BOSTON UNIVERSITY

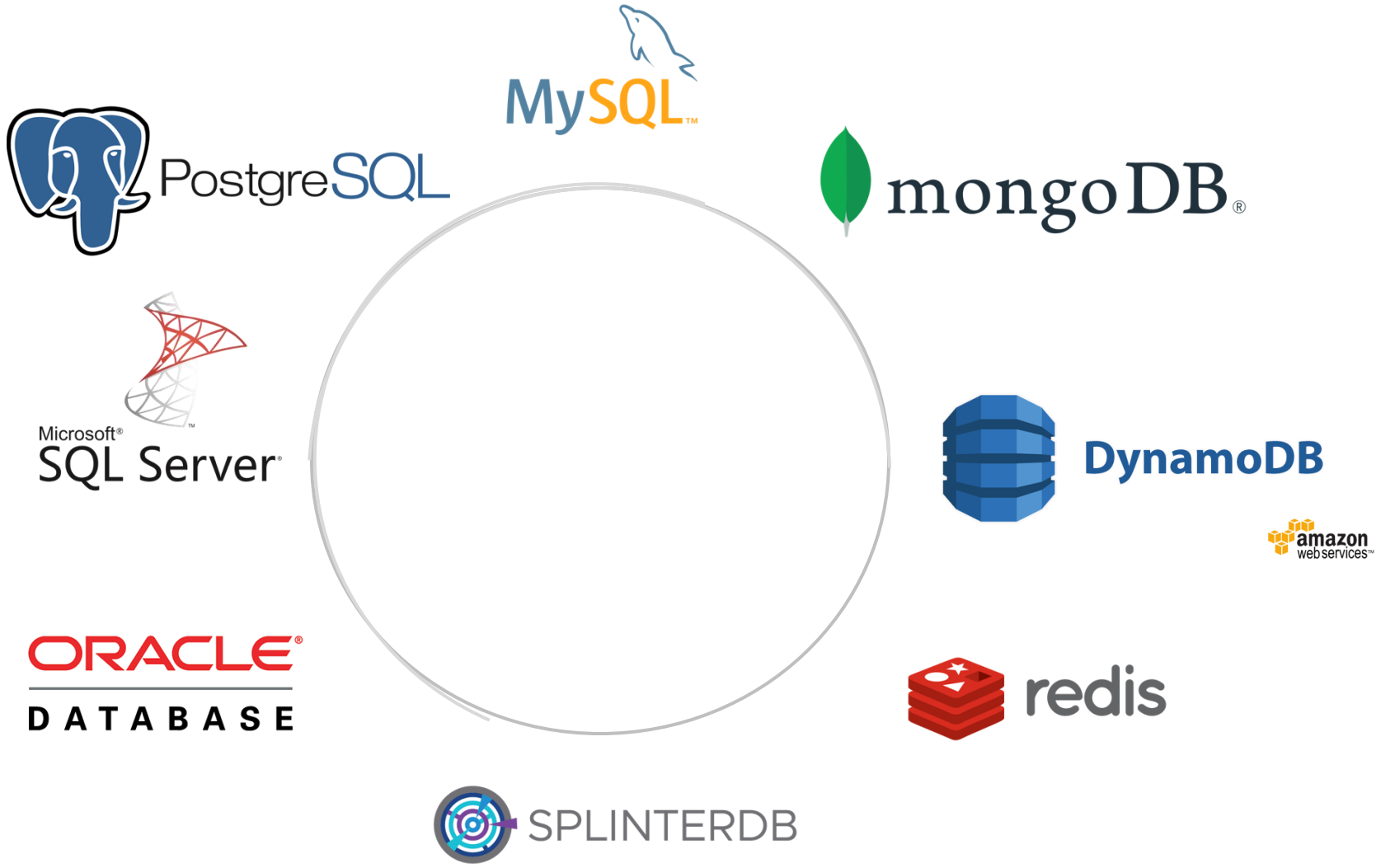
Sortedness-Aware Indexing

CS561: Data Systems Architecture

Aneesh Raman

DiSC lab

Indexes Are Everywhere!



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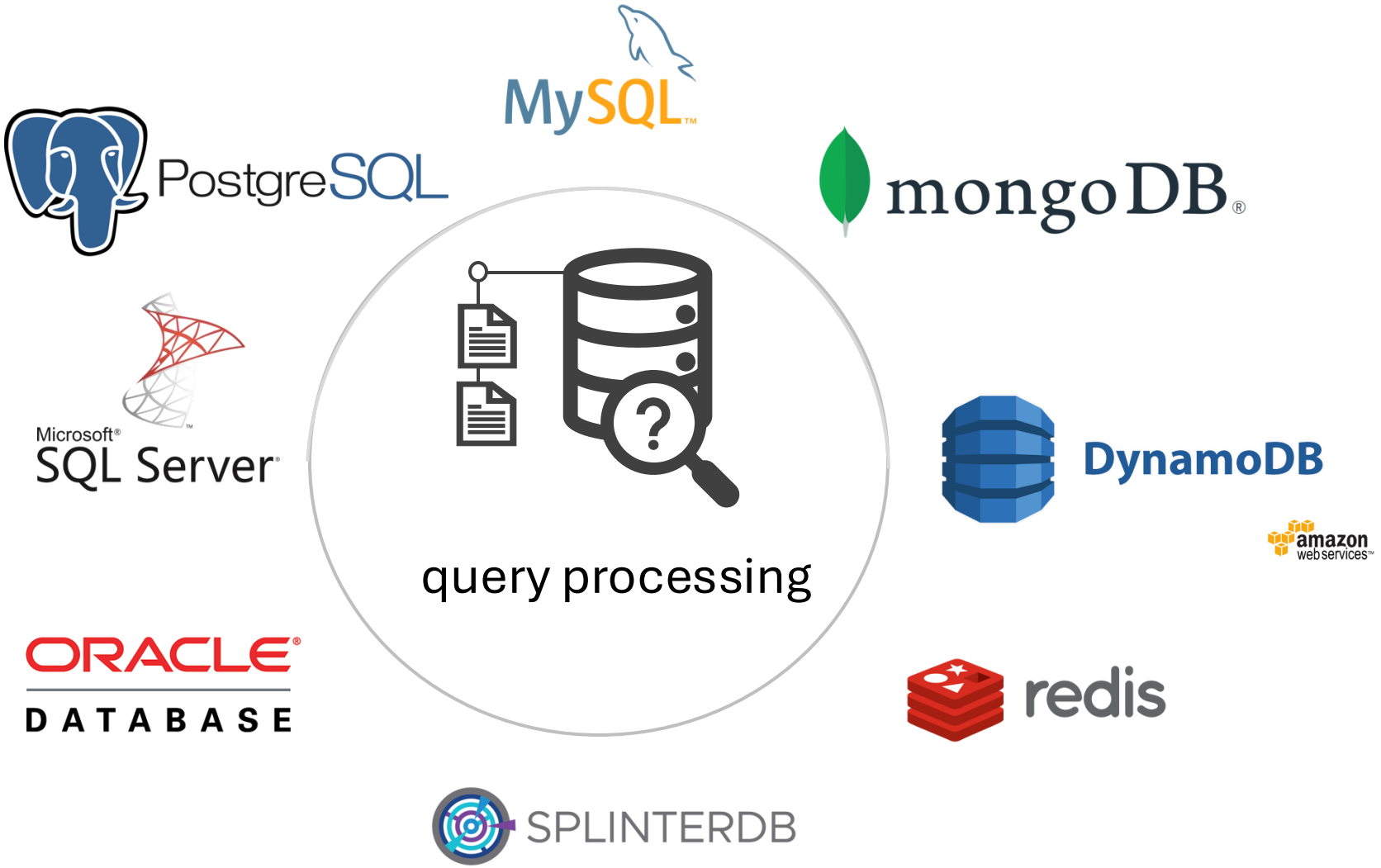

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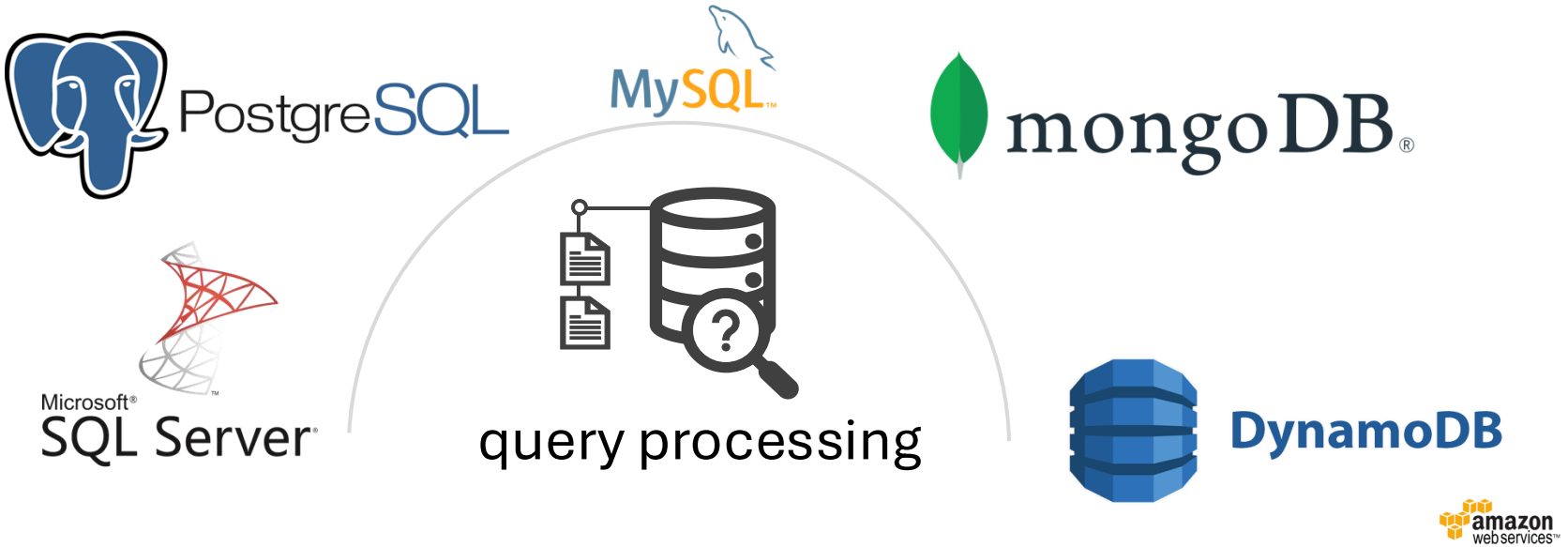

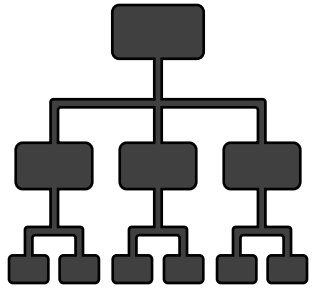

organize data

accelerates queries

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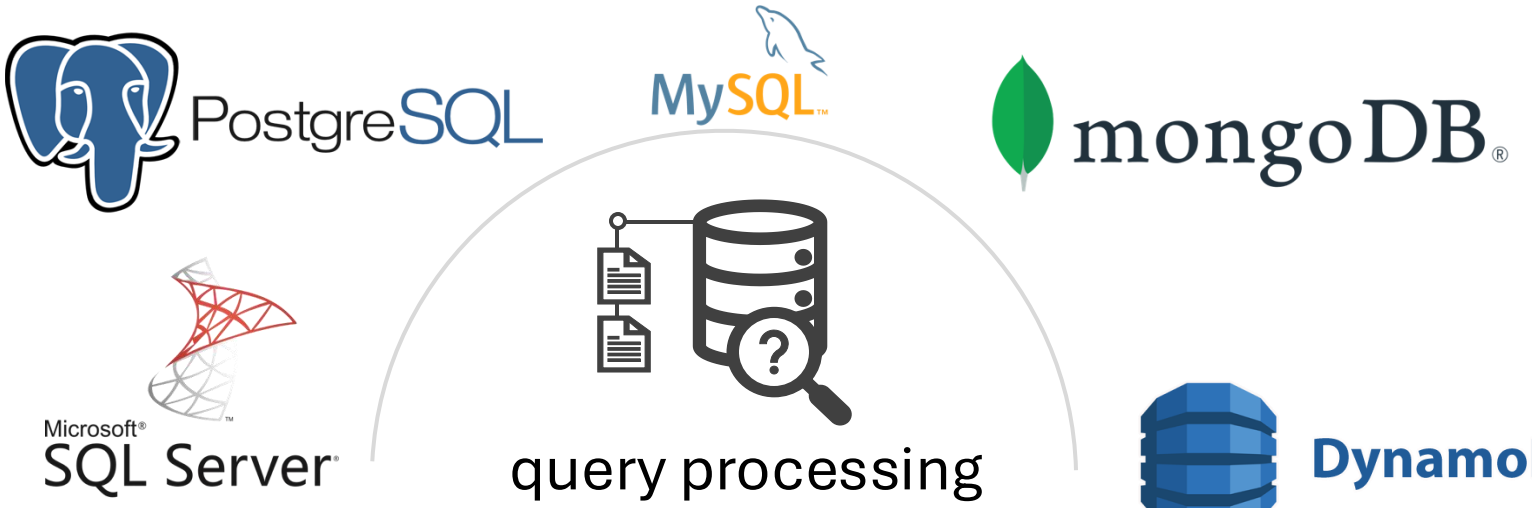

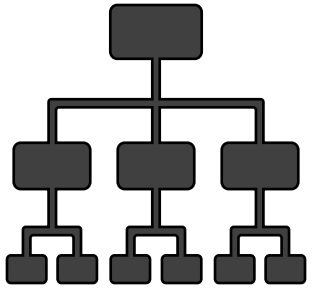

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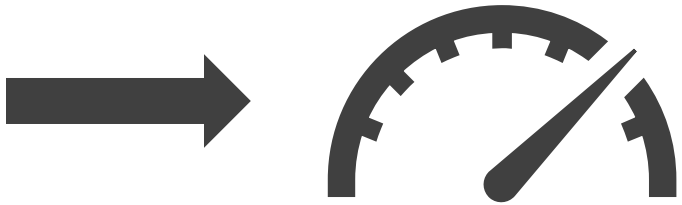
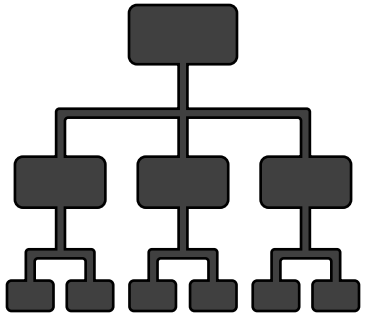


accelerates queries

build + maintain + store

Indexing Adds Structure



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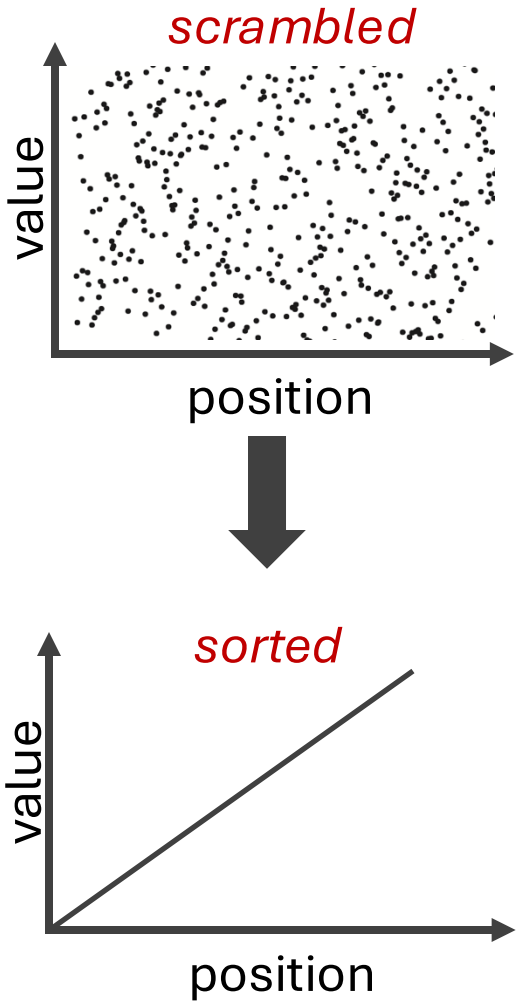
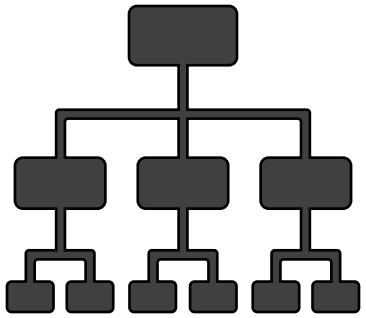


The process of ***"inducing sortedness"*** to otherwise, unsorted data

Indexing Adds Structure



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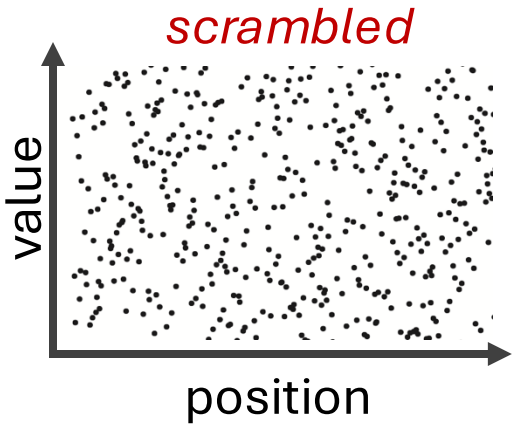

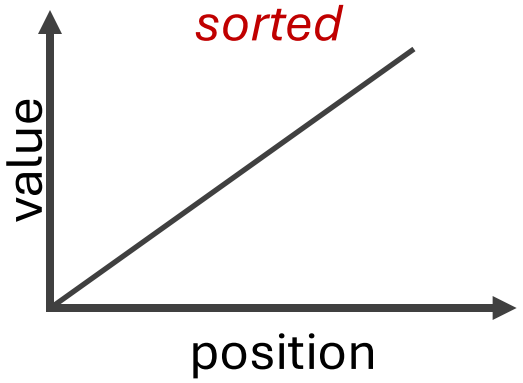

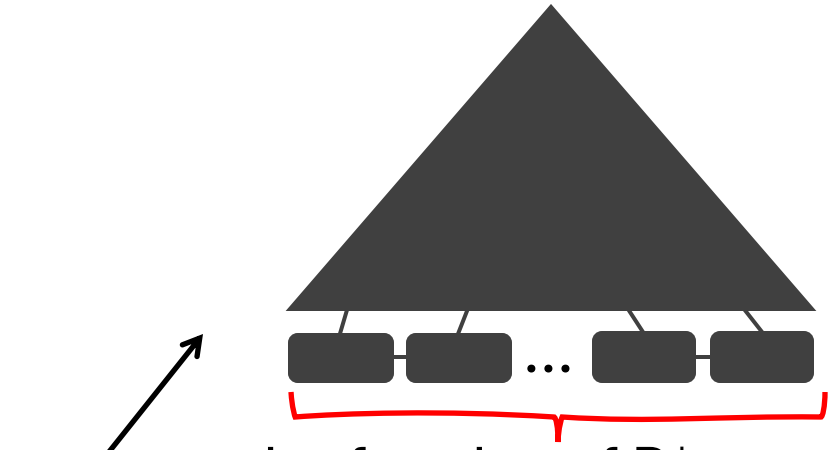

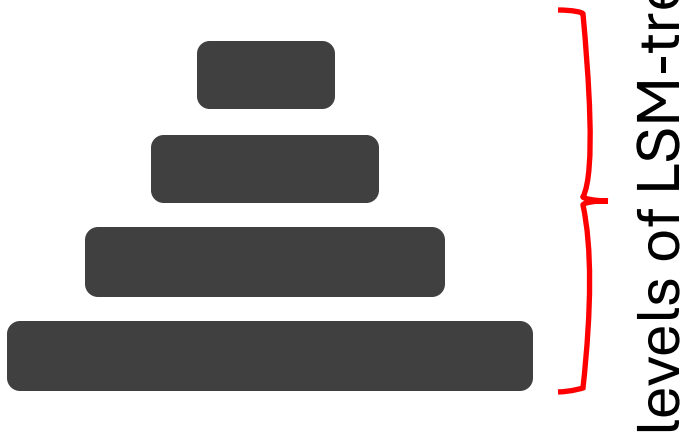

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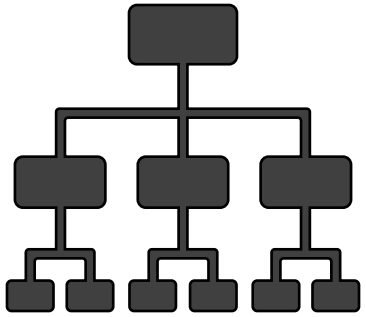

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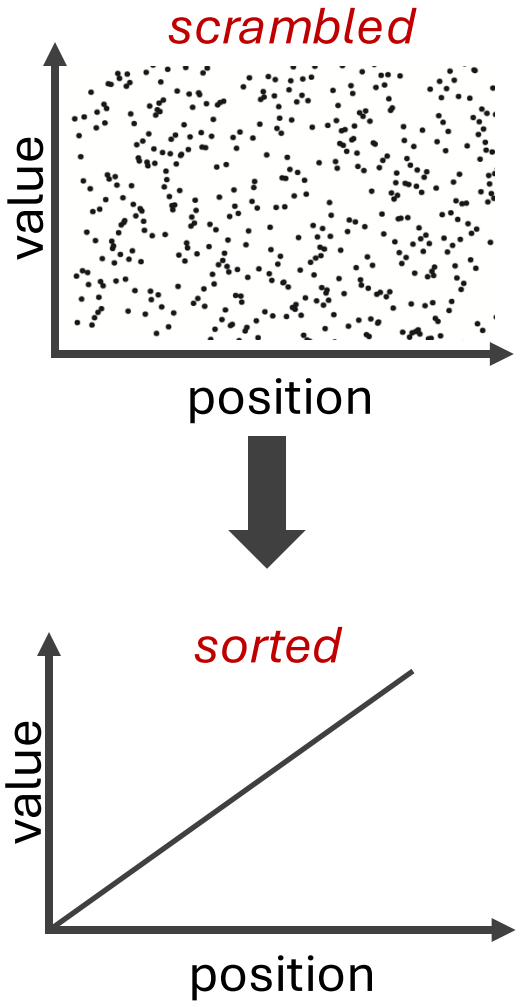
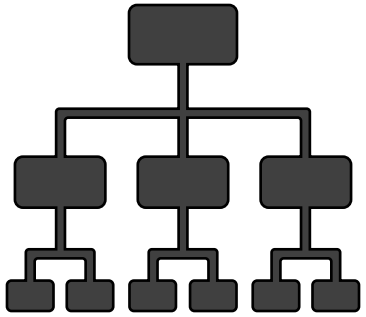


What if the incoming data is **already sorted?**

Indexing Adds Structure



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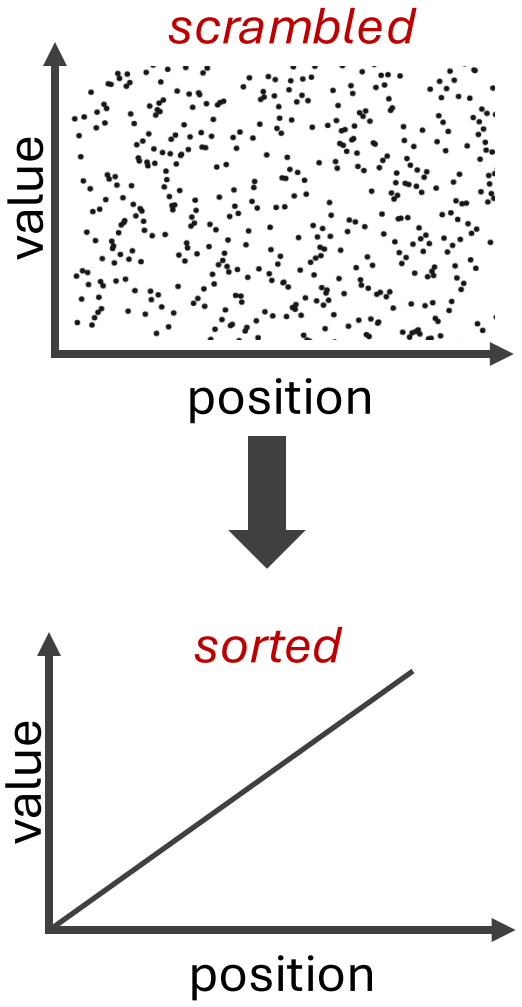

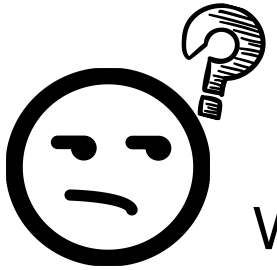

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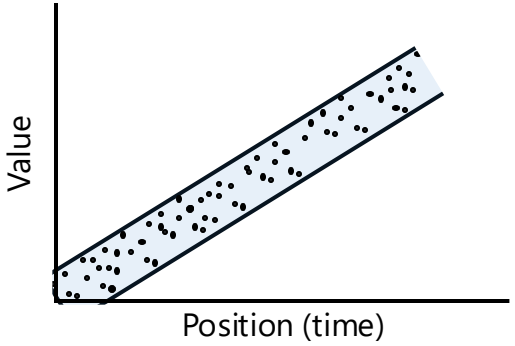

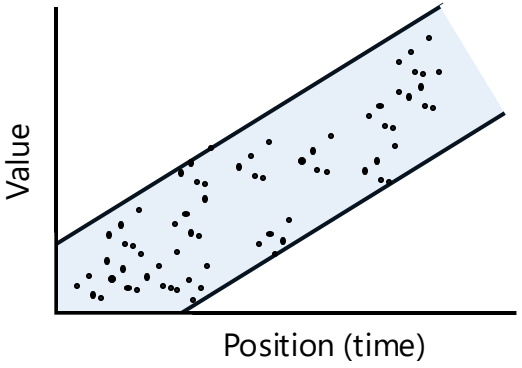

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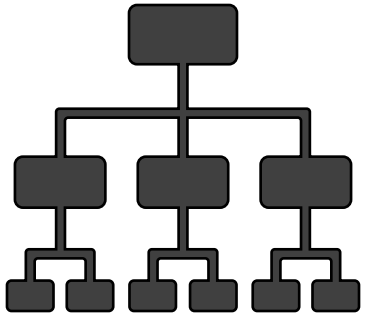

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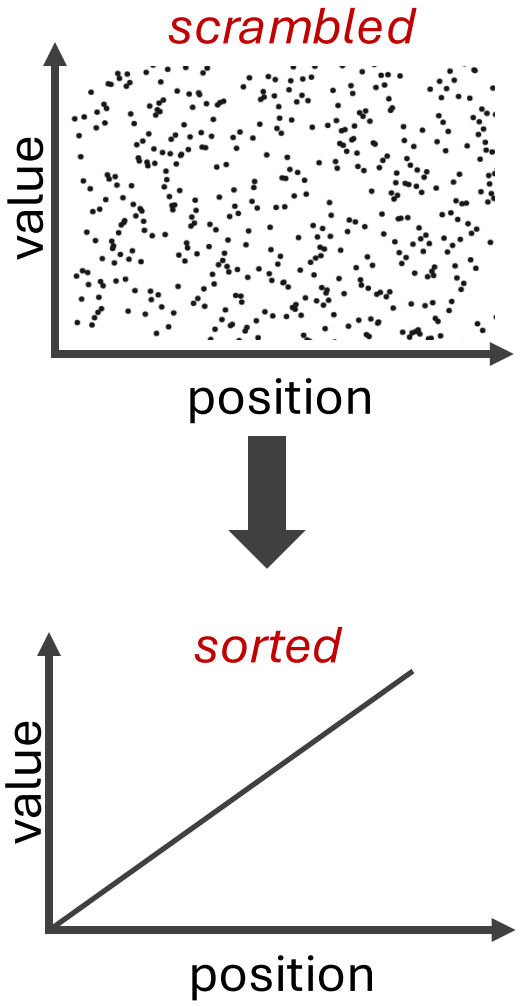

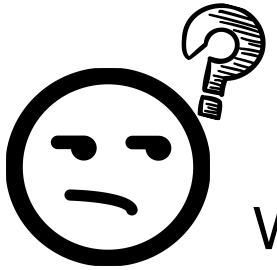

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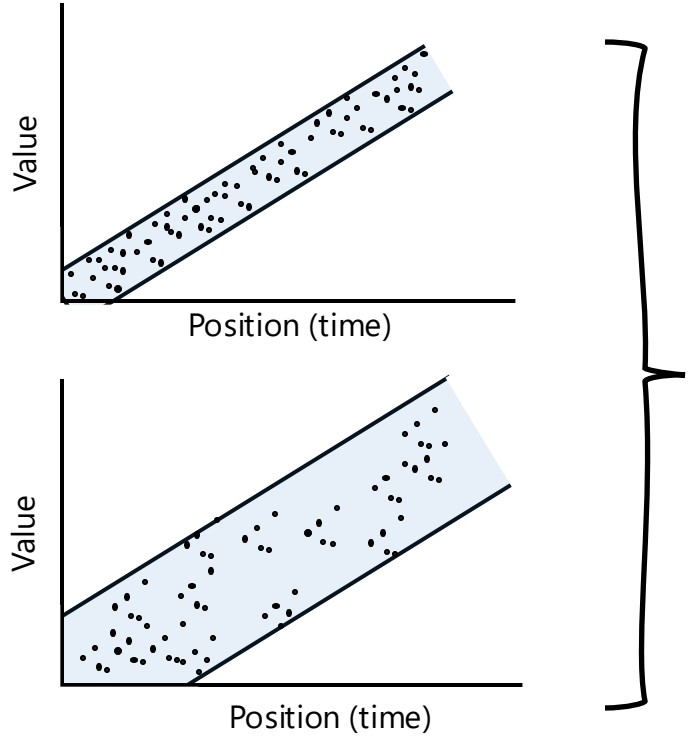
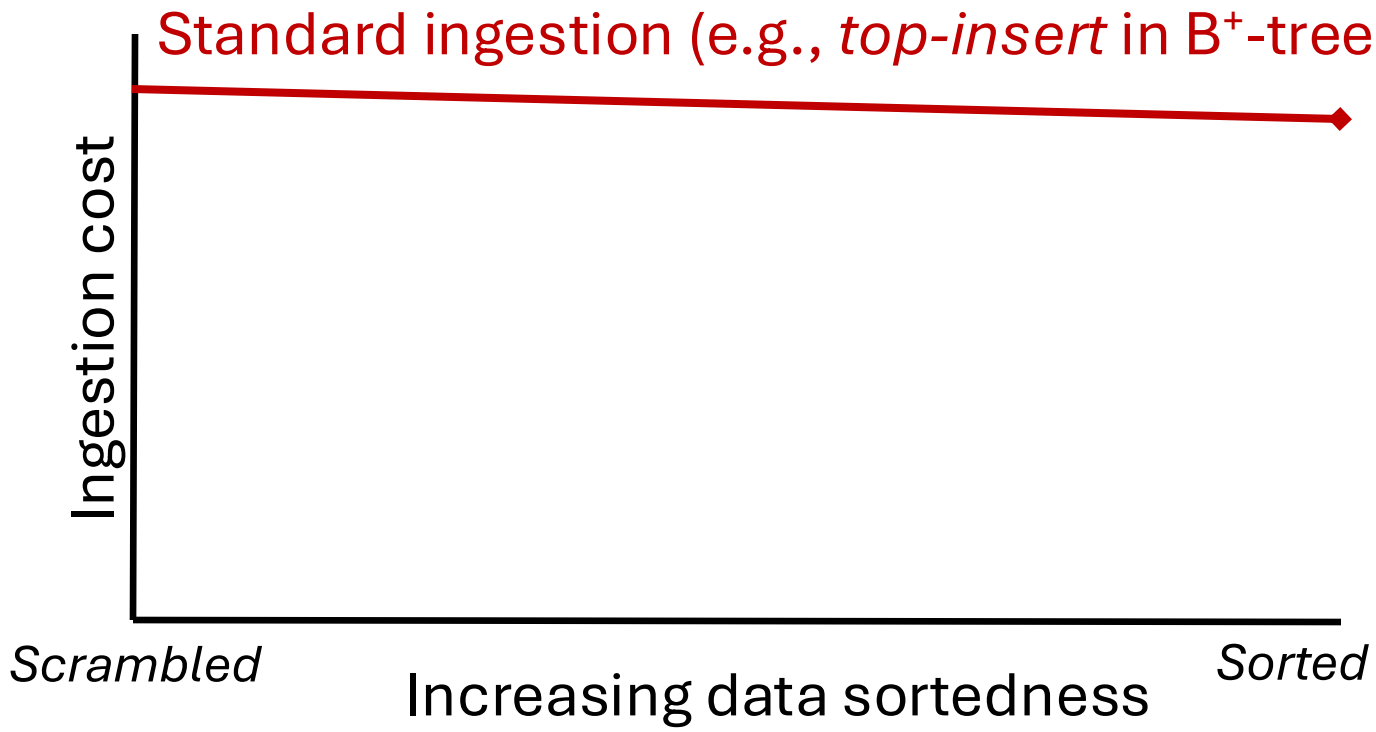


Irrespective of Sortedness, Same Performance



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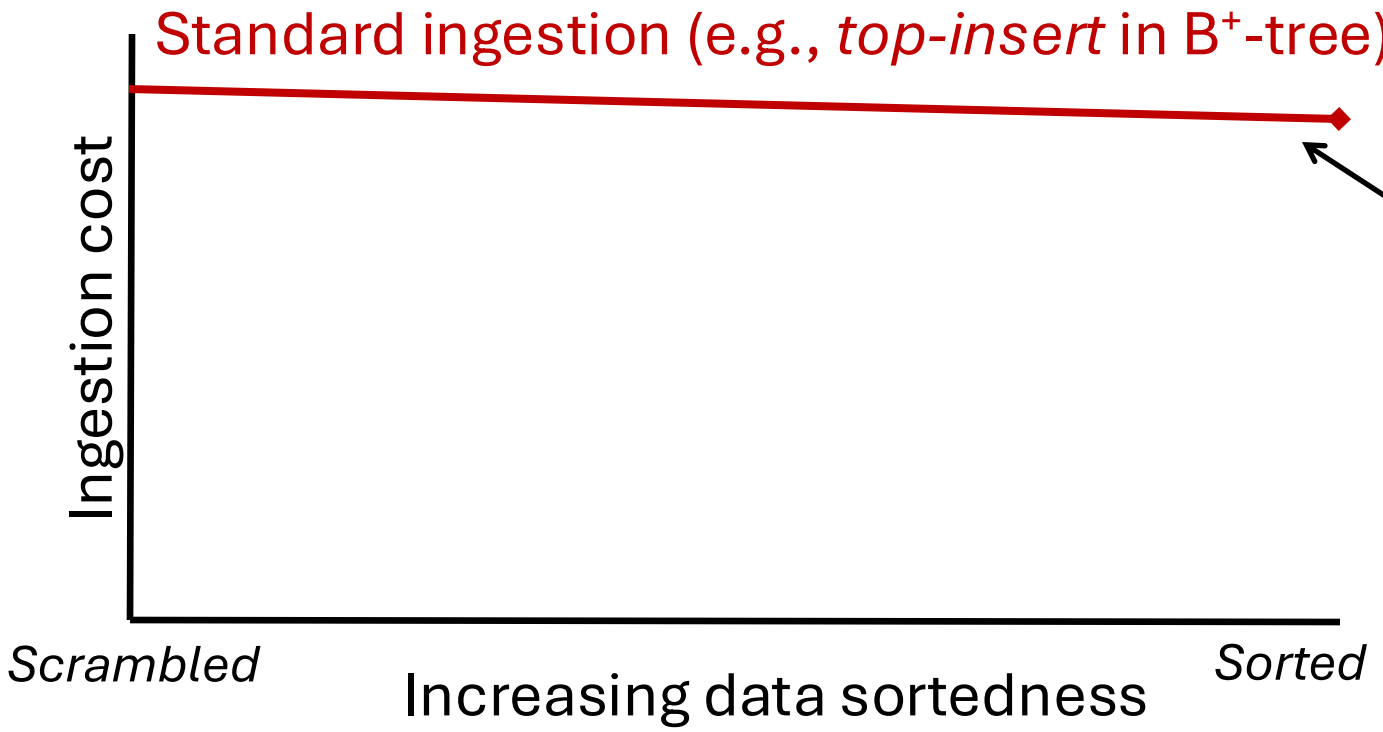
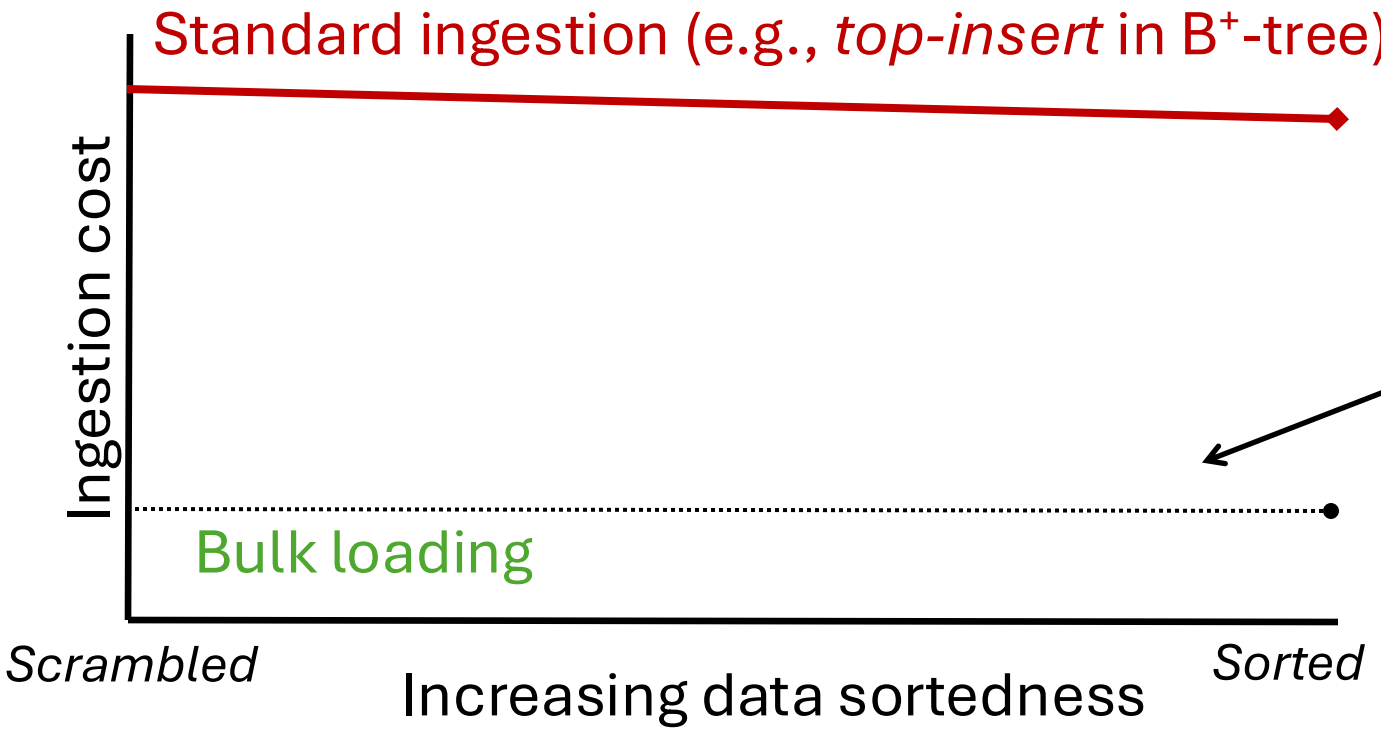


better performance, but due to increased caching

by design, **cannot exploit** inherent order

Are There Faster Alternatives?

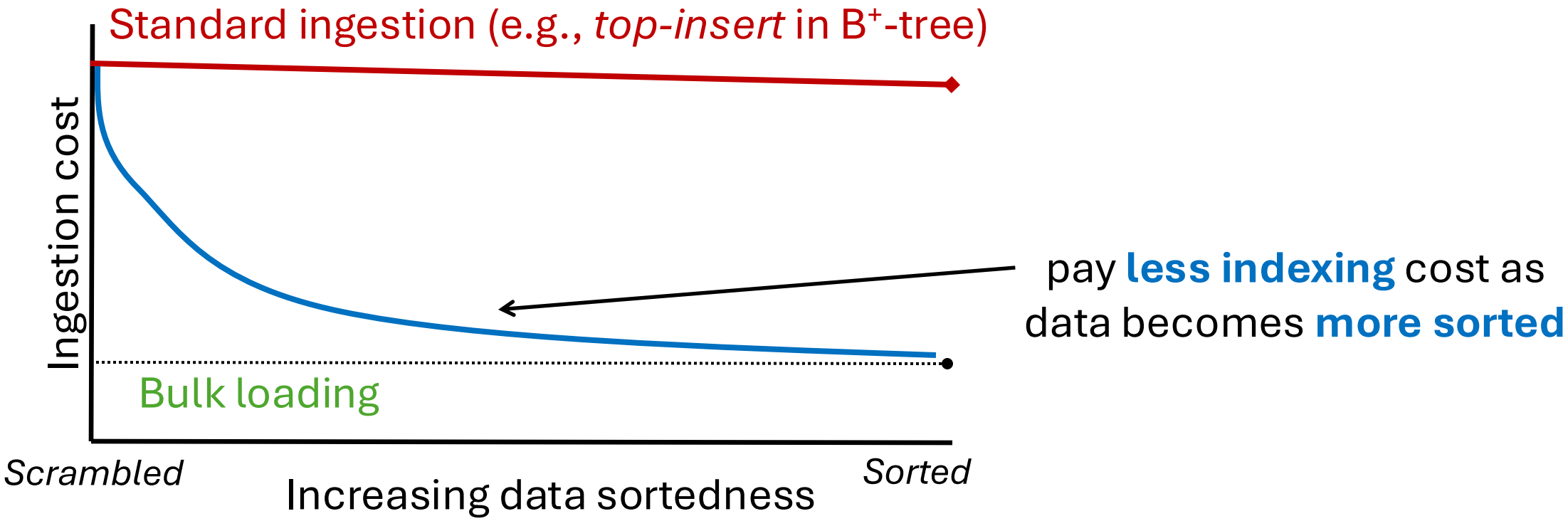


by design, **cannot exploit** inherent order

builds the index bottom-up

requires all data ***a priori***

Ideally, Higher Sortedness => Faster Ingestion



Agenda


Quantifying Data Sortedness
Quick Insertion Tree
Introduction and Vision
Sortedness-Aware (SWARE) Paradigm

Agenda

Introduction and Vision

Quantifying Data

Sortedness

Sortedness-Aware (SWARE) Paradigm

Quick Insertion Tree

Agenda


Introduction and Vision
Quantifying Data Sortedness
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Introduction and Vision
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How Do We Quantify ***Sortedness***?

inversions	# pairs in incorrect order
runs	# increasing cont. subsequences
exchanges	least # swaps to establish total order

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legacy metrics	**inversions**	# pairs in incorrect order
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simple, yet have some obvious pitfalls

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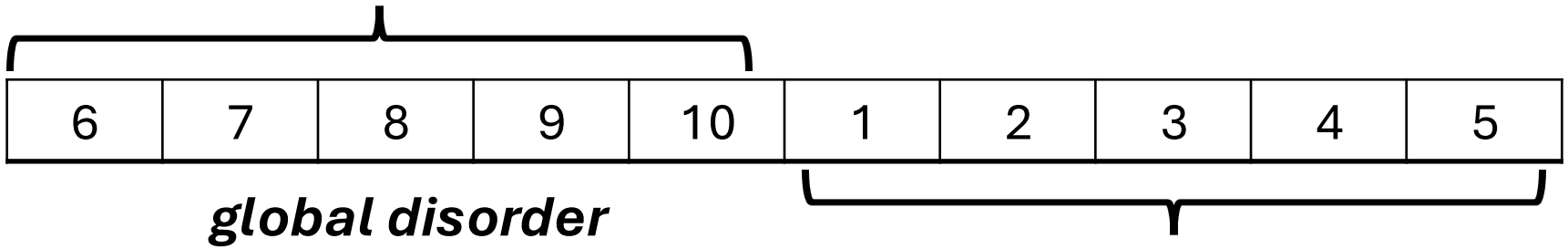

How Do We Quantify ***Sortedness***?

legacy metrics

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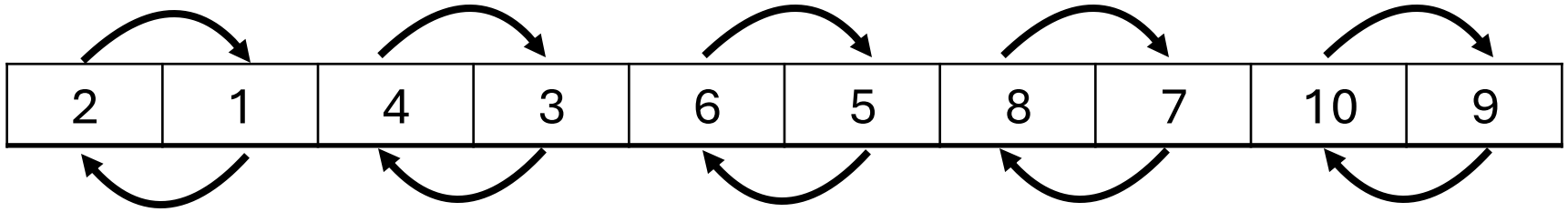


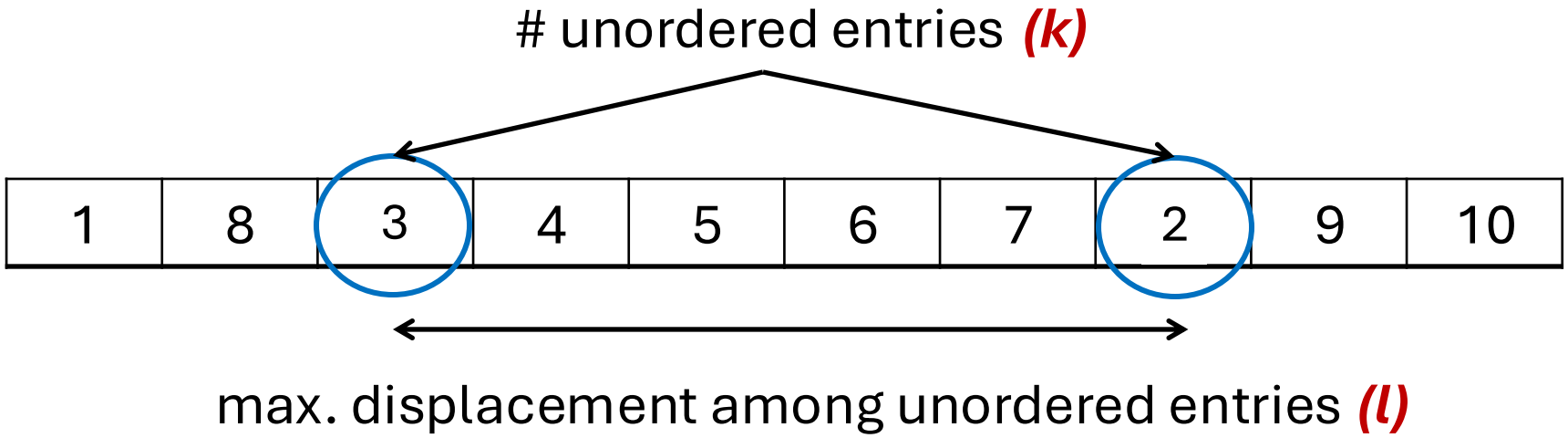
local disorder

A More Intuitive Metric?

(k-l) Sortedness Metric

[Raman2022]

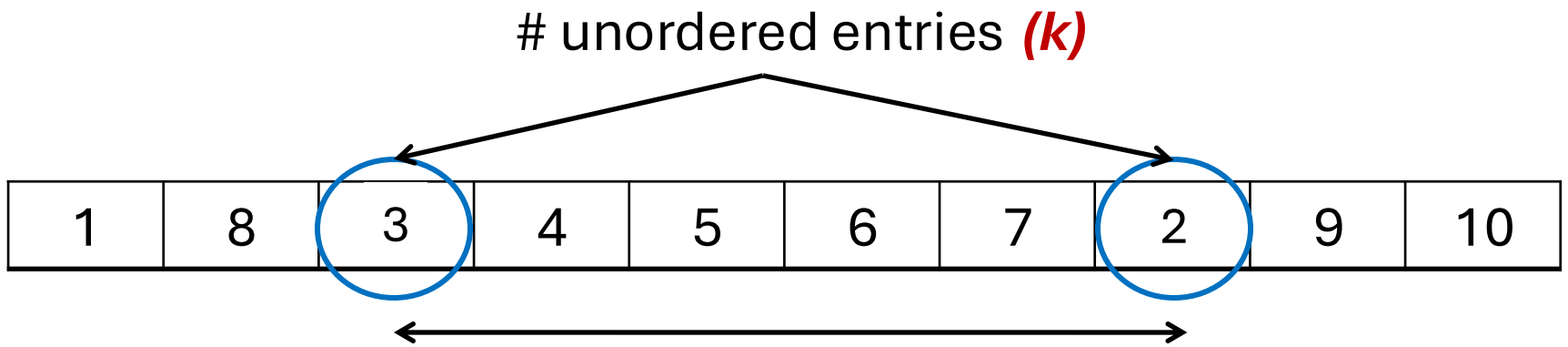
(k-l) Sortedness Metric



[inspired by BenMoshe, ICDT 2011]

[Raman2022]

(k-l) Sortedness Metric



fully sorted: K or L = 0

near-sorted: low K and low L

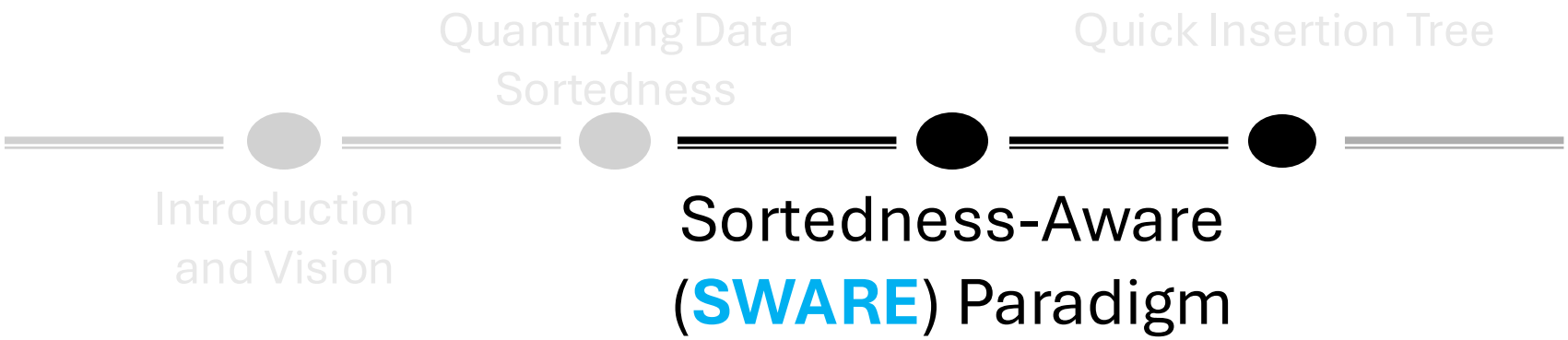
less-sorted: high K and high L

scrambled: K = L = 100%

low K and high L; or
high K and low L
} addresses global & local disorder

[inspired by BenMoshe, ICDT 2011]

Coming Up…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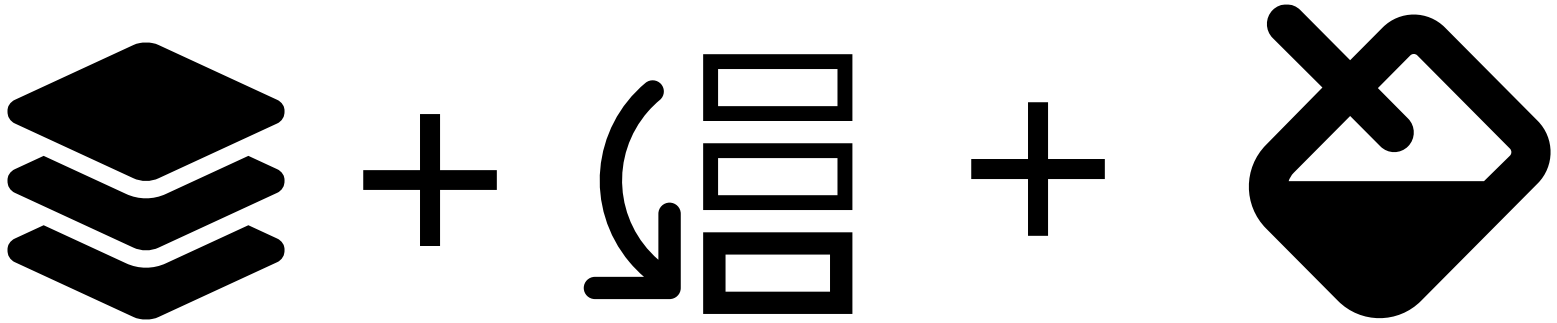
Sortedness-Aware Paradigm (**SWARE**)



intelligent buffering

opportunistic bulk loading

increased fill and split factor

SWARE framework can be **applied to any tree-index!**

SWARE Ingestion

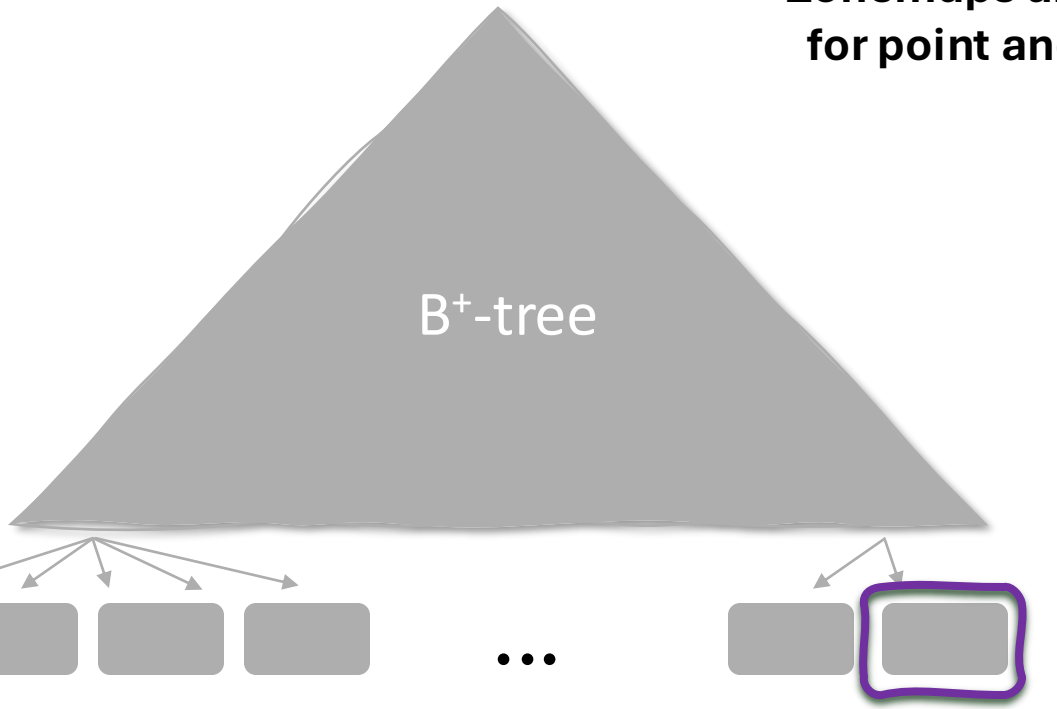
append & sort if needed

SWARE Buffer

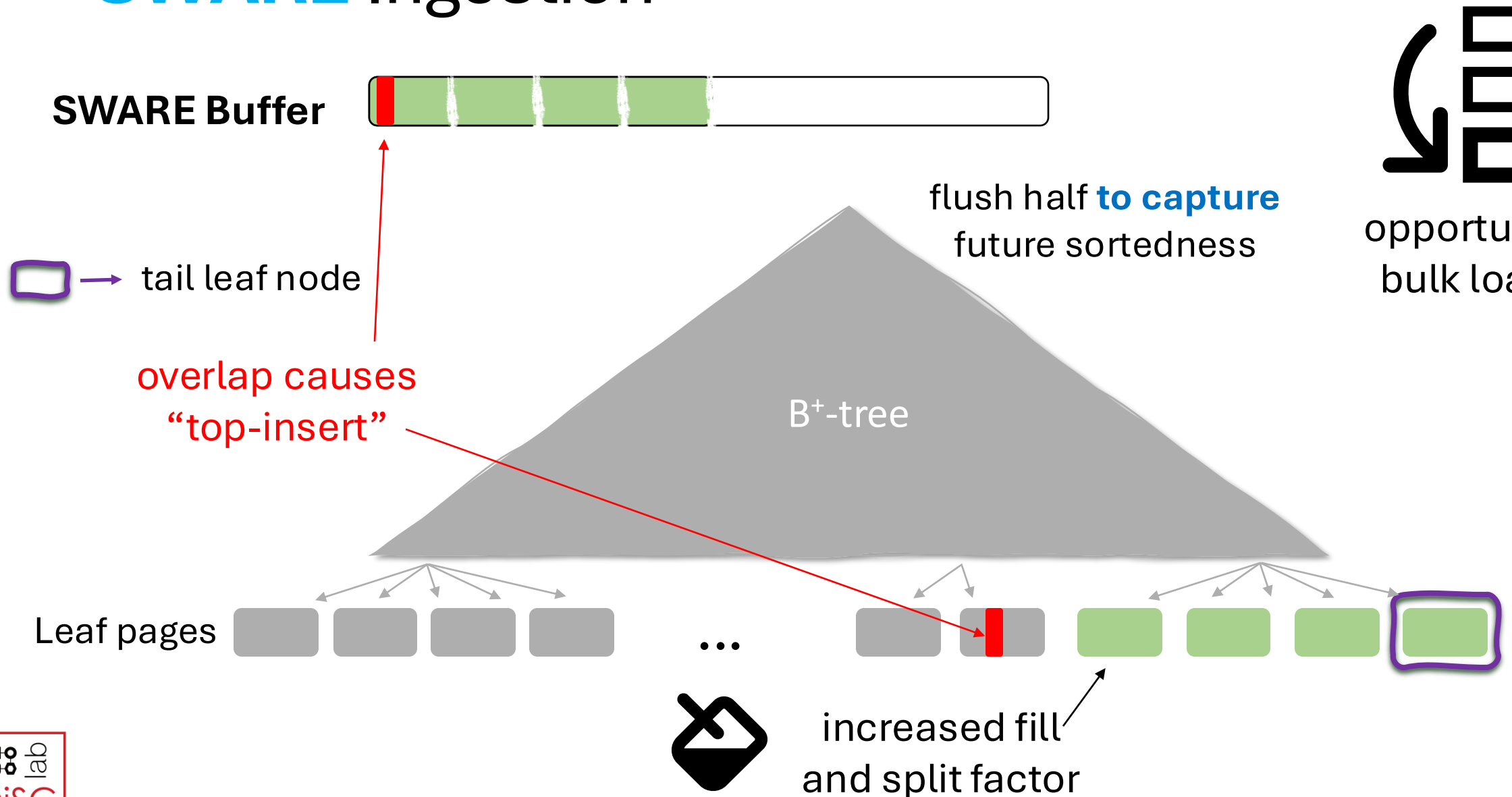
intelligent buffering

Zonemaps and Bloom filters for point and range queries

tail leaf node

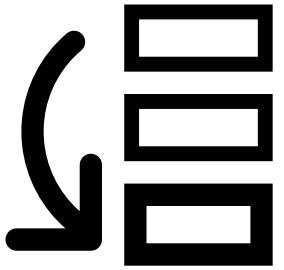


SWARE Ingestion

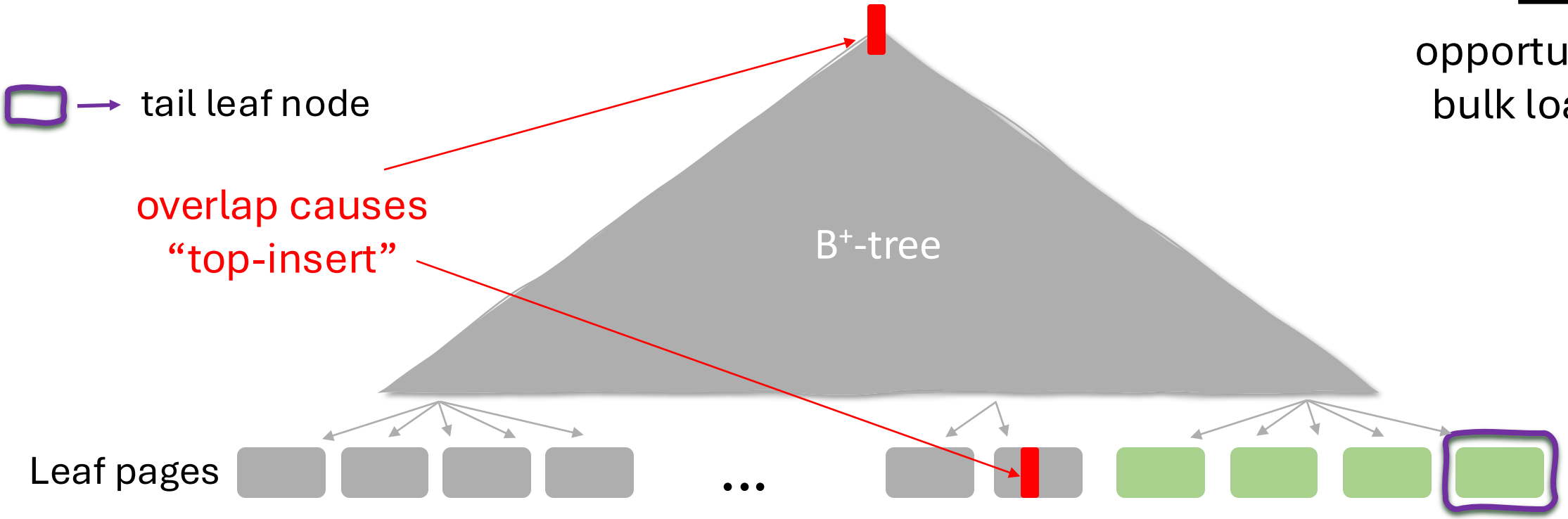


SWARE Ingestion

SWARE Buffer



opportunistic bulk loading



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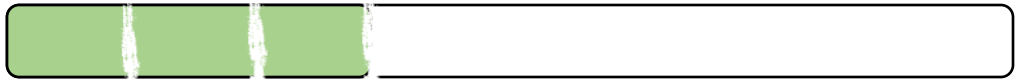
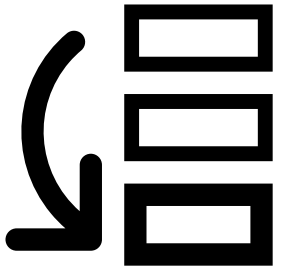


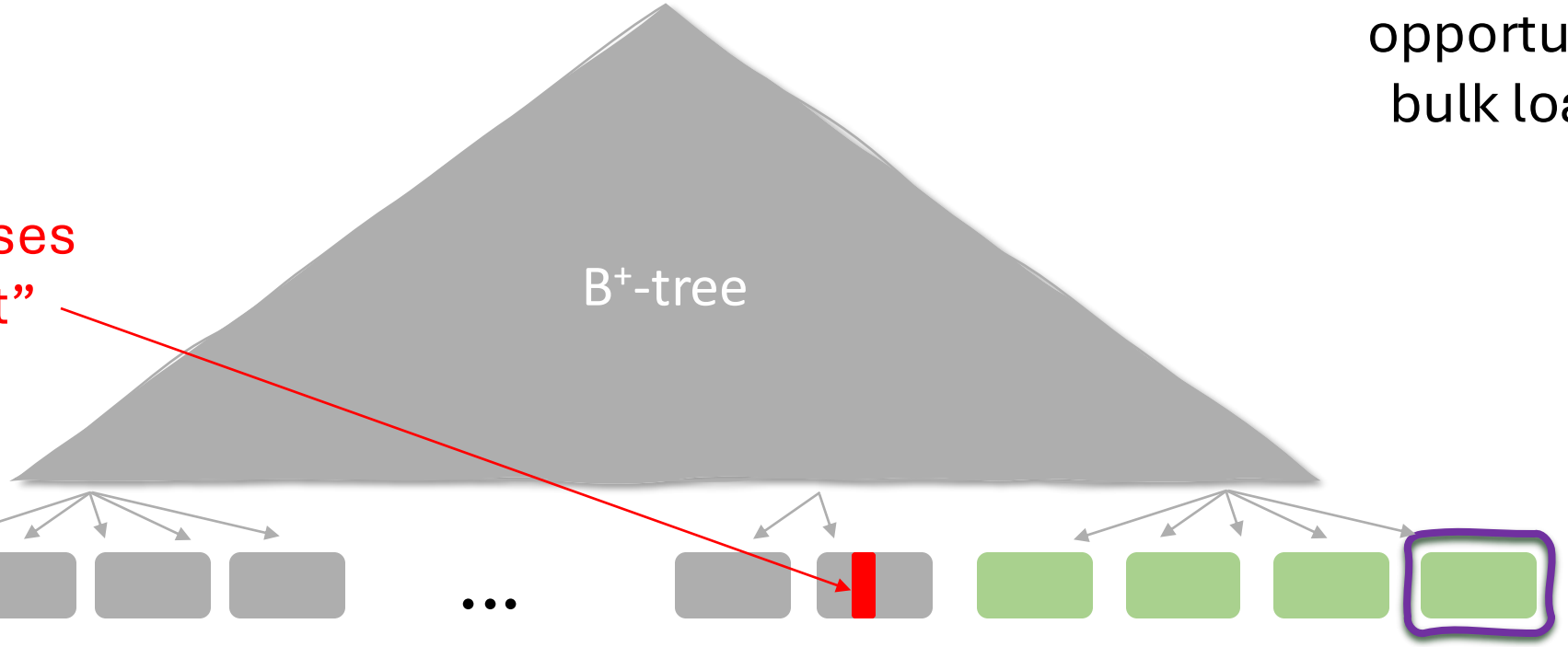
opportunistic bulk loading resumes!



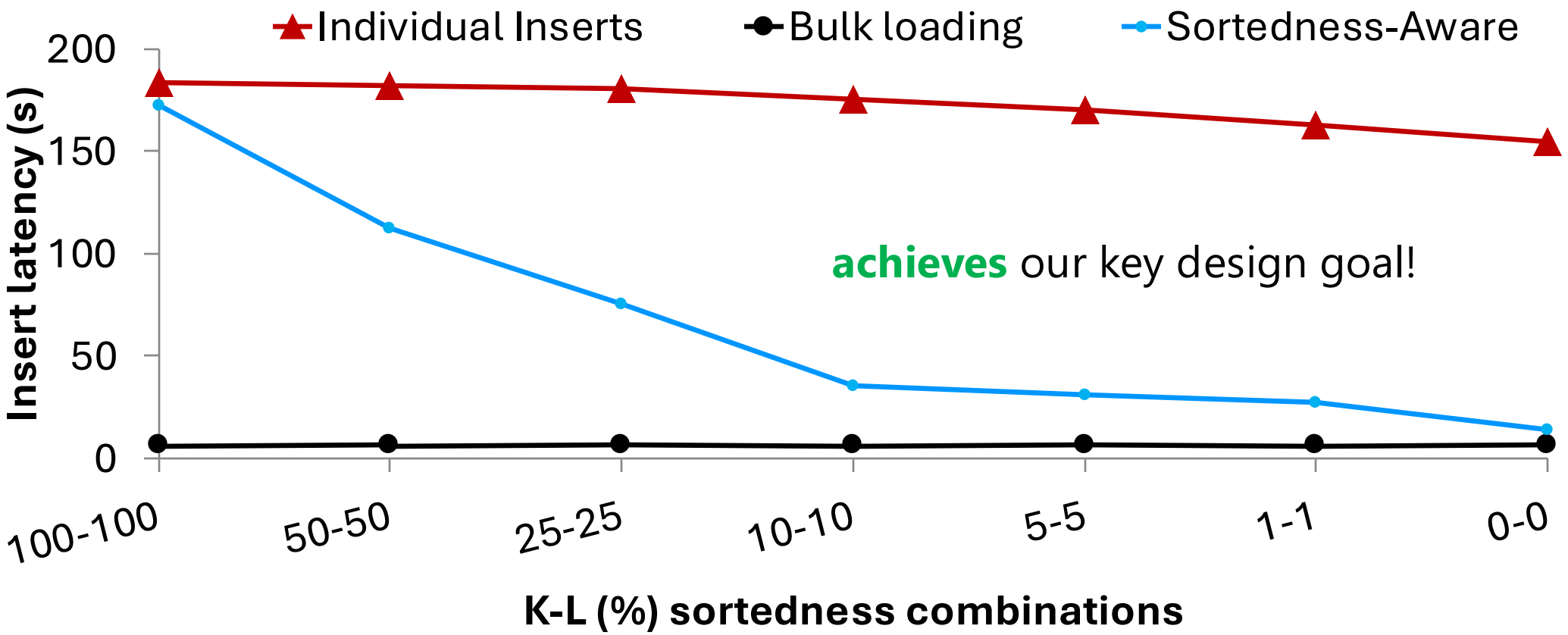
opportunistic bulk loading

tail leaf node

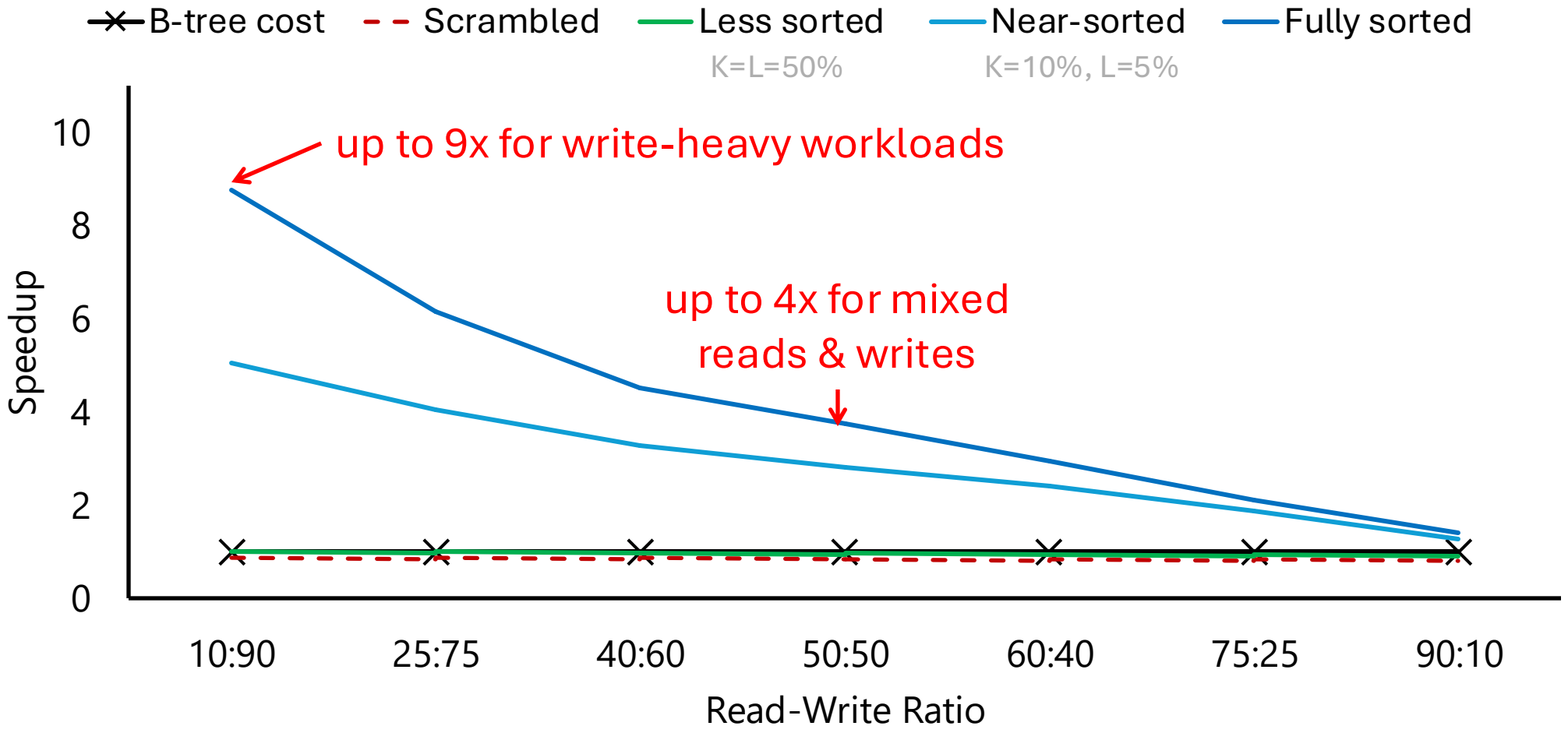
overlap causes "top-insert"



SWARE Bridges Bulk-loading & Top-Inserts



SWARE Benefits for ↑ Writes

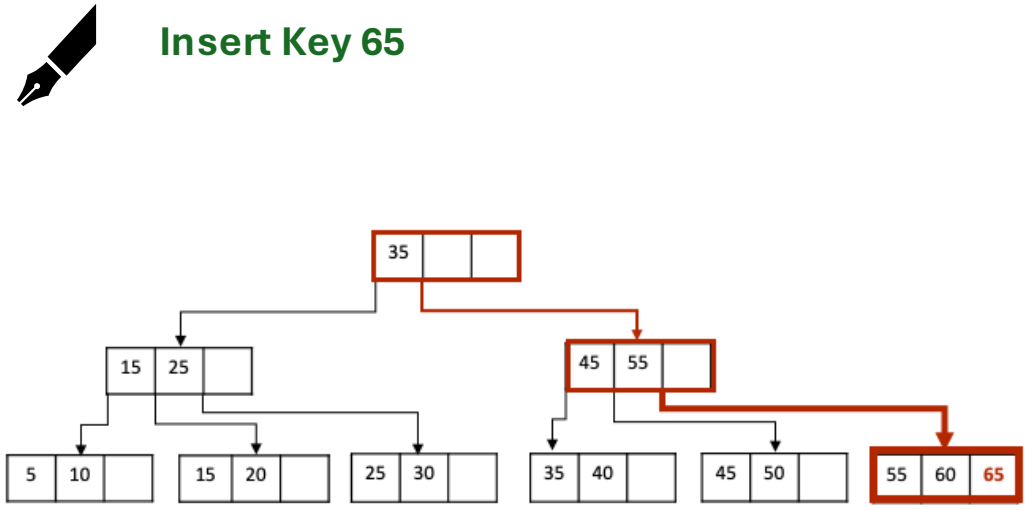


Use *sortedness* as a *resource*!

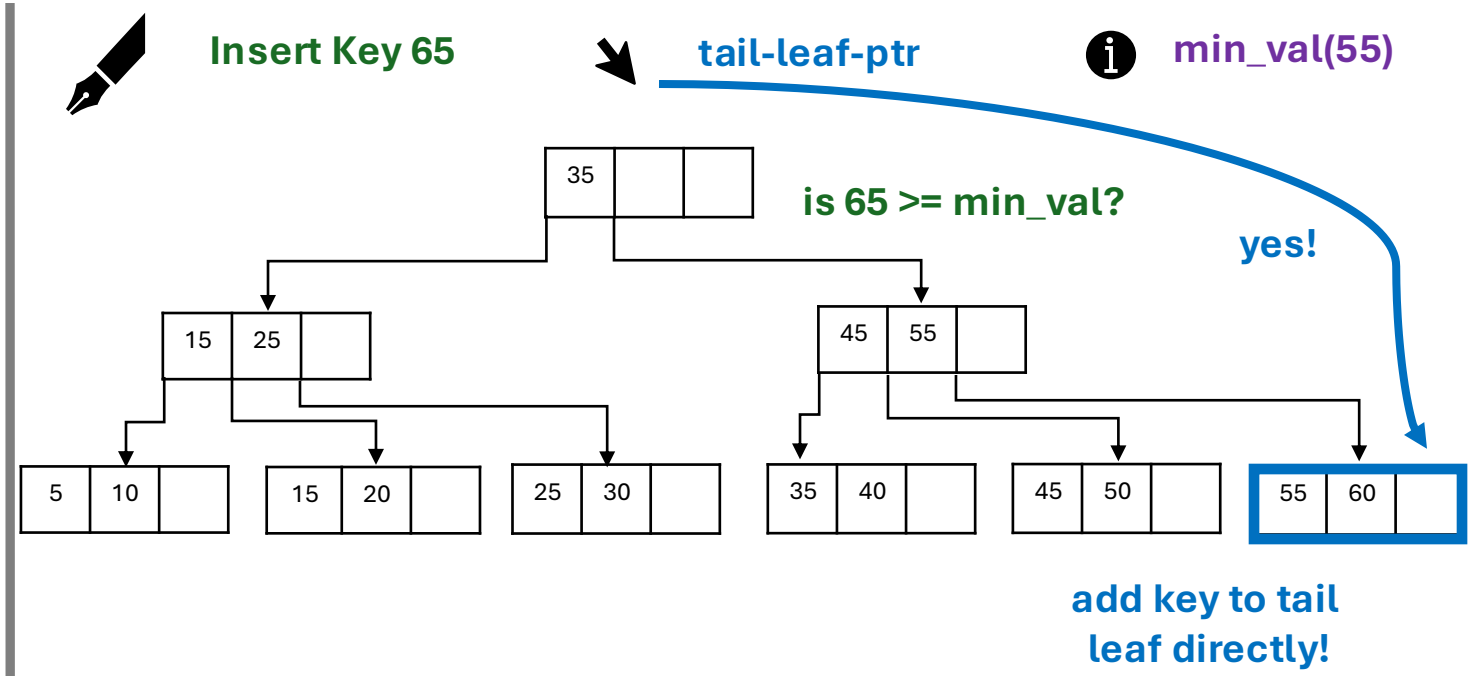
Can We Exploit Sortedness w/o Buffering?

Tail-Leaf Inserts in PostgreSQL

Normal Insertion (top-insert)

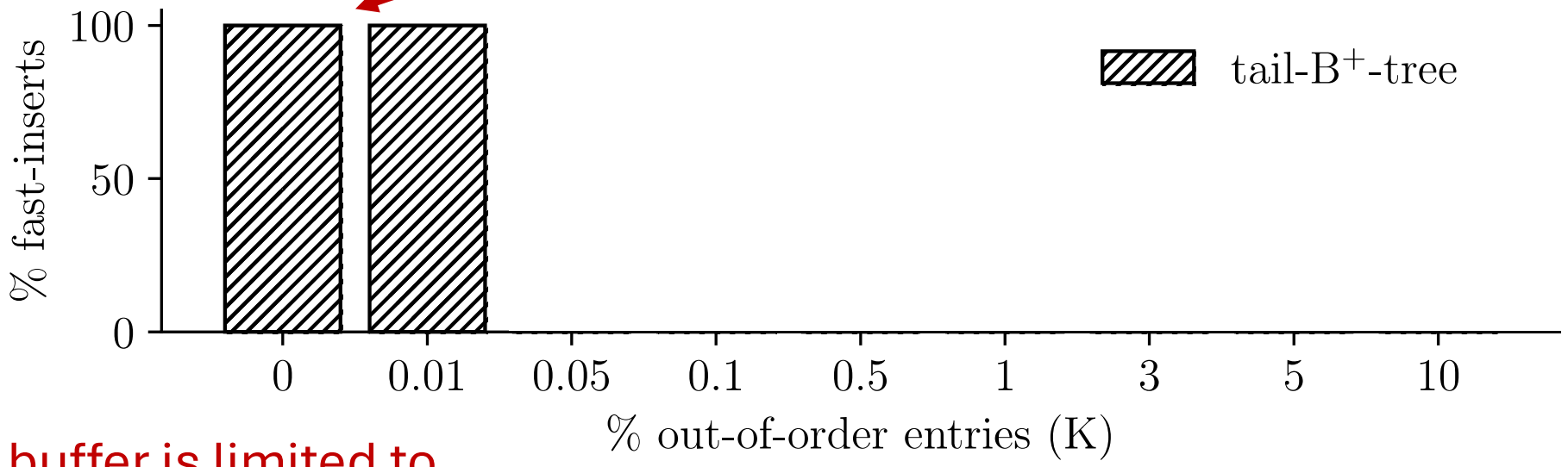


Tail-leaf Insertion



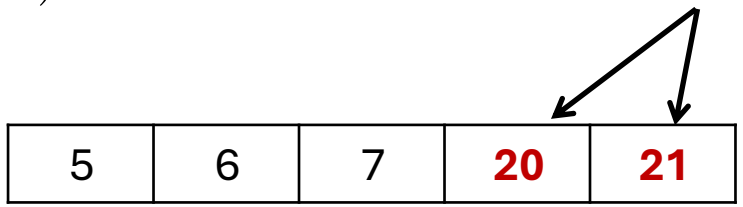
Does This Always Work?

Works for fully and very highly sorted data



Tail-leaf's buffer is limited to leaf node!

outliers



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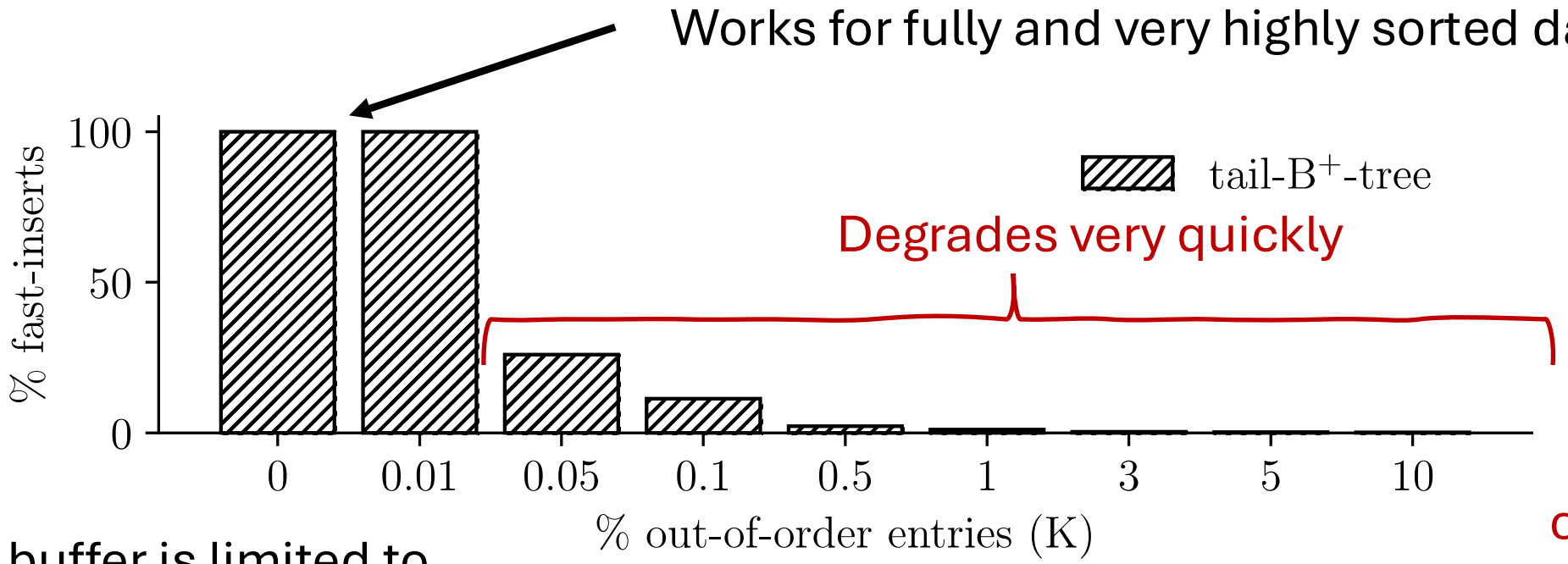

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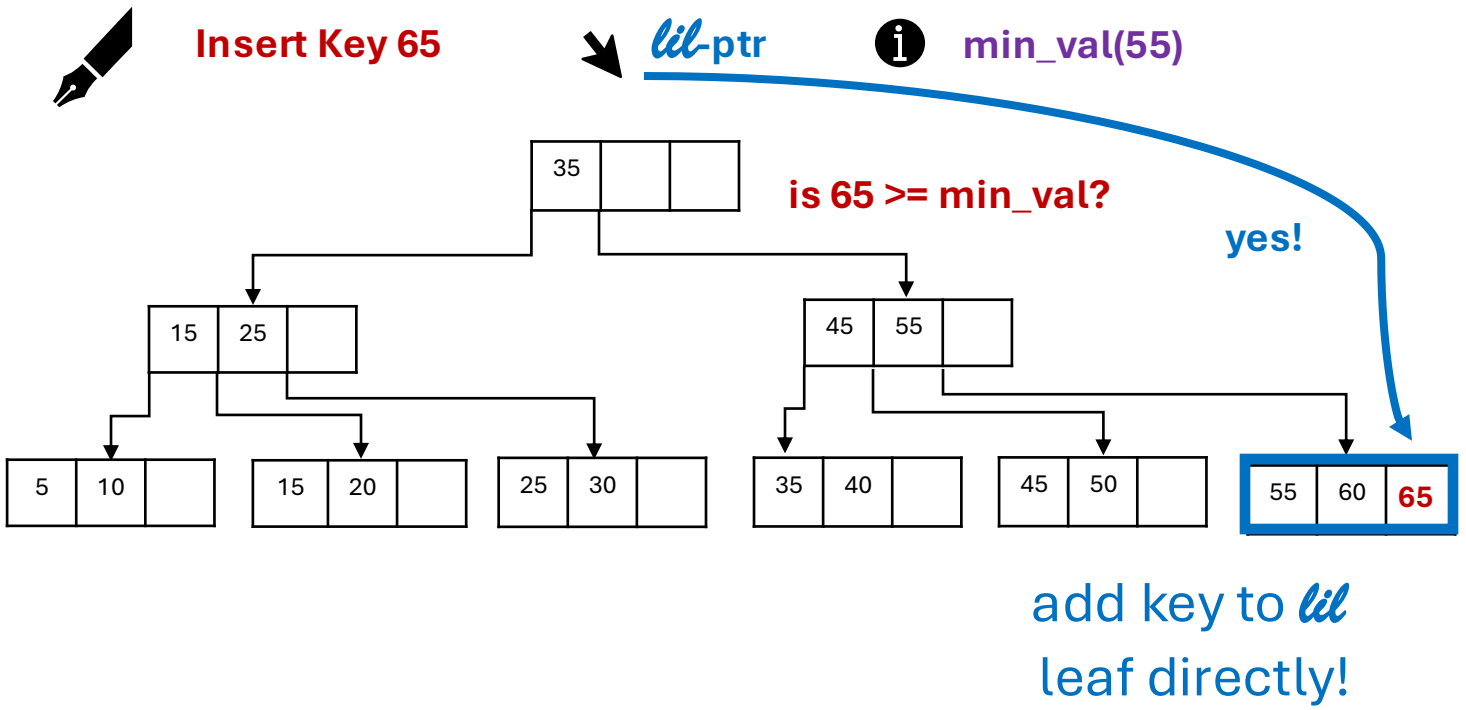
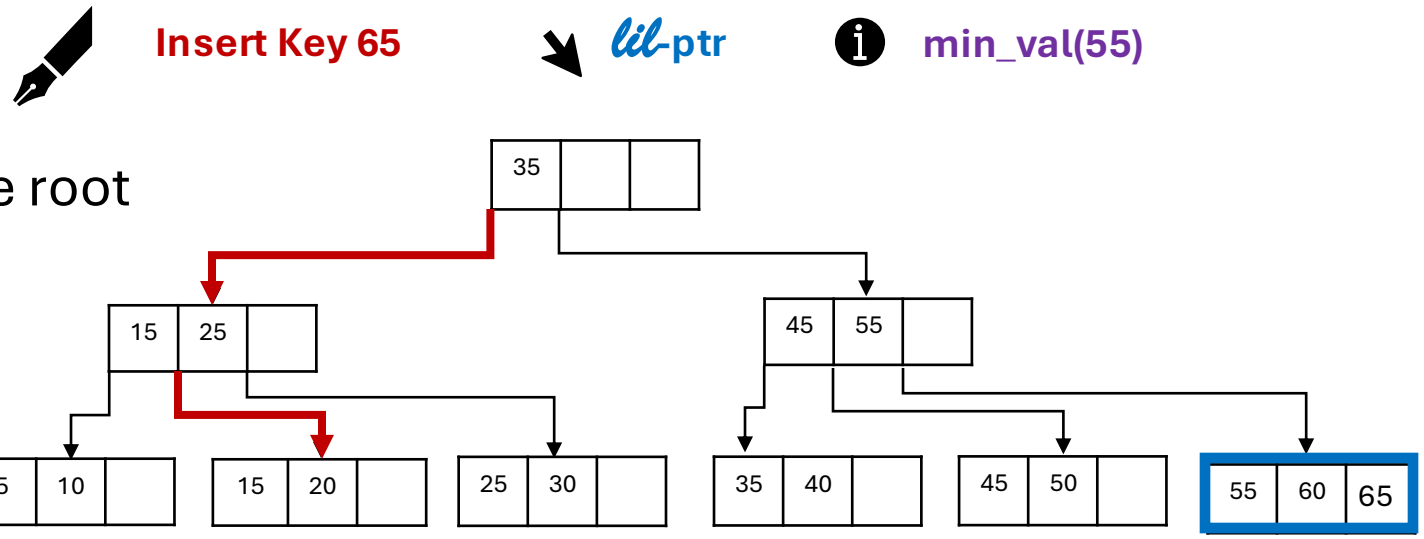
5	6	7	20	21

Last Insertion Leaf (*lil*)



What if we insert an out-of-order key instead?

Last Insertion Leaf *(lil)*



top-insert through the root

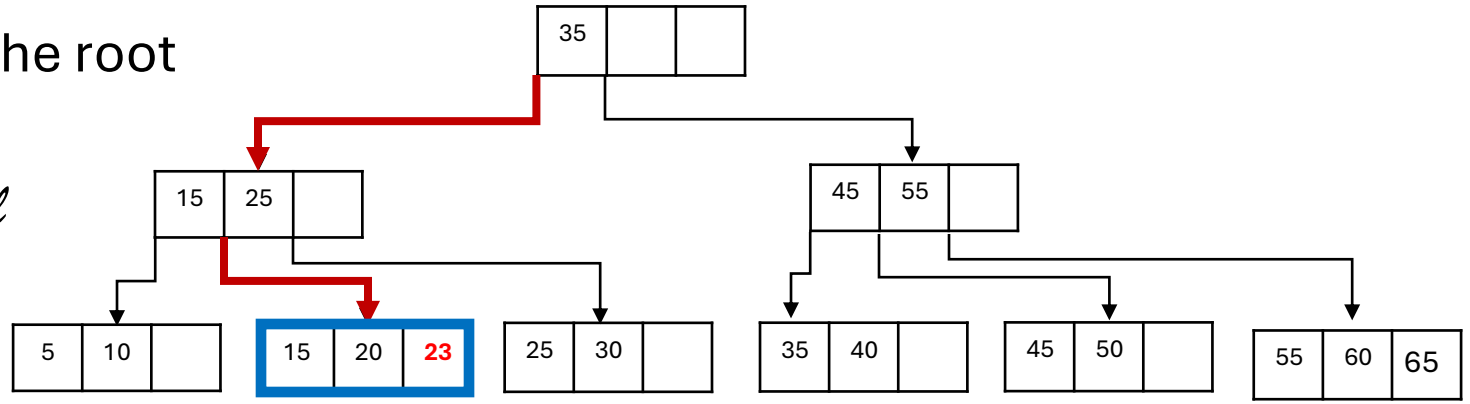
Last Insertion Leaf (*lil*)

also update min_val!

Insert Key 65 | *lil*-ptr | min_val(55)

top-insert through the root

update pointer to *lil*



Every top-insert will update *lil*

lil in Action

lil achieves higher fraction of fast-inserts

Is *lil* Ideal?

out-of-order insert in *lil* causes 2 top-inserts:

one moves *lil* to a different node

one moves *lil* back to the in-order node

***lil* pays a penalty for every out-of-order insert!**

Ideally, we should incur ***at most*** one top-insert for every out-of-order entry

Quick Insertion Tree

similar to **B⁺-tree** in design

+

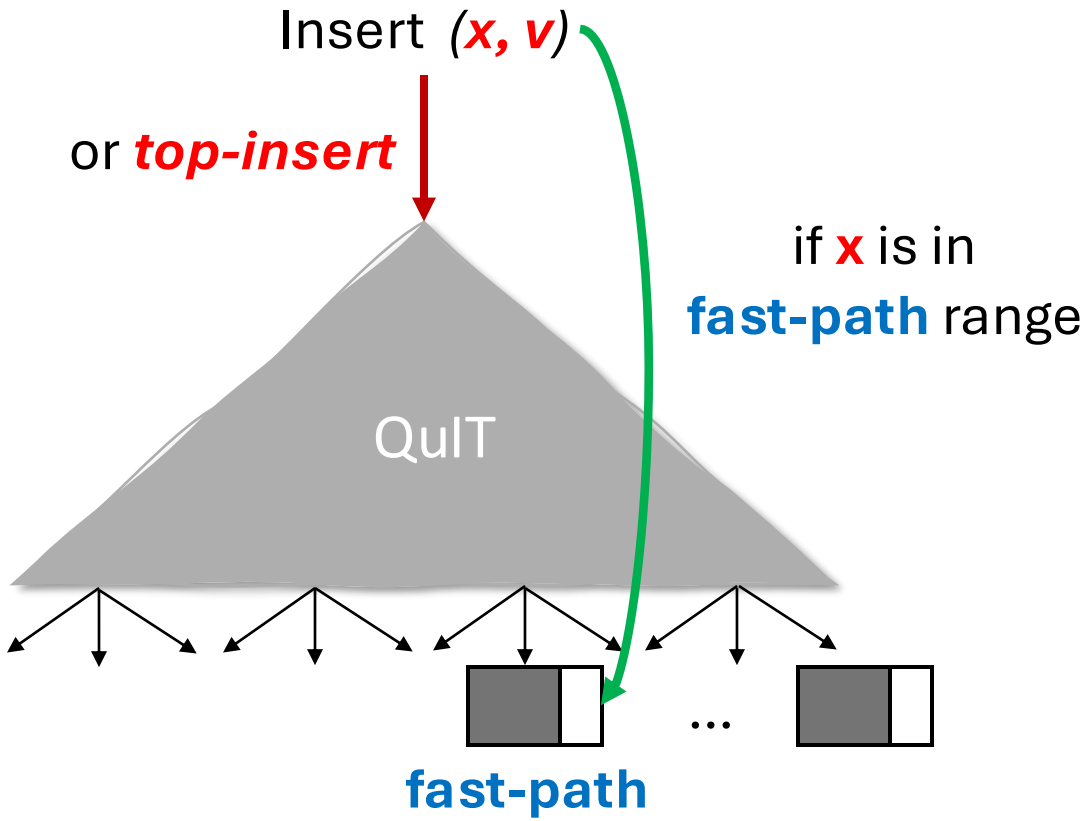
offers **fast-path** ingestion

+

sortedness-aware

+

minimal metadata + ***tuning***

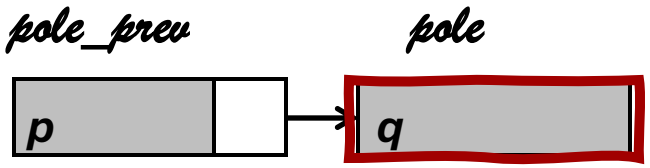


Predicting the Ordered Leaf (*pole*)

tail-leaf quickly fills up with outliers

lil naively switches fast-path

decision: when do we **update** the **fast-path** ?



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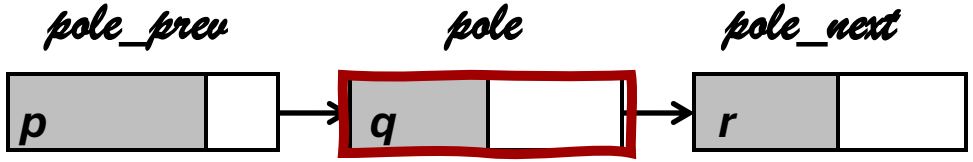

Predicting the Ordered Leaf (*pole*)

tail-leaf quickly fills up with outliers

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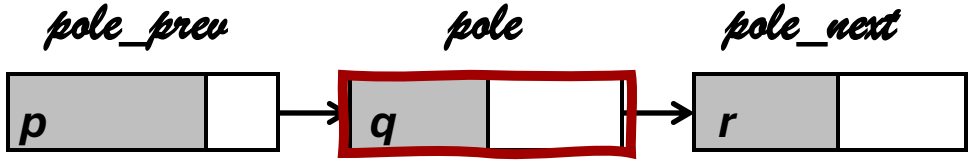


predict using *I*n-order *K*ey estimato*R* (*IKR*)

$$x = q + \left(\frac{q - p}{pole\_prev_{size}}\right) \cdot pole_{size}$$

capture (scale) small deviations

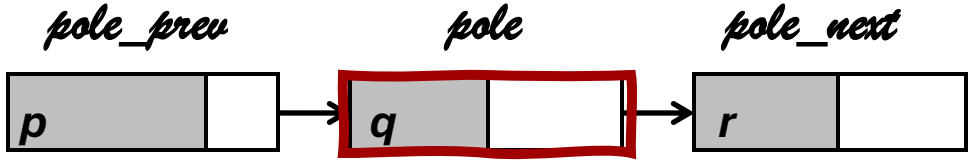
density between two non-outliers

Predicting the Ordered Leaf (*pole*)

tail-leaf quickly fills up with outliers

lil naively switches fast-path

decision: when do we **update** the **fast-path** ?



predict using *I*n-order *K*ey estimato*R* (*IKR*)

$$x = q + \left(\frac{q - p}{\lfloor pole\_prev_{size} \rfloor}\right) \cdot pole_{size}$$

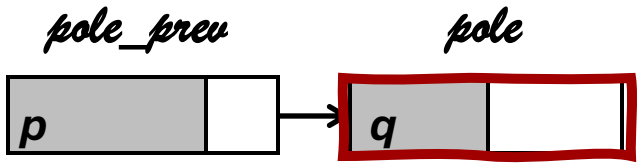
capture (scale) small deviations

density between two non-outliers

any **key** > **x** is an **outlier**

Predicting the Ordered Leaf (*pole*)

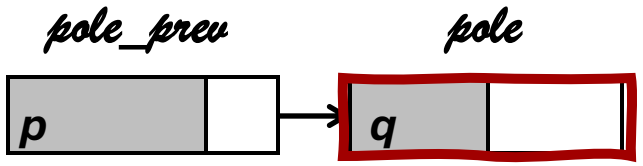
```
if(key is within pole range){
     if(pole.size < capacity){
          pole.insert(entry);
     }
     else{
          pole_next = pole.split();
          r = pole_next.min;
          x = IKR(q, p, pole_prev.size, pole.size);
          if(r <= x){
               pole_prev = pole;
               pole = pole.next;
          }
     }
}
else{
     l = insert(entry);
}
```



Predicting the Ordered Leaf (*pole*)

```
if(key is within pole range){
    if(pole.size < capacity){
        pole.insert(entry);
    }
    else{
        pole_next = pole.split();
        r = pole_next.min;
        x = IKR(q, p, pole_prev.size, pole.size);
        if(r <= x){
            pole_prev = pole;
            pole = pole.next;
        }
    }
}
else{
    l = insert(entry);
}
```

check if *key* qualifies for a fast-insert

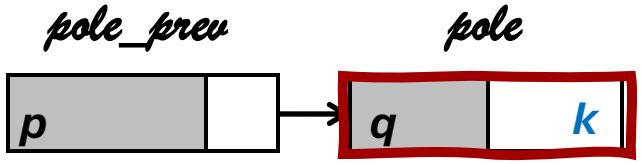


otherwise, *top-insert* through root

Predicting the Ordered Leaf (*pole*)

```
if(key is within pole range){
     if(pole.size < capacity){
          pole.insert(entry);
     }
     else{
          pole_next = pole.split();
          if(key > pole_next.min)
               pole = pole_next;
          x = IKR(q, p, pole_prev.size, pole.size);
          if(r <= x){
               pole_prev = pole;
               pole = pole.next;
          }
     }
}
else{
     l = insert(entry);
}
```

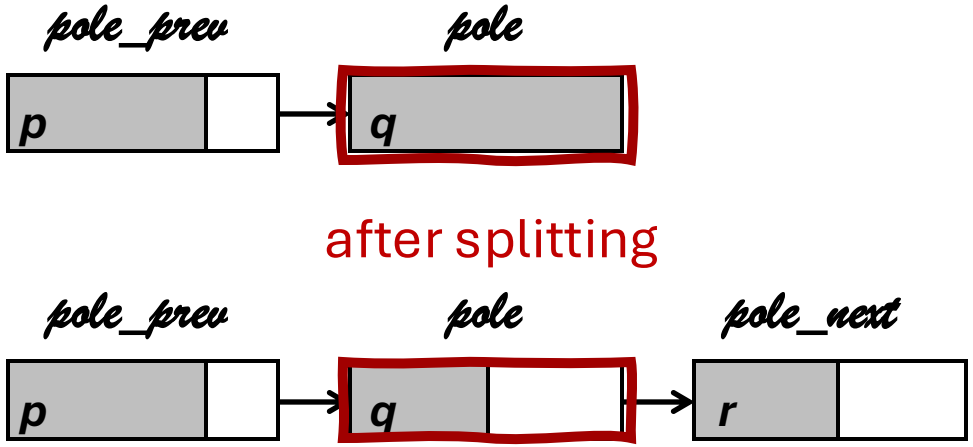
if *pole* is not full, simply insert



Predicting the Ordered Leaf (*pole*)

```
if(key is within pole range){
     if(pole.size < capacity){
          pole.insert(entry);
     }
     else{
          pole_next = pole.split();
          r = pole_next.min;
          x = IKR(q, p, pole_prev.size, pole.size);
          if(r <= x){
               pole_prev = pole;
               pole = pole.next;
          }
     }
}
else{
     l = insert(entry);
}
```

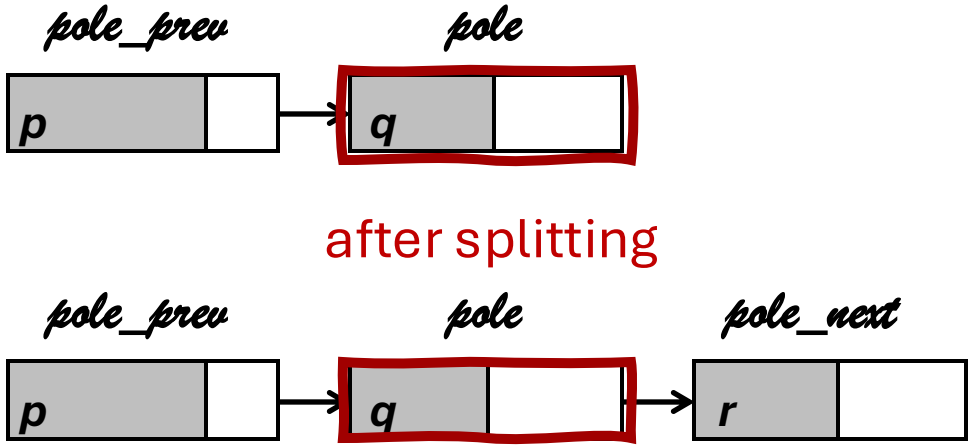
otherwise, split *pole*



Predicting the Ordered Leaf (*pole*)

```
if(key is within pole range){
     if(pole.size < capacity){
          pole.insert(entry);
     }
     else{
          pole_next = pole.split();
          r = pole_next.min;
          x = IKR(q, p, pole_prev.size, pole.size);
          if(r <= x){
               pole_prev = pole;
               pole = pole.next;
          }
     }
}
else{
     l = insert(entry);
}
```

calculate *x*



$$x = q + \left(\frac{q - p}{pole\_prev_{size}}\right) \cdot pole_{size} \cdot (scale)$$

density between two non-outliers

capture small deviations

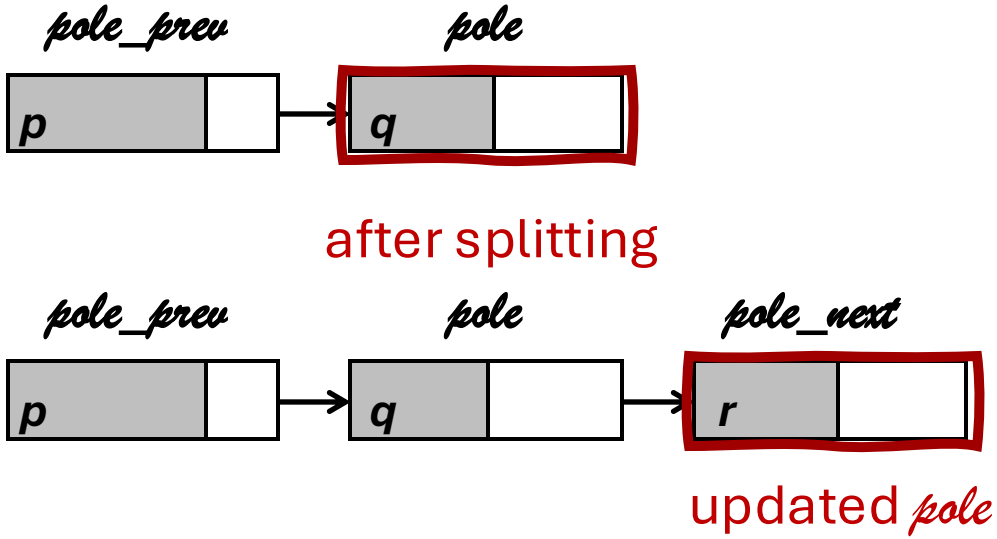
default to ***1.5***

Predicting the Ordered Leaf (*pole*)

```
if(key is within pole range){
     if(pole.size < capacity){
          pole.insert(entry);
     }
     else{
          pole_next = pole.split();
          r = pole_next.min;
          x = IKR(q, p, pole_prev.size, pole.size);
          if(r <= x){
               pole_prev = pole;
               pole = pole.next;
          }
     }
}
else{
     l = insert(entry);
}
```

if *pole_next* has at least one non-outlier

otherwise, *pole* remains as is



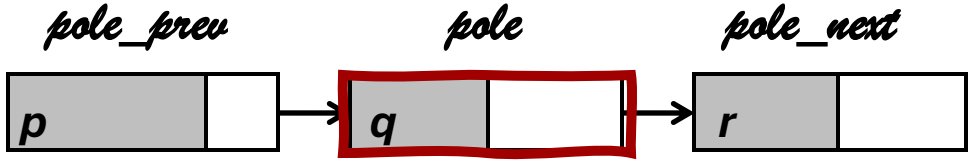
Can We Better Utilize Space?

high sortedness => poor space utilization

can we find better split points?

IKR can also return the split point

return last key <= x in *pole*

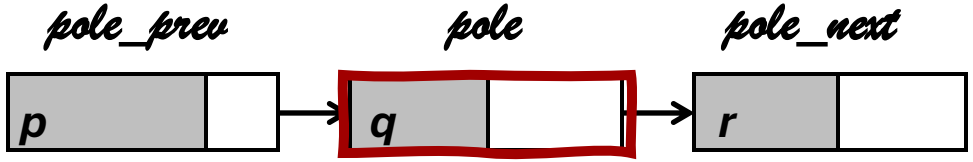


Can We Better Utilize Space?

high sortedness => poor space utilization

```
l_pos = IKR(q, p, pole_prev.size);

if(l_pos <= 50%){
     pole_next = pole.split(l_pos);
}
else{
     pole.next = pole.split(l_pos - 1);
     pole_prev = pole;
     pole = pole.next;
}
```



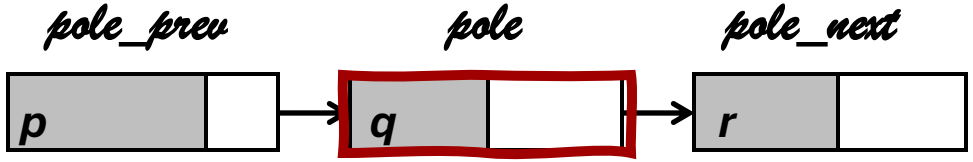
let's call this key ℓ

Can We Better Utilize Space?

high sortedness => poor space utilization

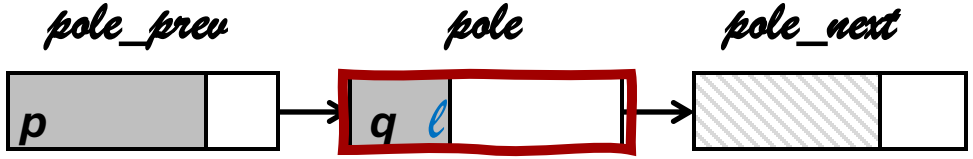
```
l, l_pos = IKR(q, p, pole_prev.size);

if(l_pos <= 50%){
     pole_next = pole.split(l_pos);
}
else{
     pole.next = pole.split(l_pos - 1);
     pole_prev = pole;
     pole = pole.next;
}
```



let's call this key ℓ

after splitting, if $\ell\_pos \leq 50\%$



split at ℓ

this moves all outliers to *pole_next*

Can We Better Utilize Space?

high sortedness => poor space utilization

```
l_pos = IKR(q, p, pole_prev.size);

if(l_pos <= 50%){
     pole_next = pole.split(l_pos);
}
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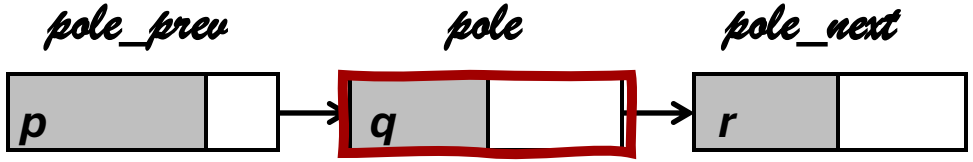
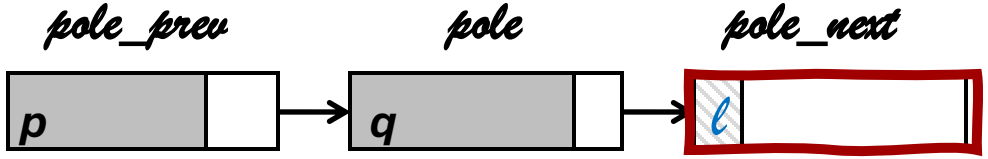


let's call this key ℓ

after splitting, if ℓ_pos > 50%



split at ℓ_pos - 1 updated *pole*

this moves at least one non-outlier to ***pole_next***

Evaluating QuIT

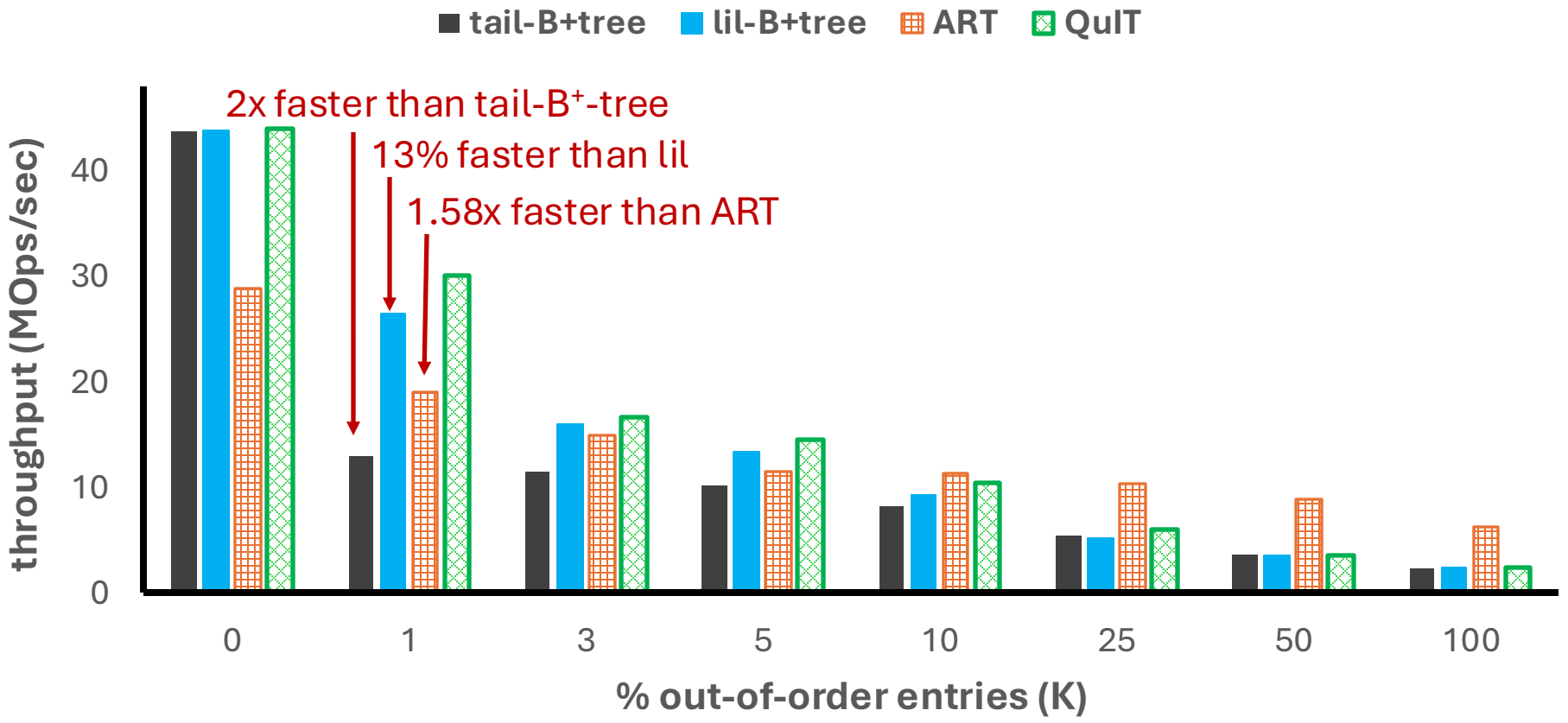
System:

- Intel Xeon Gold 5230
- 2.1GHZ processor w. 20 cores
- 384GB RAM, 28MB L3 cache

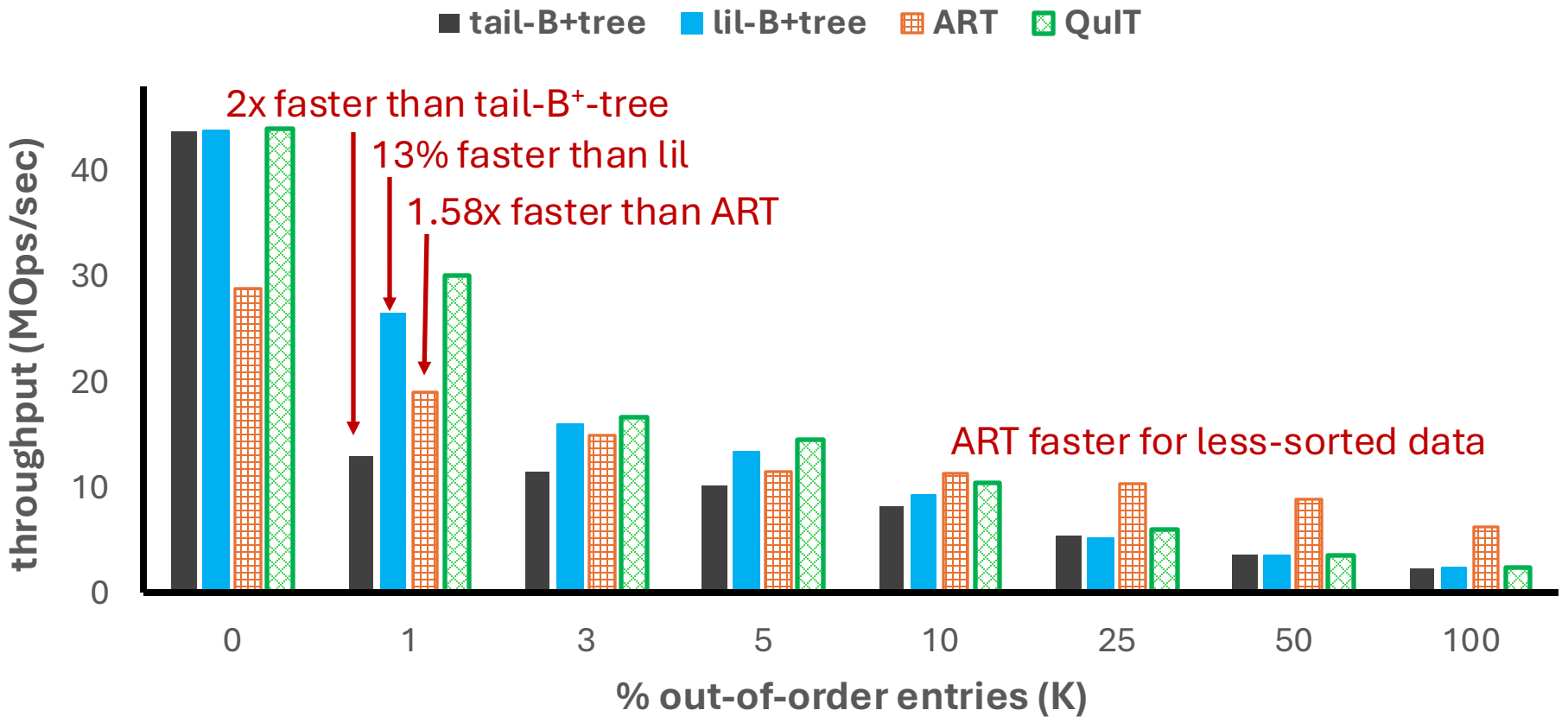
Index Setup:

- Node size = 4KB
- Entire index in memory
- fuzzy scale in IKR = 1.5
- 500M entries (4B + 4B)

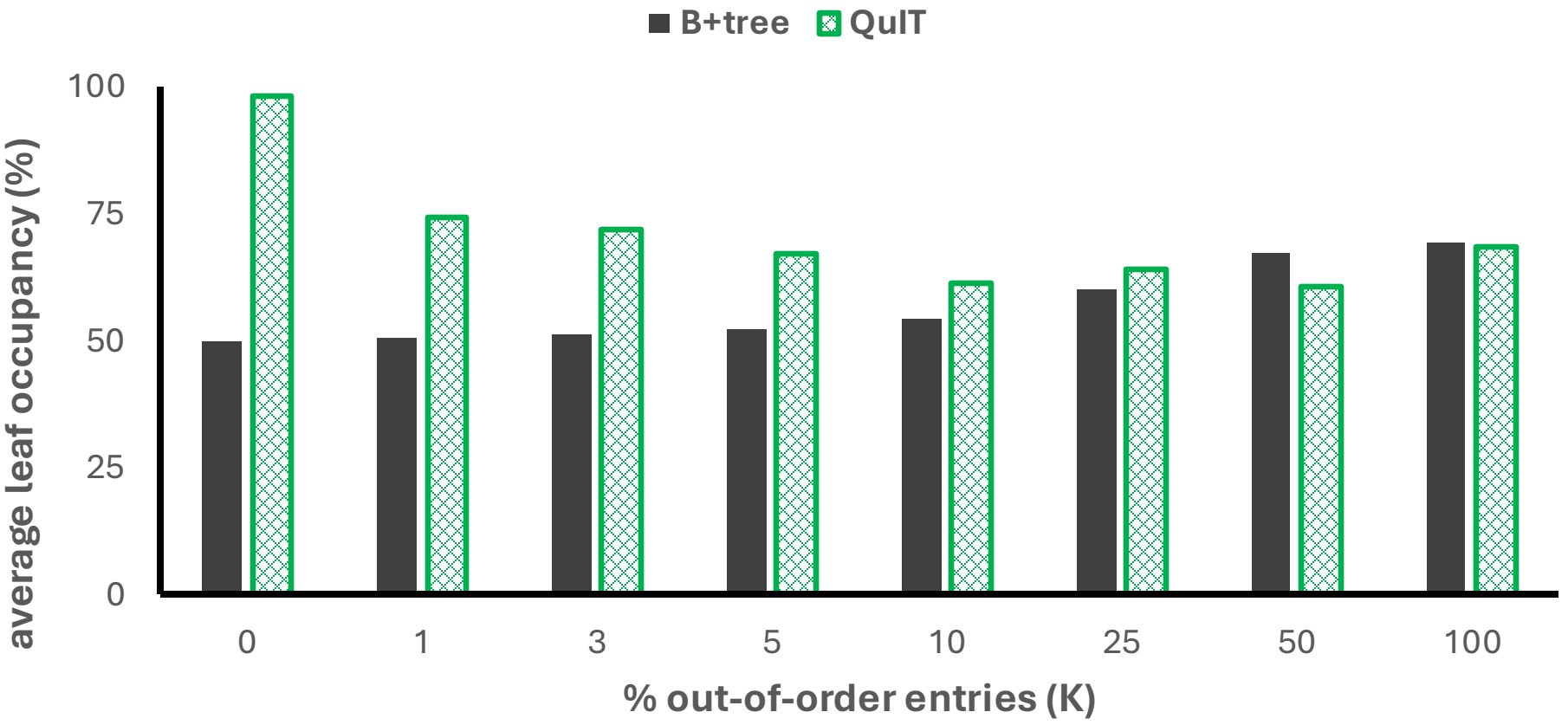
QuIT Outperforms All Baselines



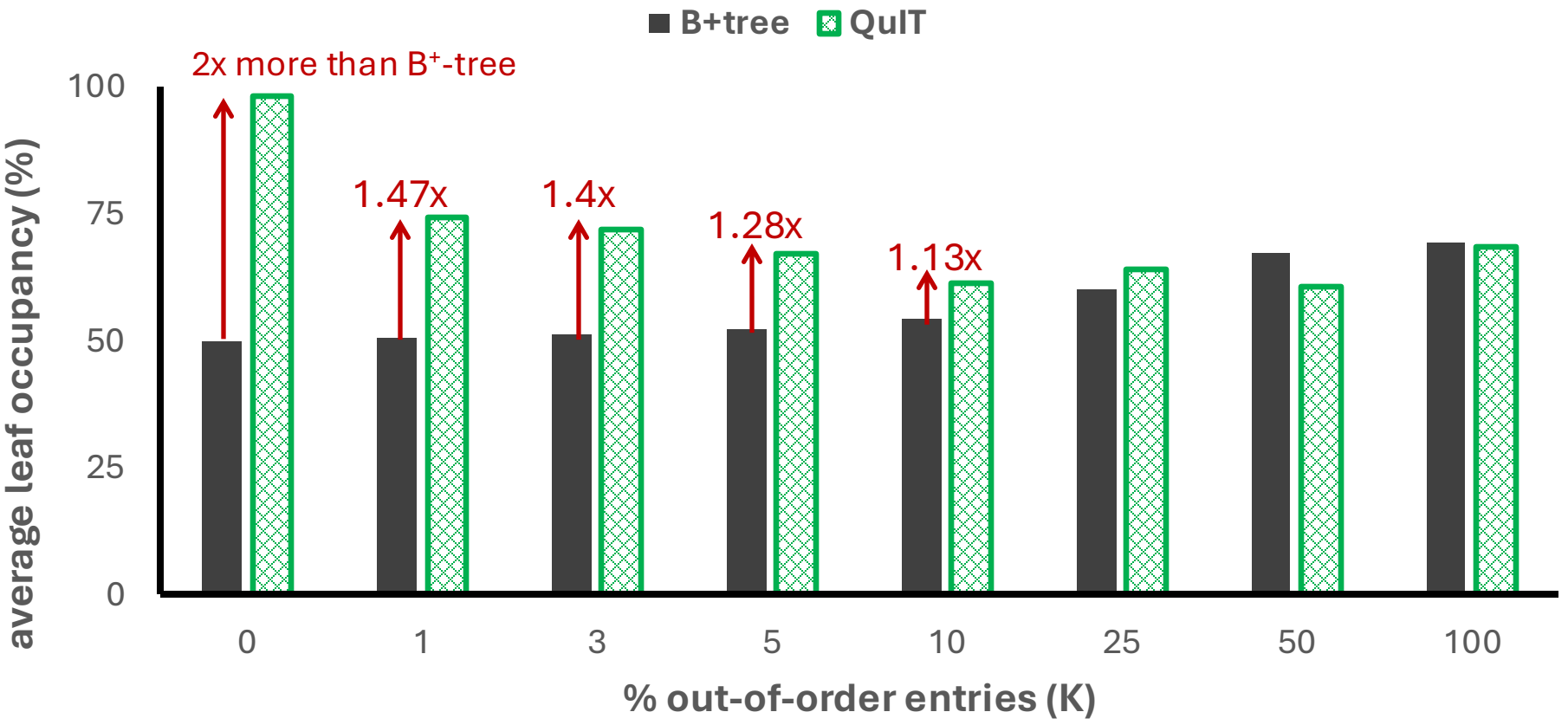
QuIT Outperforms All Baselines



QuIT Increases Occupancy in L

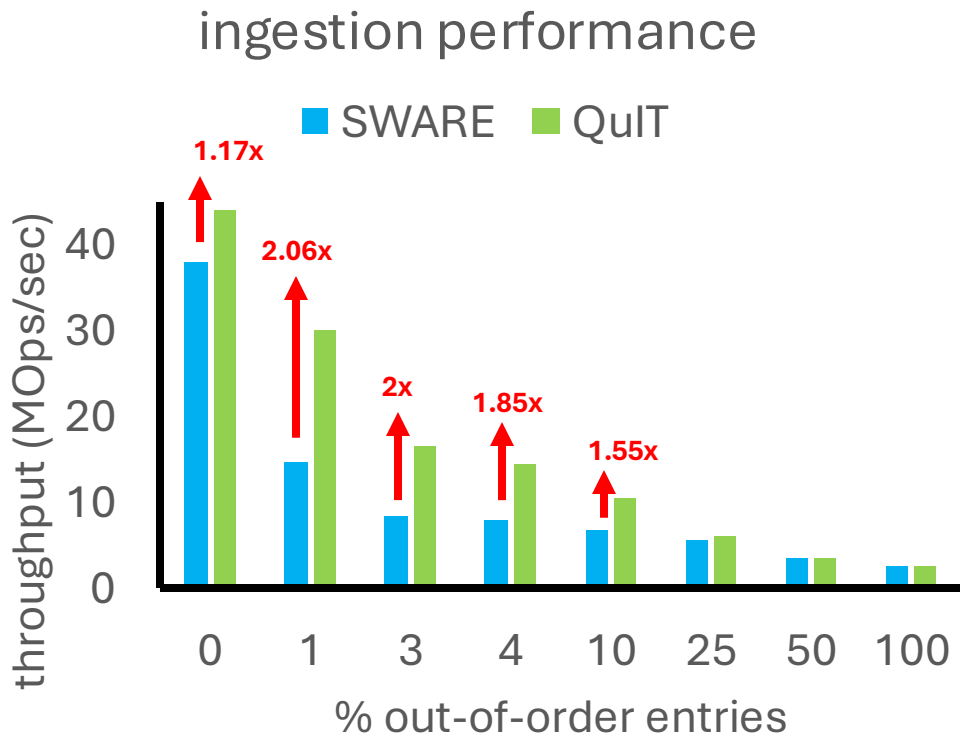


QuIT Increases Occupancy in L



higher leaf occupancy reduces memory footprint✓

QuIT v/s SWARE



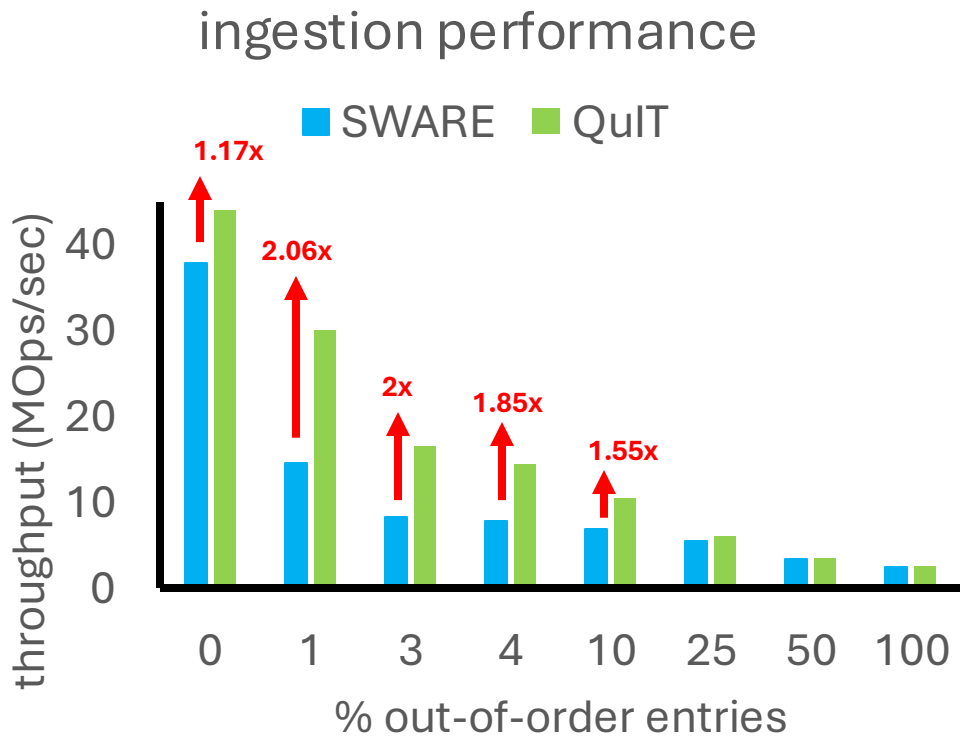
integrate SWARE with same B⁺-tree as QuIT

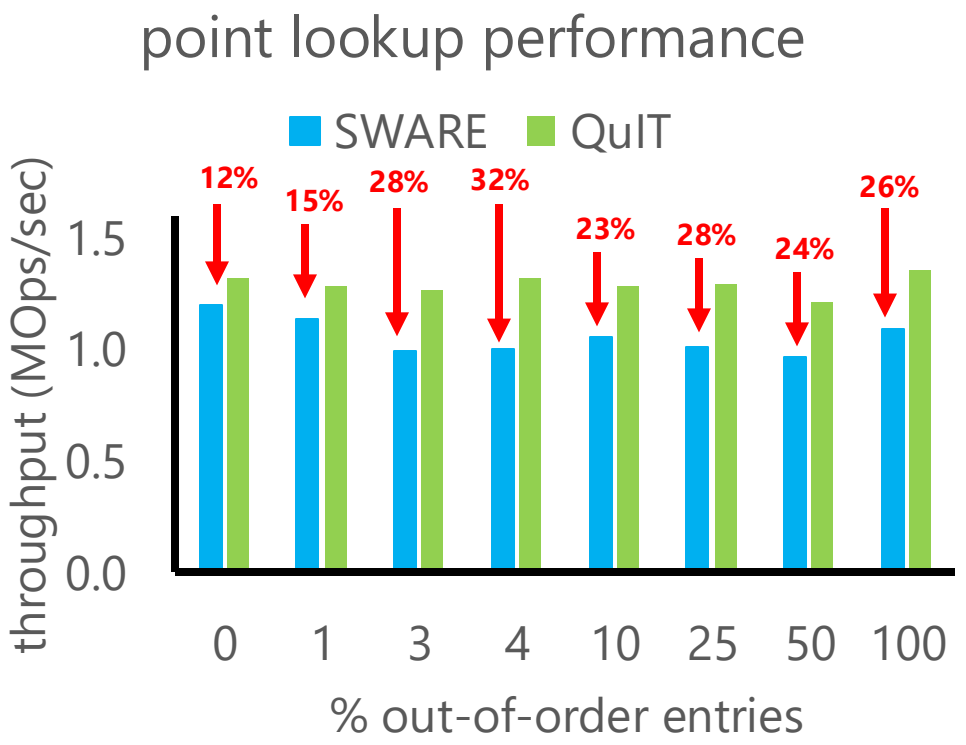
up to 2.06x faster

avoids SWARE buffer management ✓

minimal metadata ✓

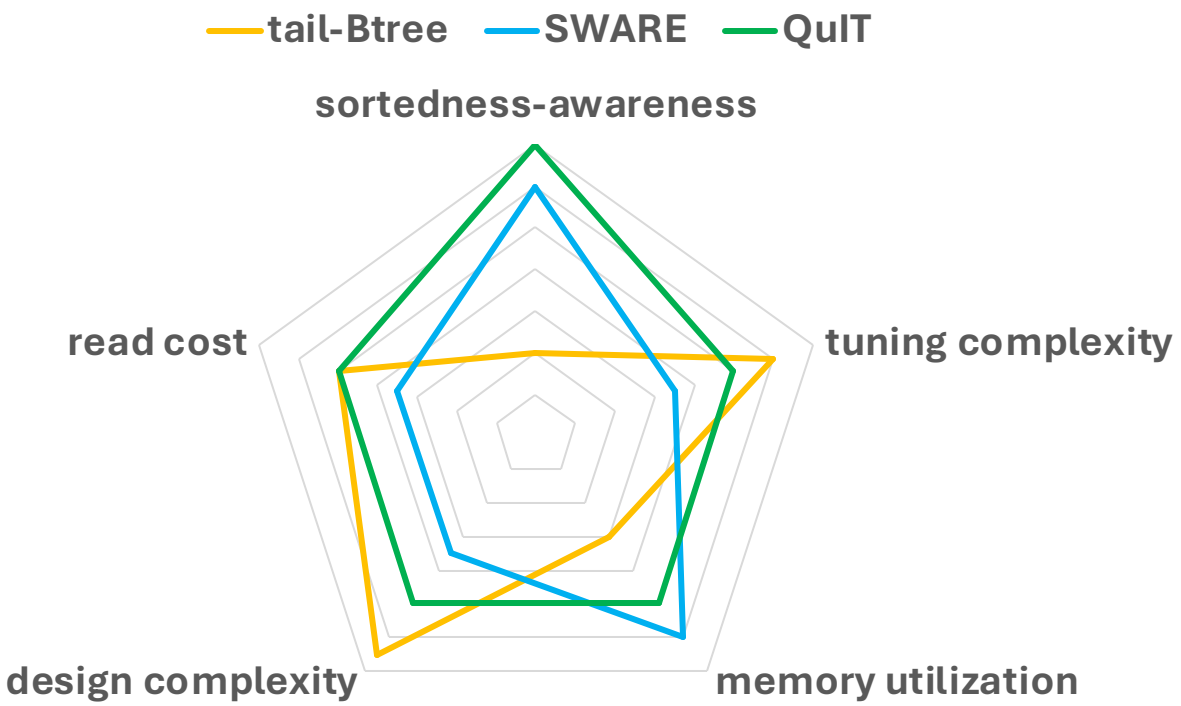
QuIT v/s SWARE





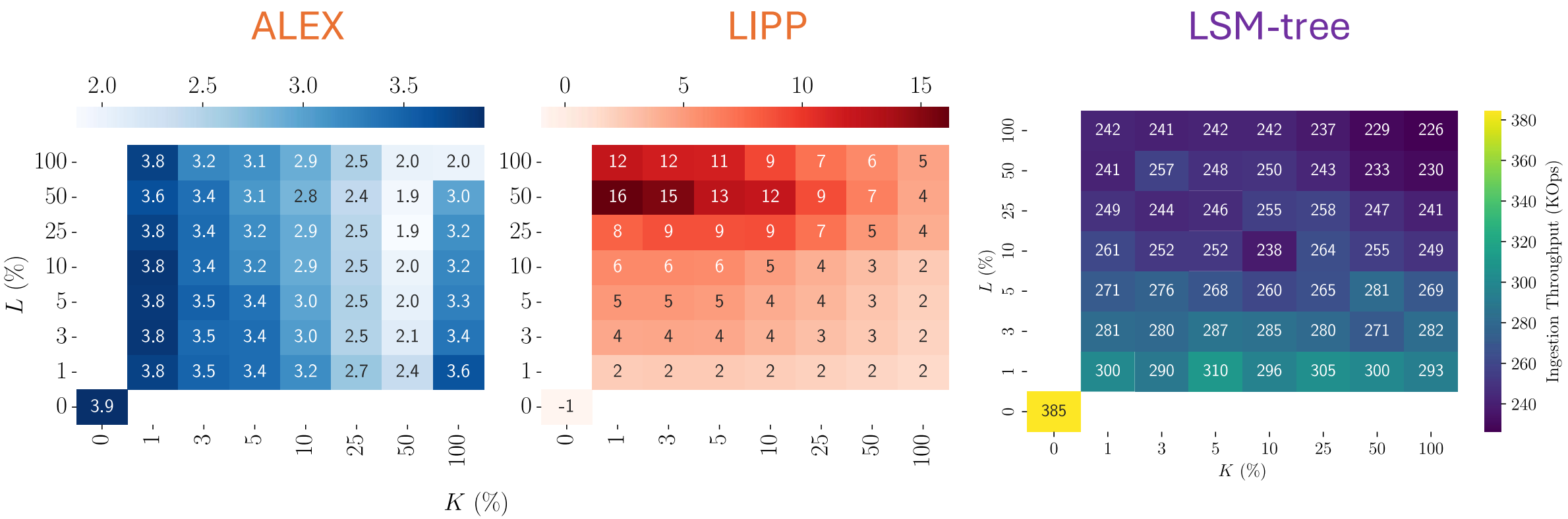
No buffering ⇒ no read overhead!

Qualitatively Comparing SWARE & QuIT



QuIT offers: higher sortedness-awareness + no read penalty + minimal design & tuning complexity

Benchmarking Learned and LSM Indexes



Summary

Identify “sortedness” as a resource to reduce indexing cost

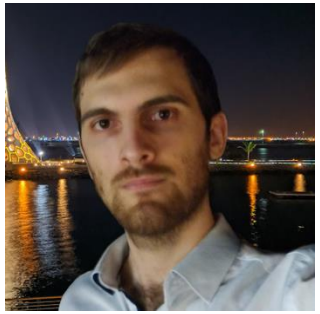
SWARE framework offers sortedness-awareness to any index, but incurs read penalty

QuIT offers fast ingestion with no read penalty + lightweight design

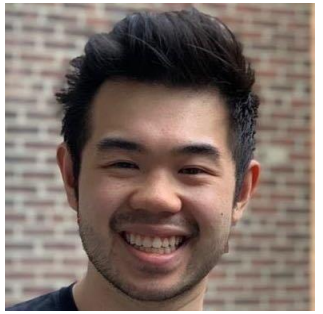
Currently exploring concurrency control for QuIT

Our Team

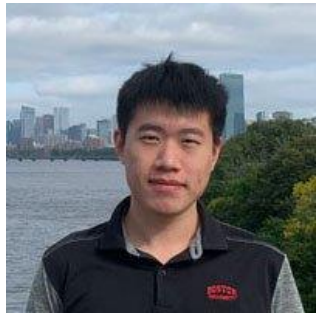
Aneesh Raman



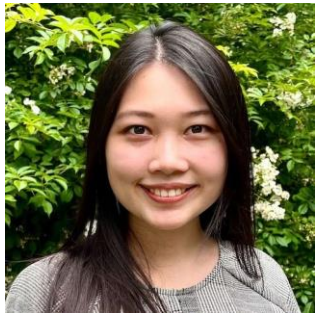
Kostas Karatsenidis



Andy Huynh



Jinqi Lu



Shaolin Xie

Subhadeep Sarkar

Matthaios Olma