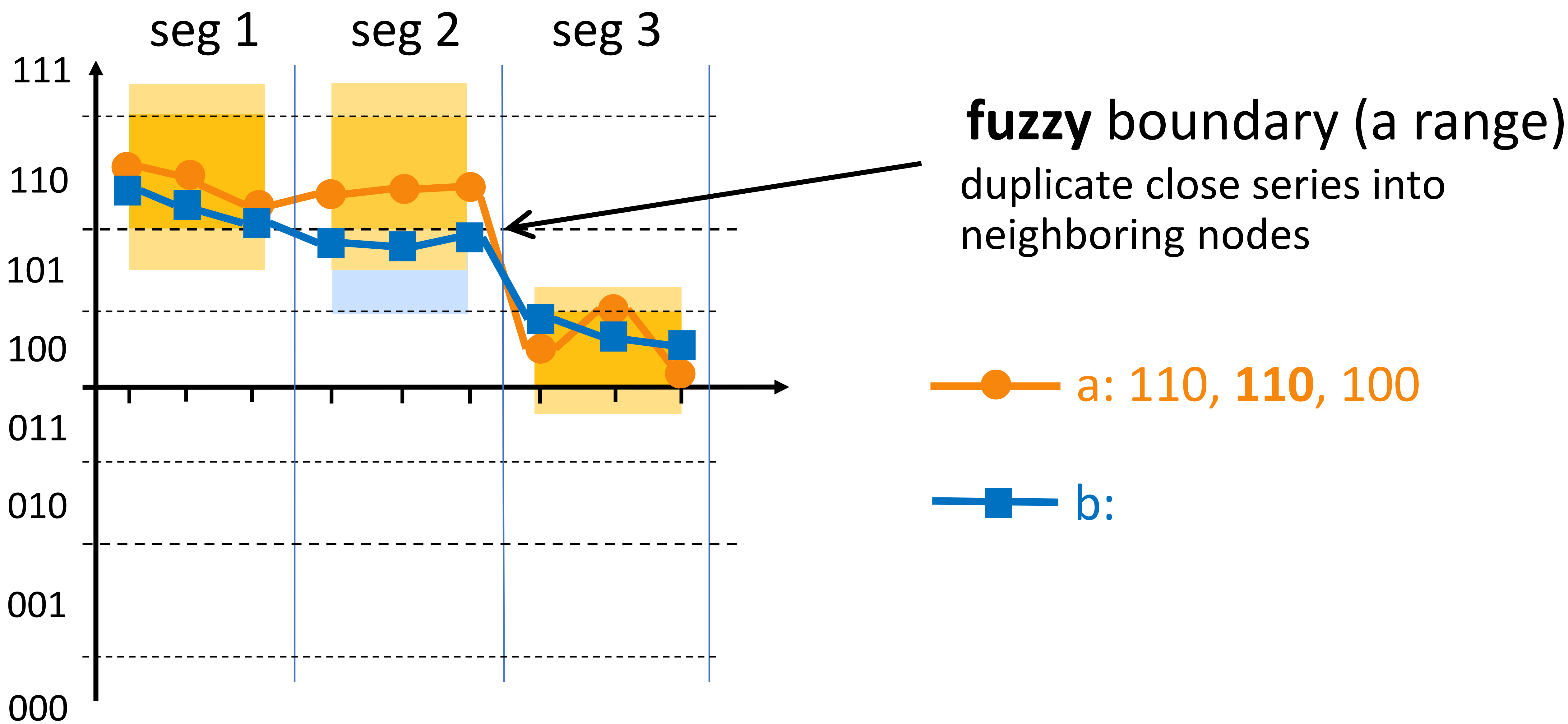
11-Dumpy-Fuzzy

An example of *Boundary Issue*:



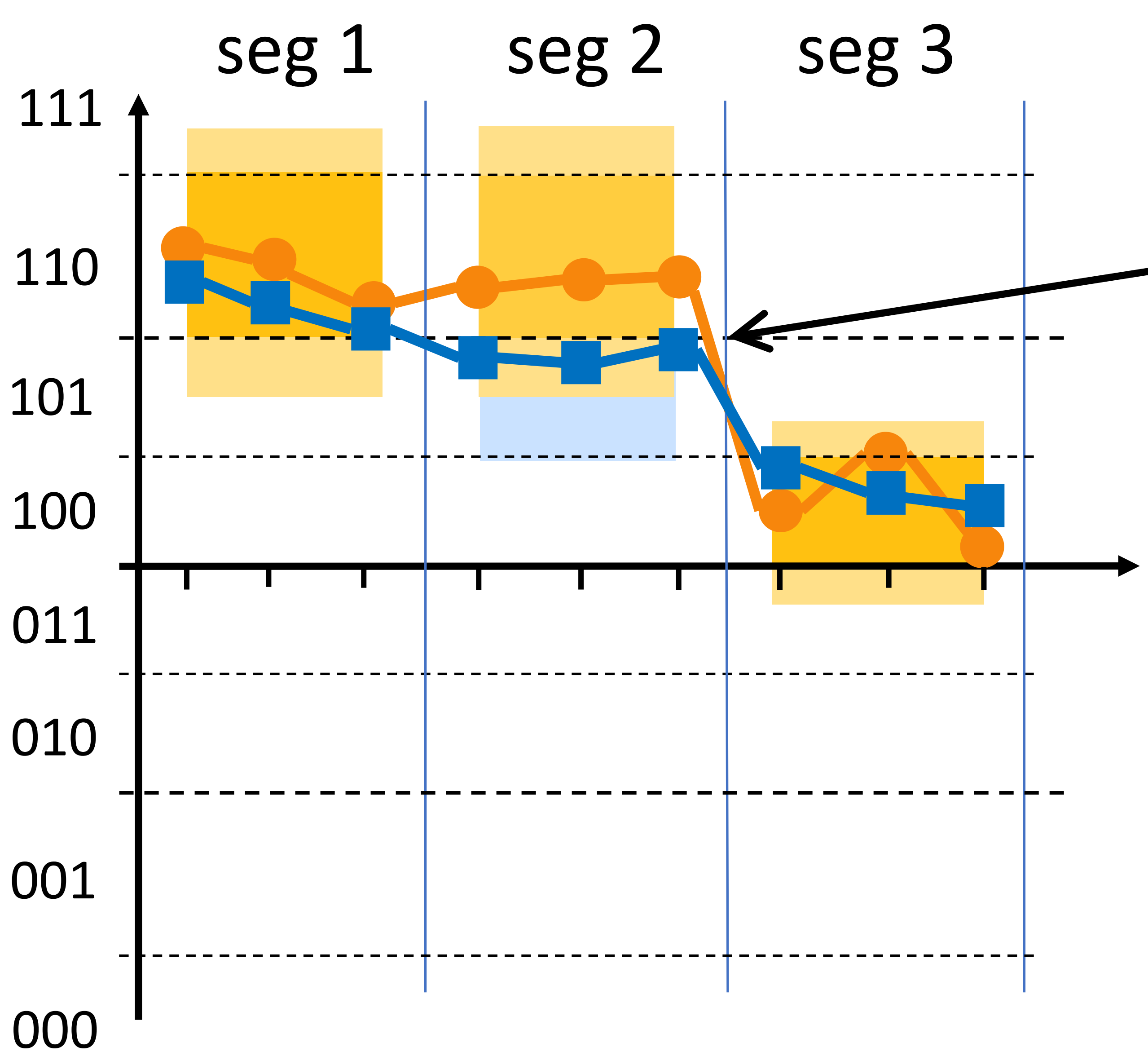
11-Dumpy-Fuzzy

An example of ***Boundary Issue***:



11-Dumpy-Fuzzy

An example of ***Boundary Issue***:



fuzzy boundary (a range)
duplicate close series into neighboring nodes

a: 110, **110**, 100

b: 110, **110**, 100
110, **101**, 100

belongs to **2** leaves

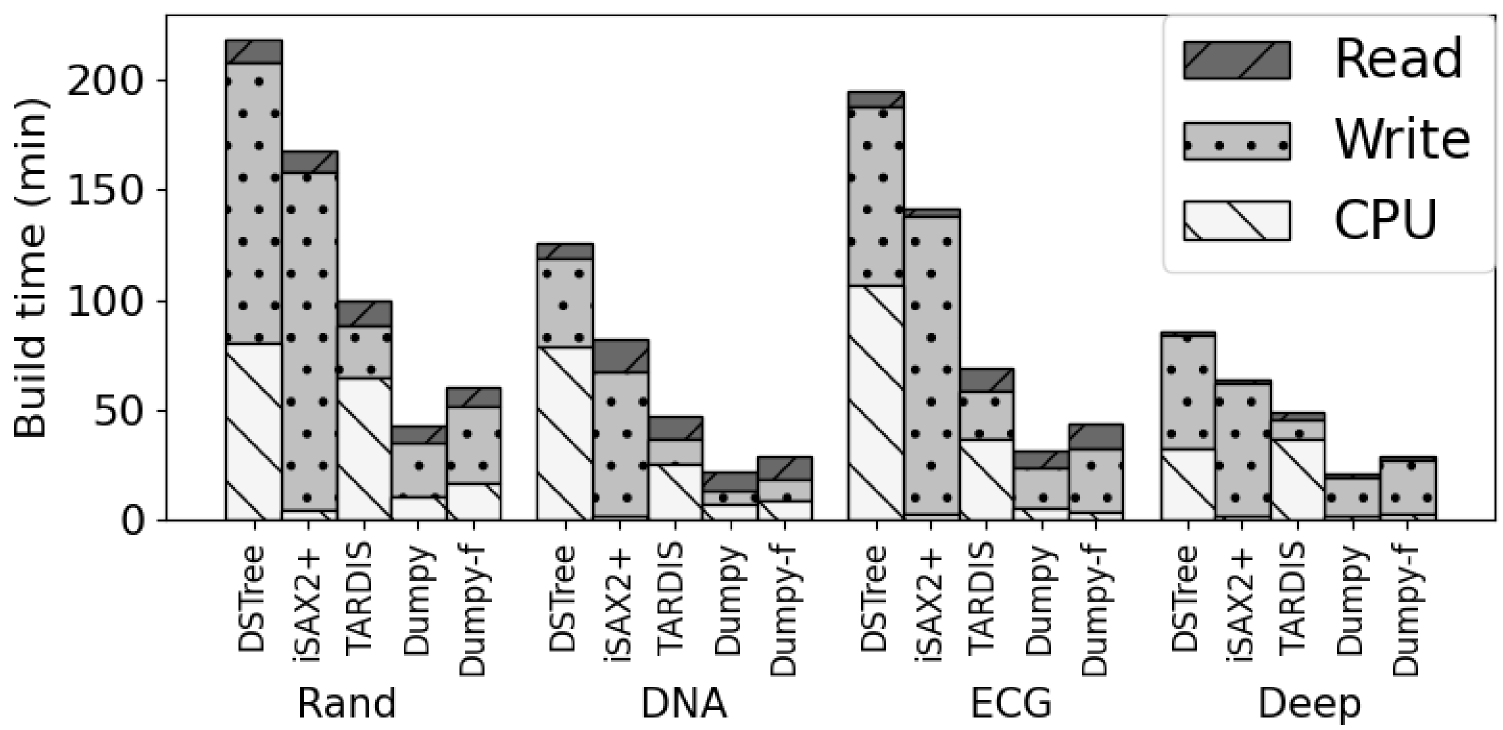
12-Experimental Setup

- Datasets
  - synthetic: Rand
  - real: DNA, ECG, Deep

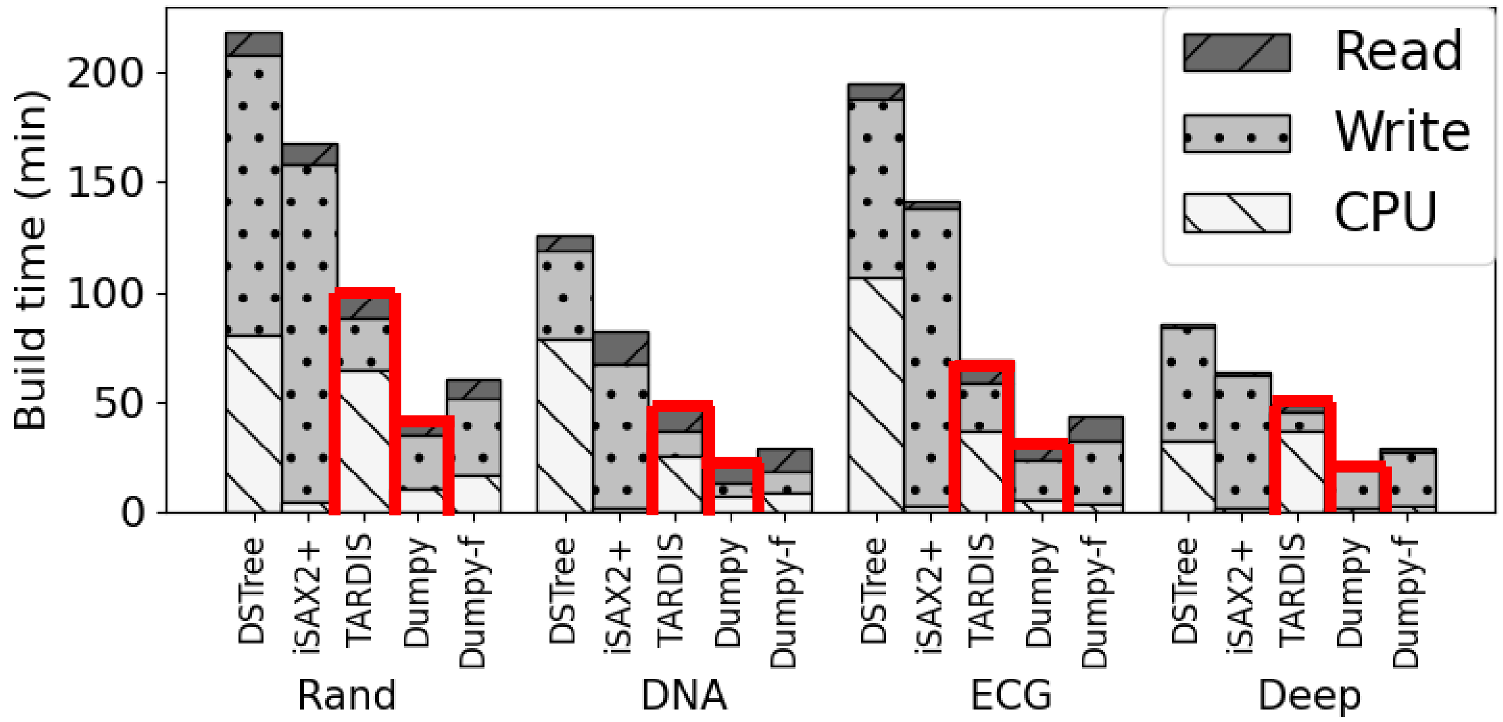
- Comparison methods
  - iSAX2+ (2-ary iSAX-based)
  - TARDIS (full-ary iSAX-based)
  - DSTree (EAPCA-based)

Dataset	***Length***	***Dataset size***
RandomWalk	256	100m (100GB)
DNA	1024	26m (113GB)
ECG	320	97m (117 GB)
Deep1B	96	100m (38GB)

13-Scalability on Index Building



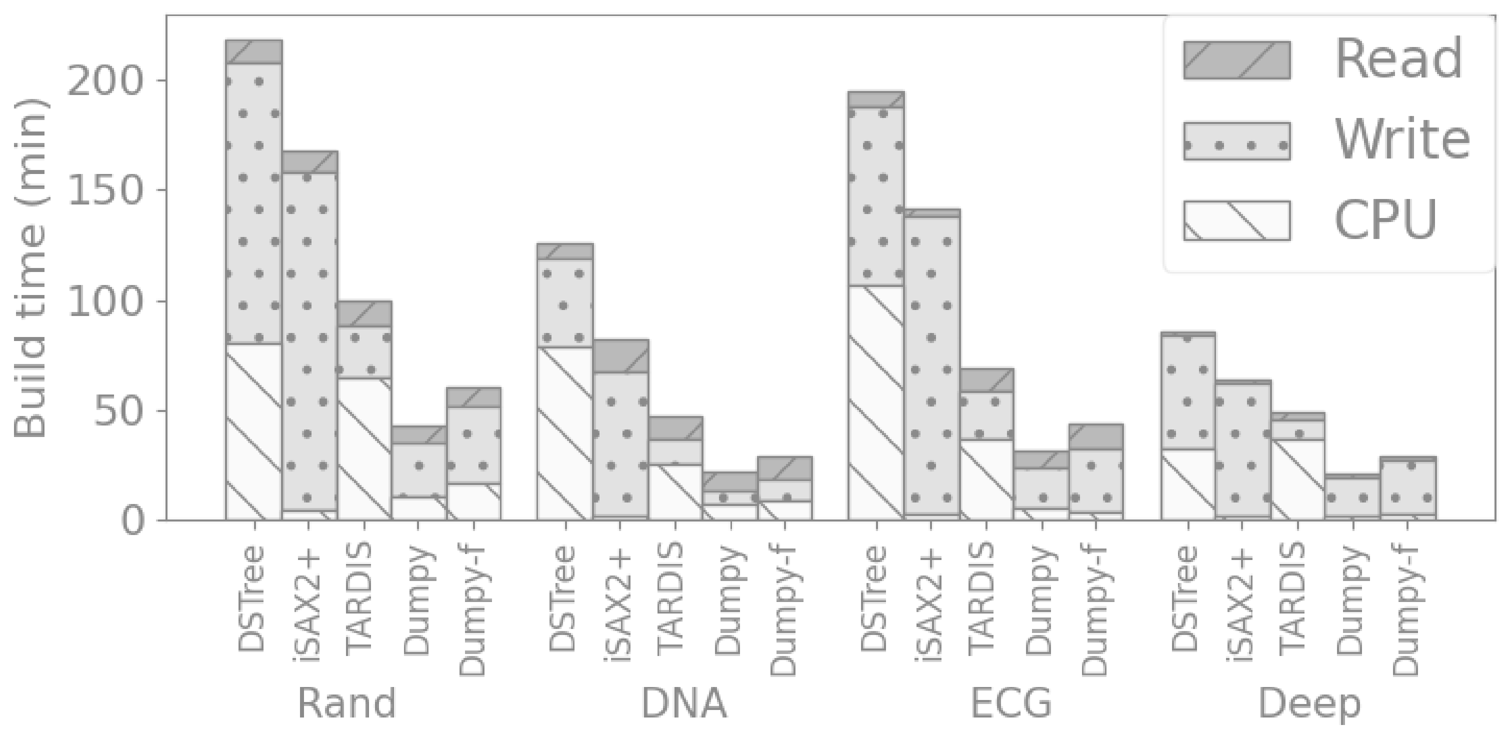
13-Scalability on Index Building

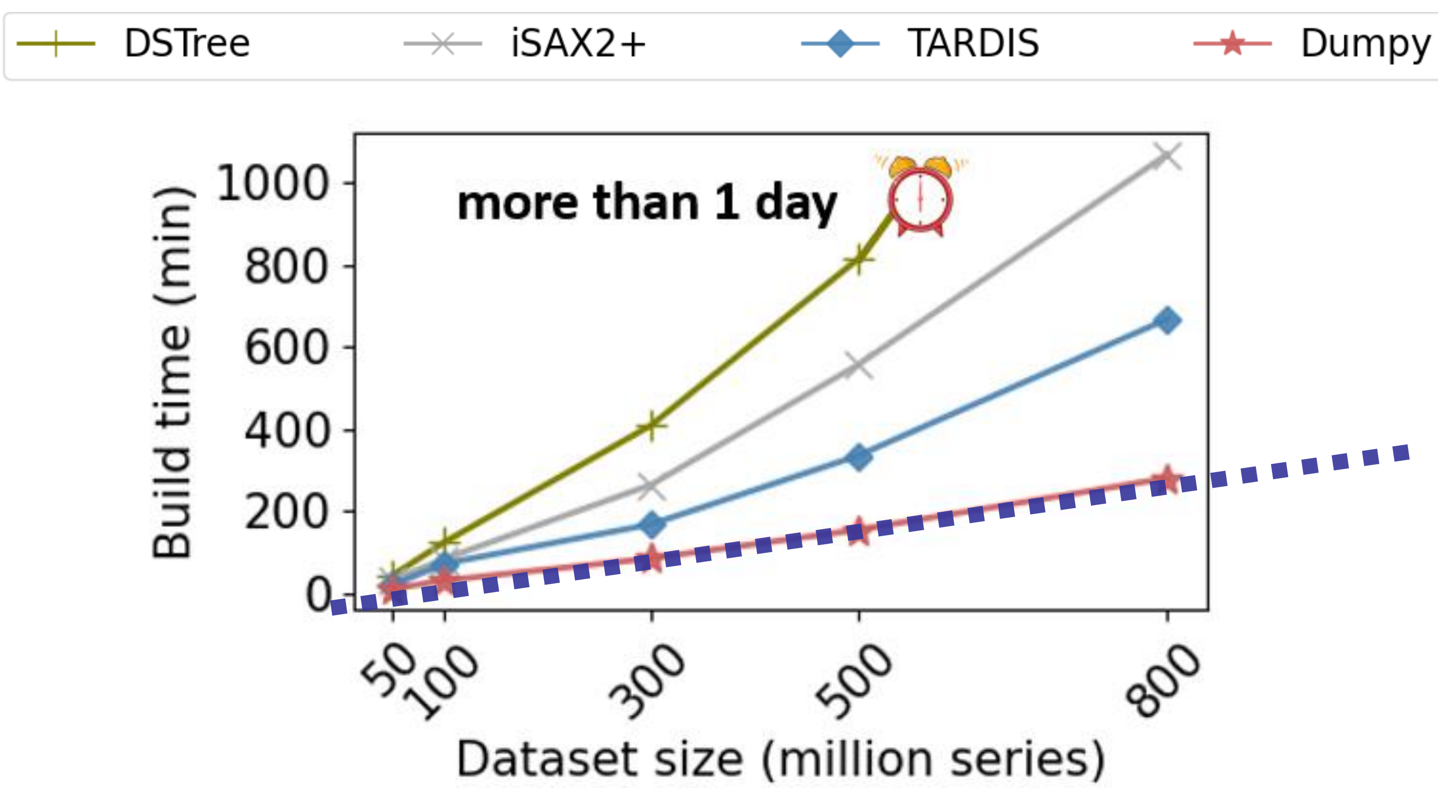


✓fastest index building, 2.5x~5.3x faster than SOTA

- Most compact structure

13-Scalability on Index Building



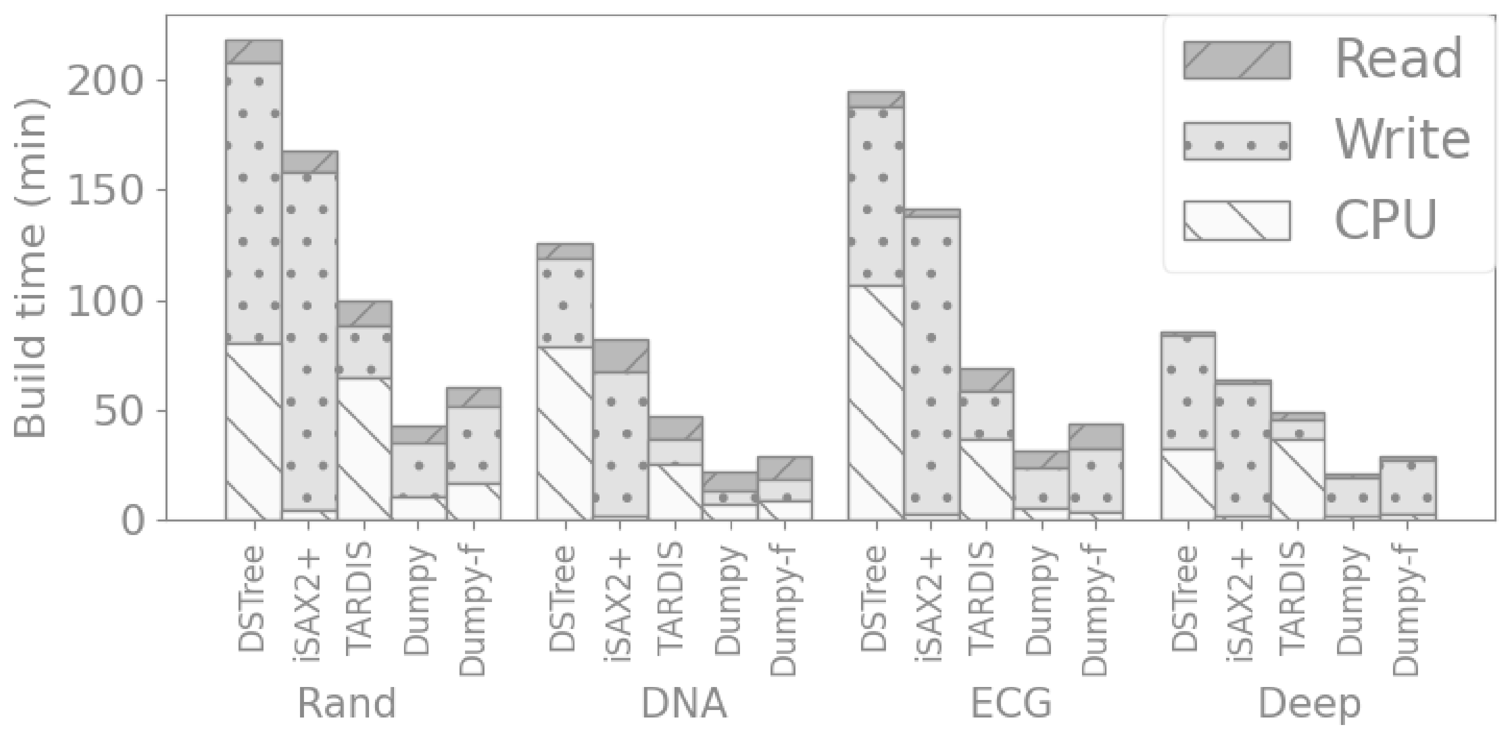


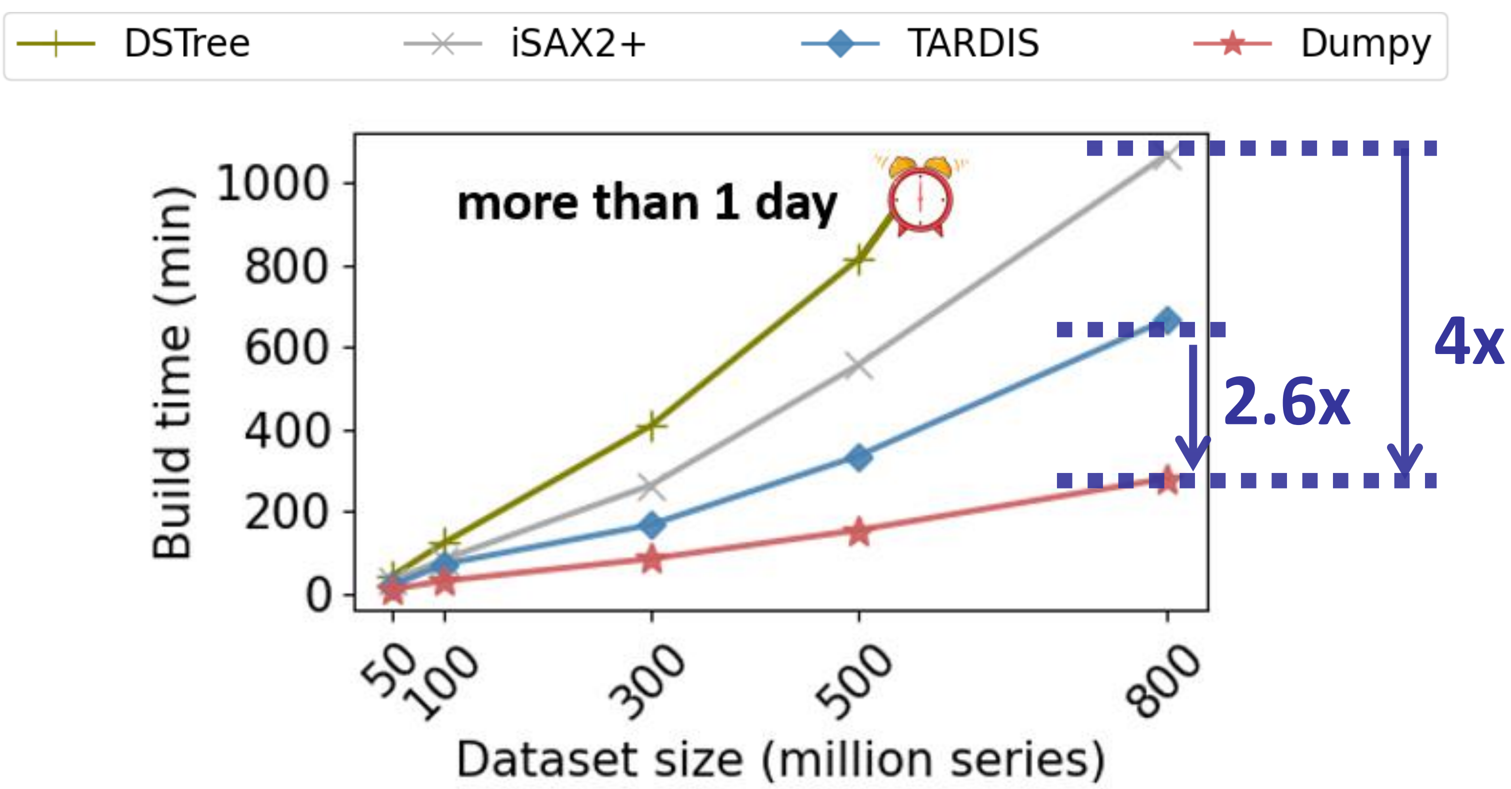
✓fastest index building, 2.5x faster than TARDIS (SOTA)

- Most compact structure

✓linear scalability (R^2> 0.99)

13-Scalability on Index Building





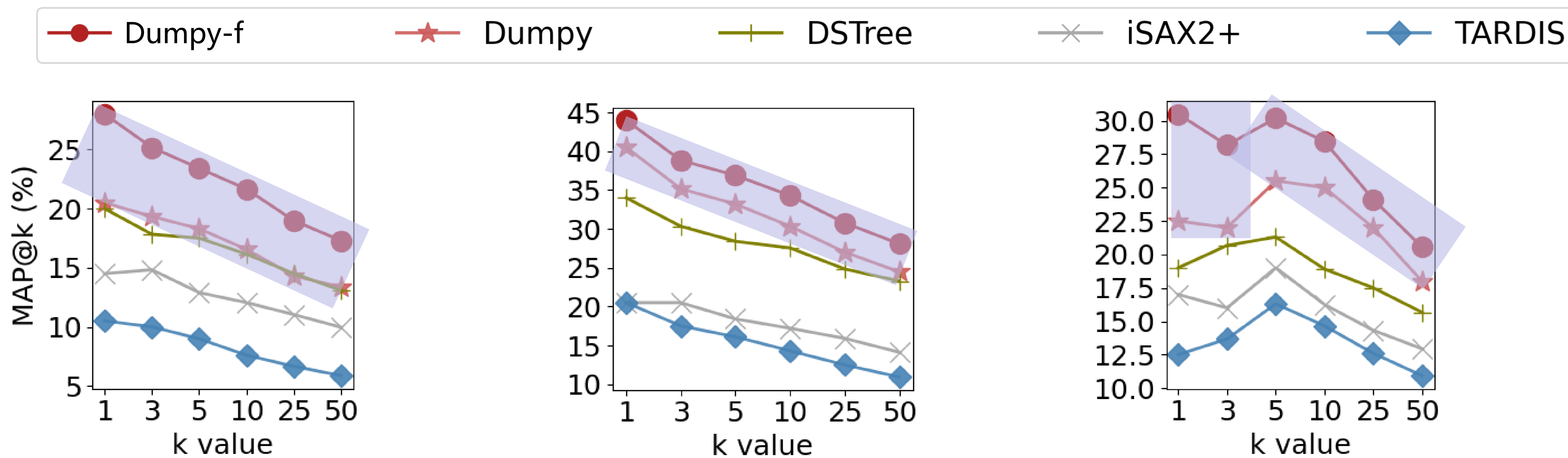
✓fastest index building, 2.5x faster than TARDIS (SOTA)

- Most compact structure

✓linear scalability

✓up to 4x faster than SOTA for 800GB data

14-Search Accuracy (search one node)

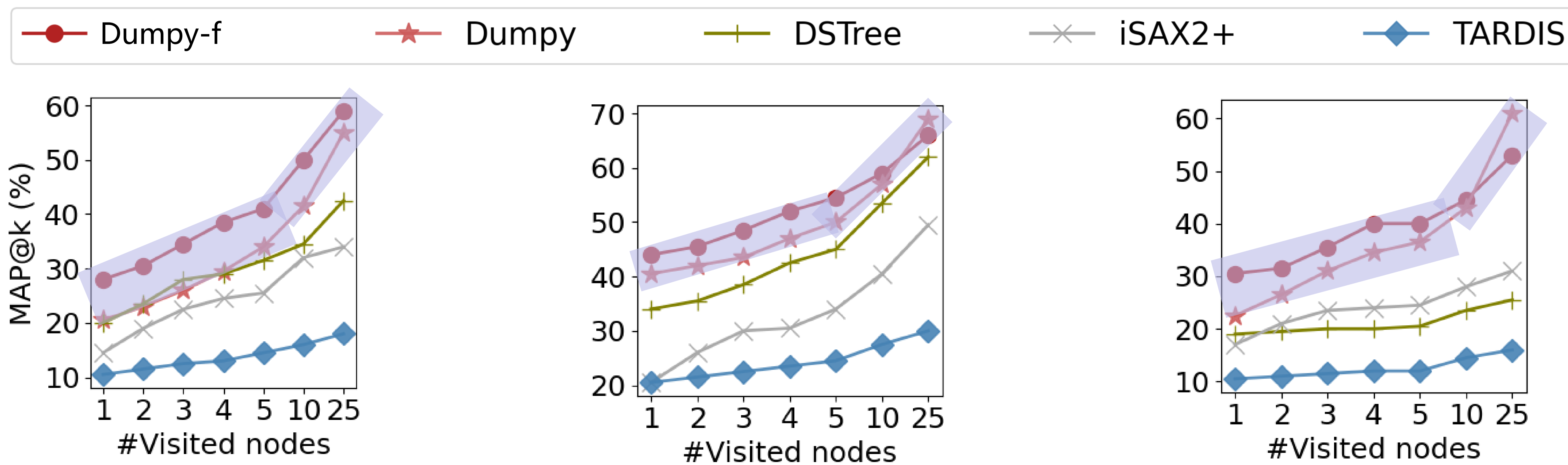


(a) Rand (b) DNA (c) ECG

✓highest MAP (Mean Average Precision)

- Best proximity of nodes
- 11%~84% higher MAP than SOTA

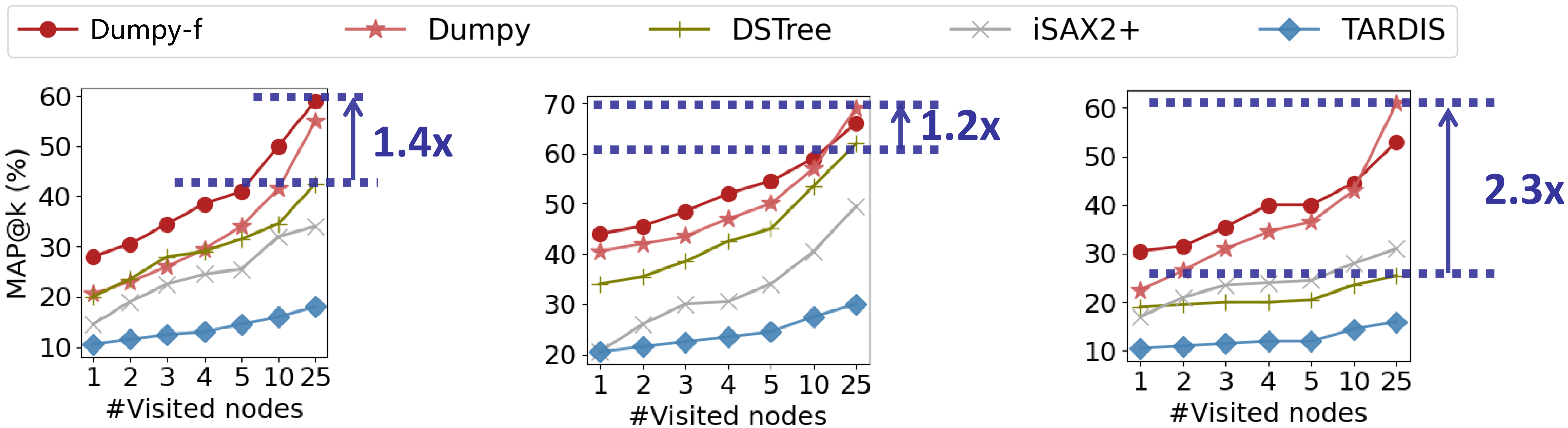
14-Search Accuracy (search more nodes)



(a) Rand (b) DNA (c) ECG

✓16%~125% higher MAP than SOTA

14-Search Accuracy (search one node)

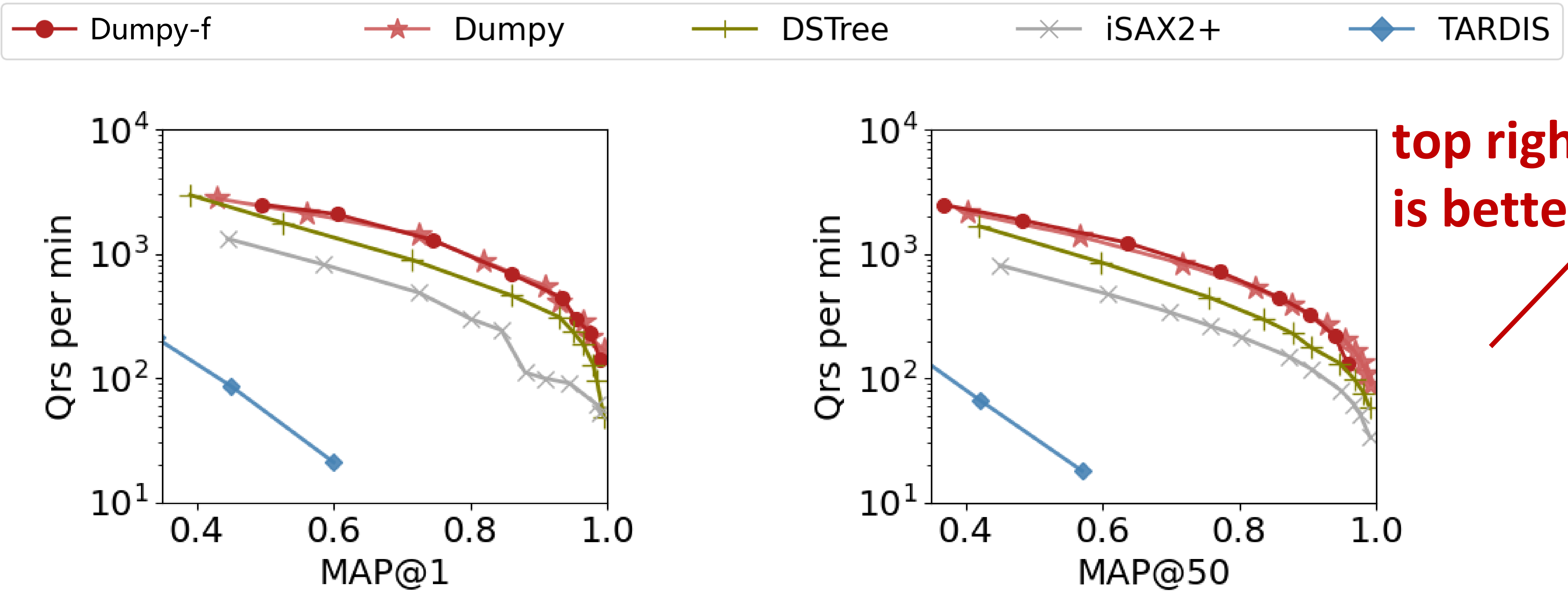


(a) Rand (b) DNA (c) ECG

✓16%~125% higher MAP than SOTA

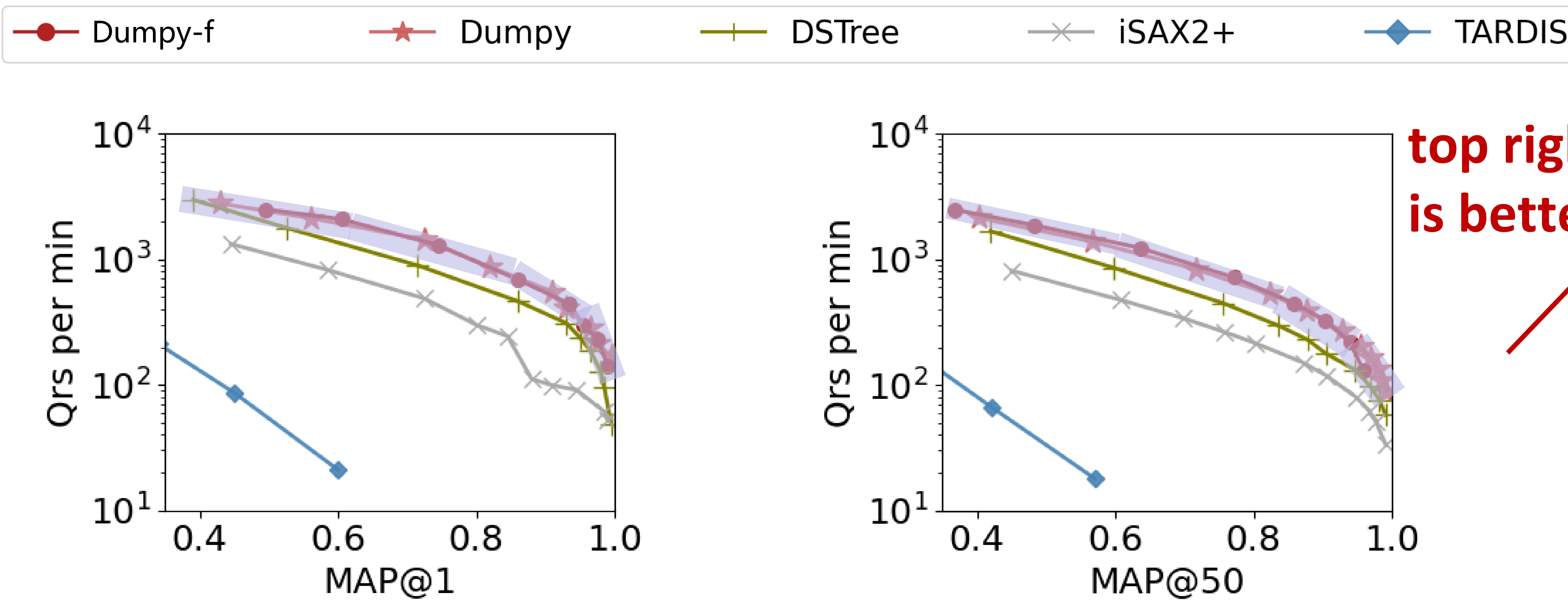
✓60% more accurate than DSTree when visiting 25 nodes (~100ms query time)

15-Pruning-based (approximate) search



top right is better

15-Pruning-based (approximate) search



top right is better

- ✓Best throughput under the same accuracy
  - ✓67% higher throughput than DSTree under 80% MAP

16-Conclusions

- Identify the inherent proximity-compactness trade-off in the structural design of SOTA iSAX-index family
- Propose Dumpy, a compact and adaptive multi-ary data series index striking the right balance of this trade-off
  - faster index-building and better scalability
  - more accurate and efficient simialrity searh
- Devise Dumpy-Fuzzy that further improves search accuracy by mitigating the hard boundary issue

Thanks!

Dumpy: A Compact and Adaptive Index for Large Data Series Collections

Zeyu Wang, Qitong Wang, Peng Wang, Themis Palpanas and Wei Wang

ACM SIGMOD 2023, Seattle

paper: https://helios2.mi.parisdescartes.fr/~themisp/publications/sigmod23-dumpy.pdf
video: https://files.atypon.com/acm/99f6febc21ad6c5a979f504caf188d9a
code: https://github.com/DSM-fudan/Dumpy