Columnstore and B+ tree – Are Hybrid Physical Designs Important?

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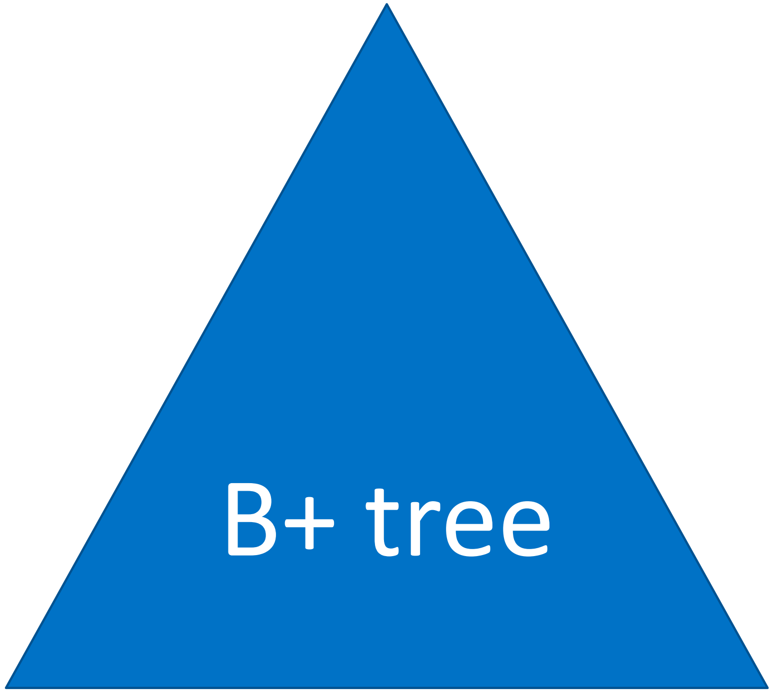
Physical designs for diverse workloads

OLTP



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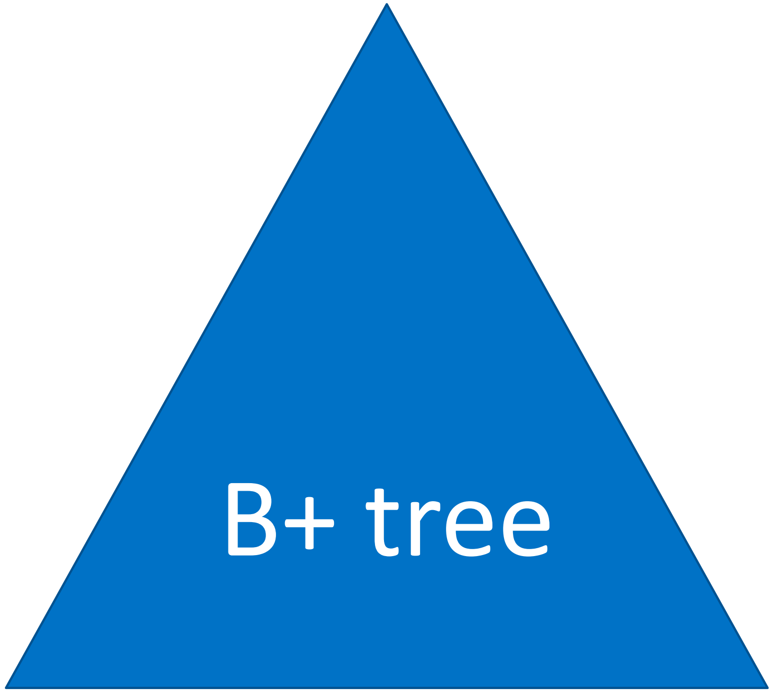
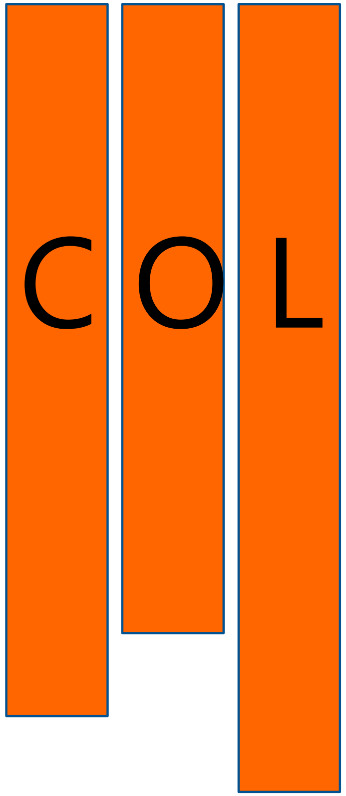
Analytics





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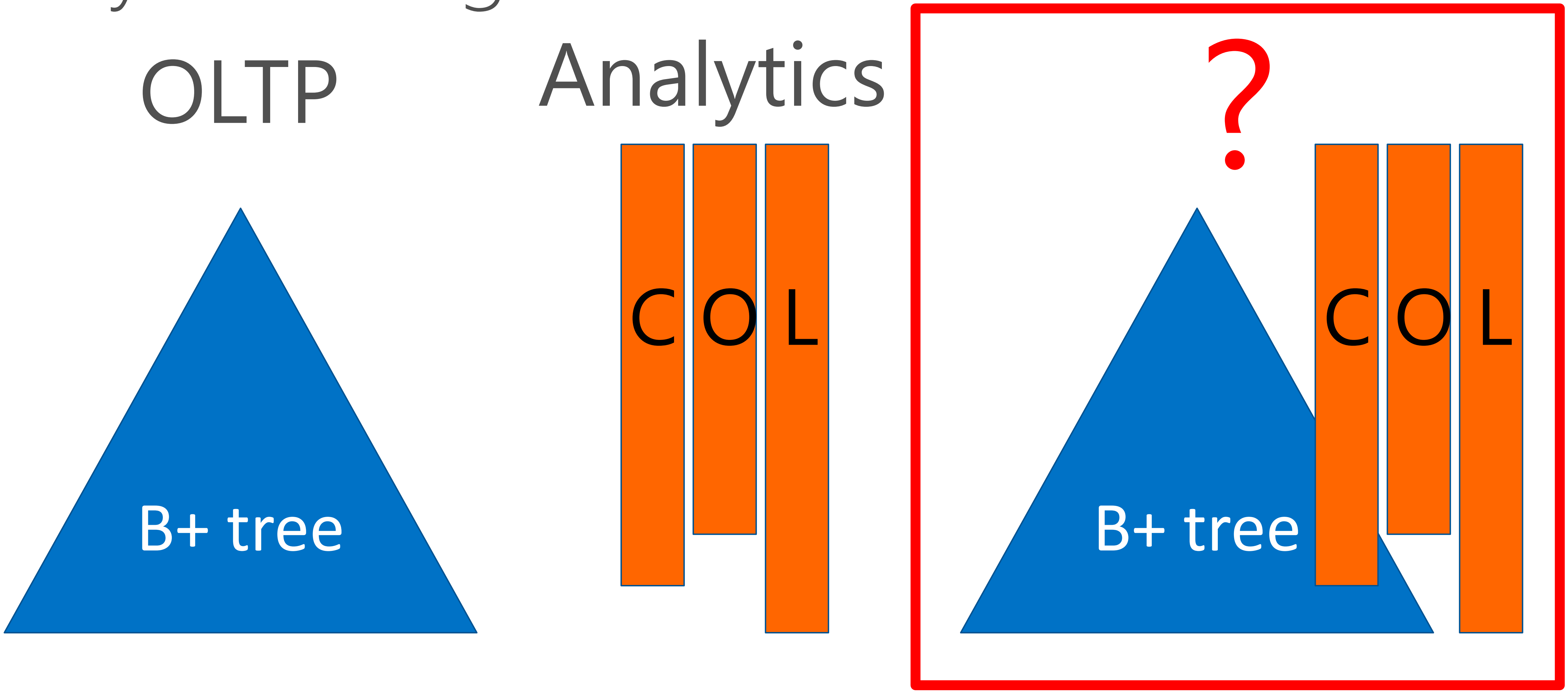
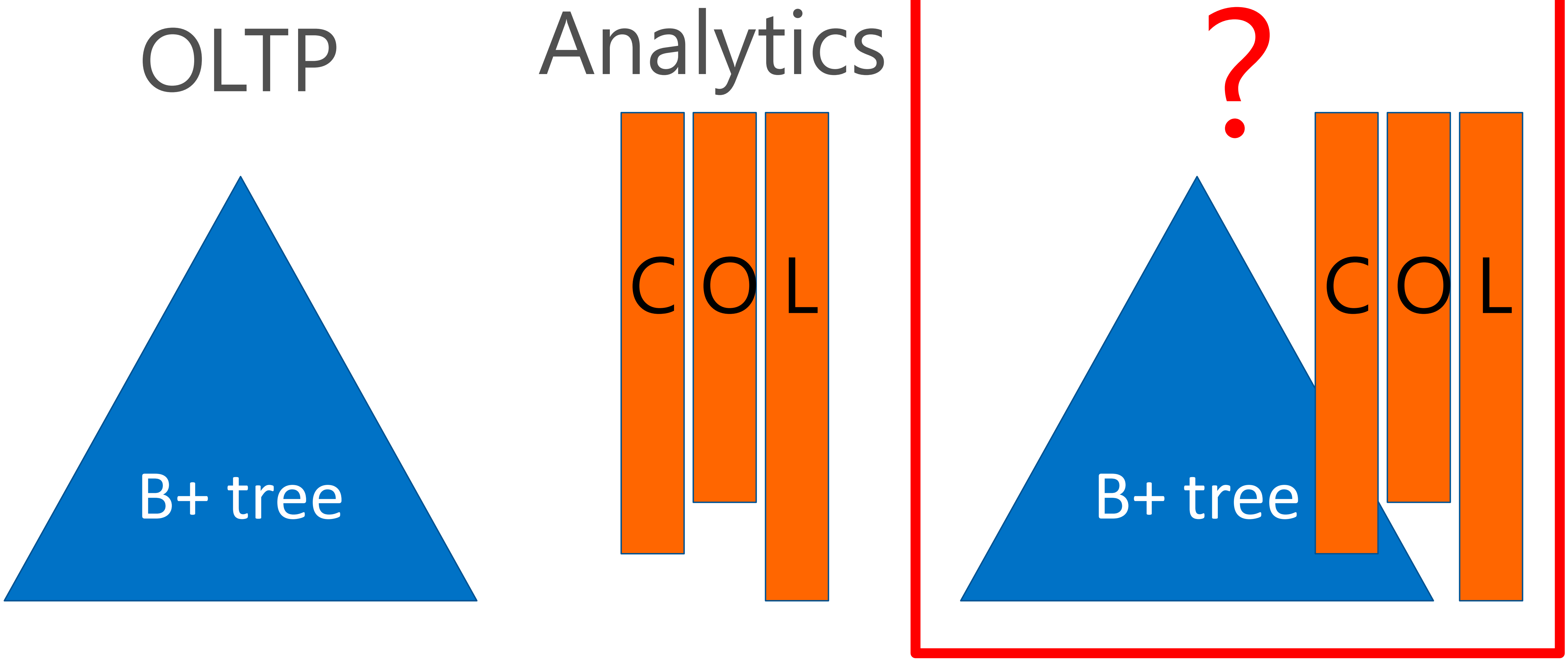


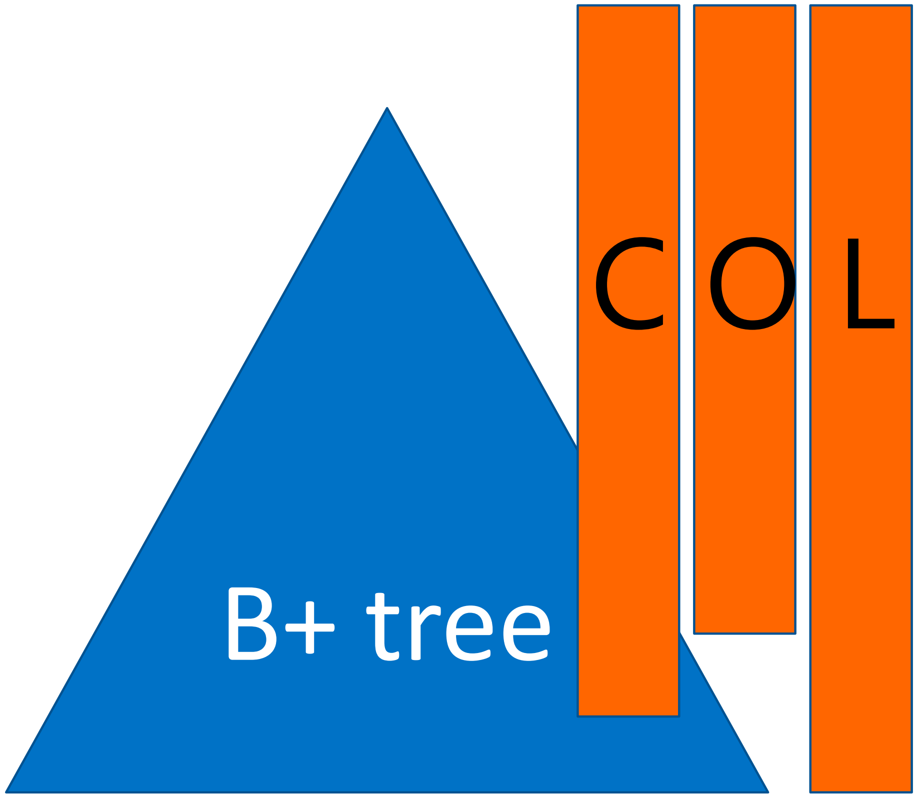
B+ tree & Columnstore on same table = Hybrid design

Physical designs for diverse workloads

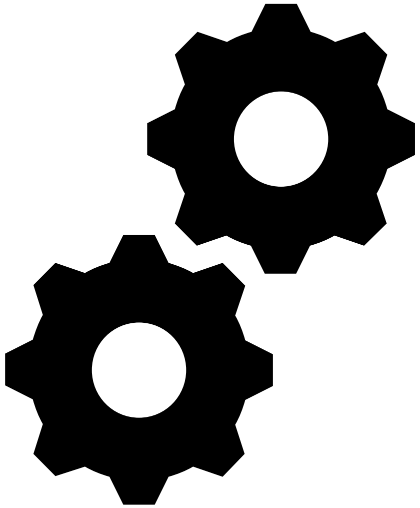


Are Hybrid Designs important and which workloads can benefit?

Hybrid design = B+ tree & Columnstore



EVALUATE



AUTO
RECOMMEND

Hybrid design = B+ tree & Columnstore

1. Micro-benchmarks

2. Auto Recommend Hybrid Designs

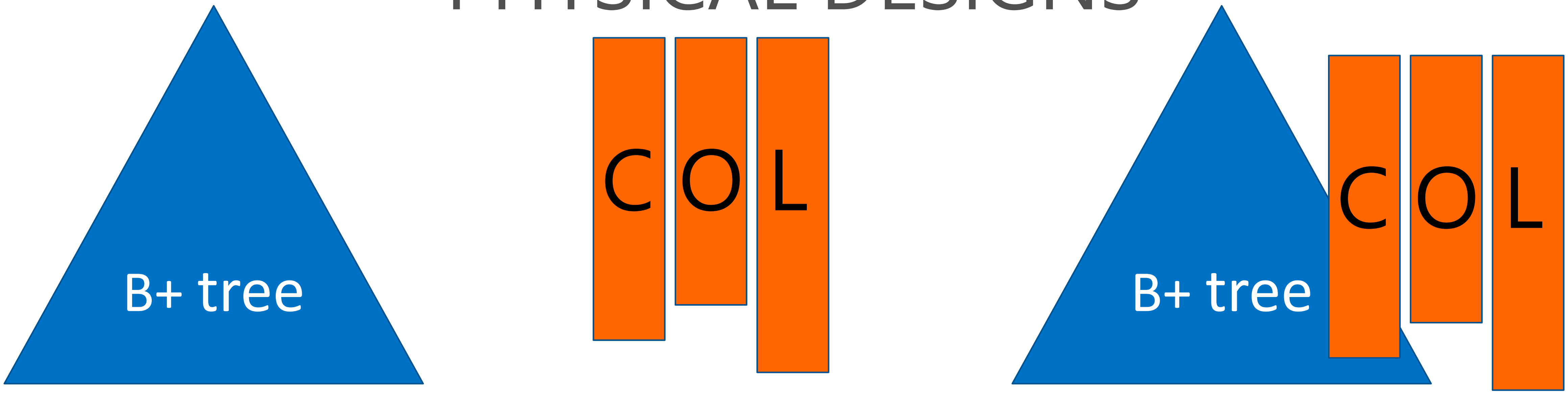
3. End-to-end evaluation

Micro-benchmarking HYBRID DESIGNS

QUERIES

- Selectivity
- Sort order
- Updates
- Mix: Scans & Updates
- Concurrency

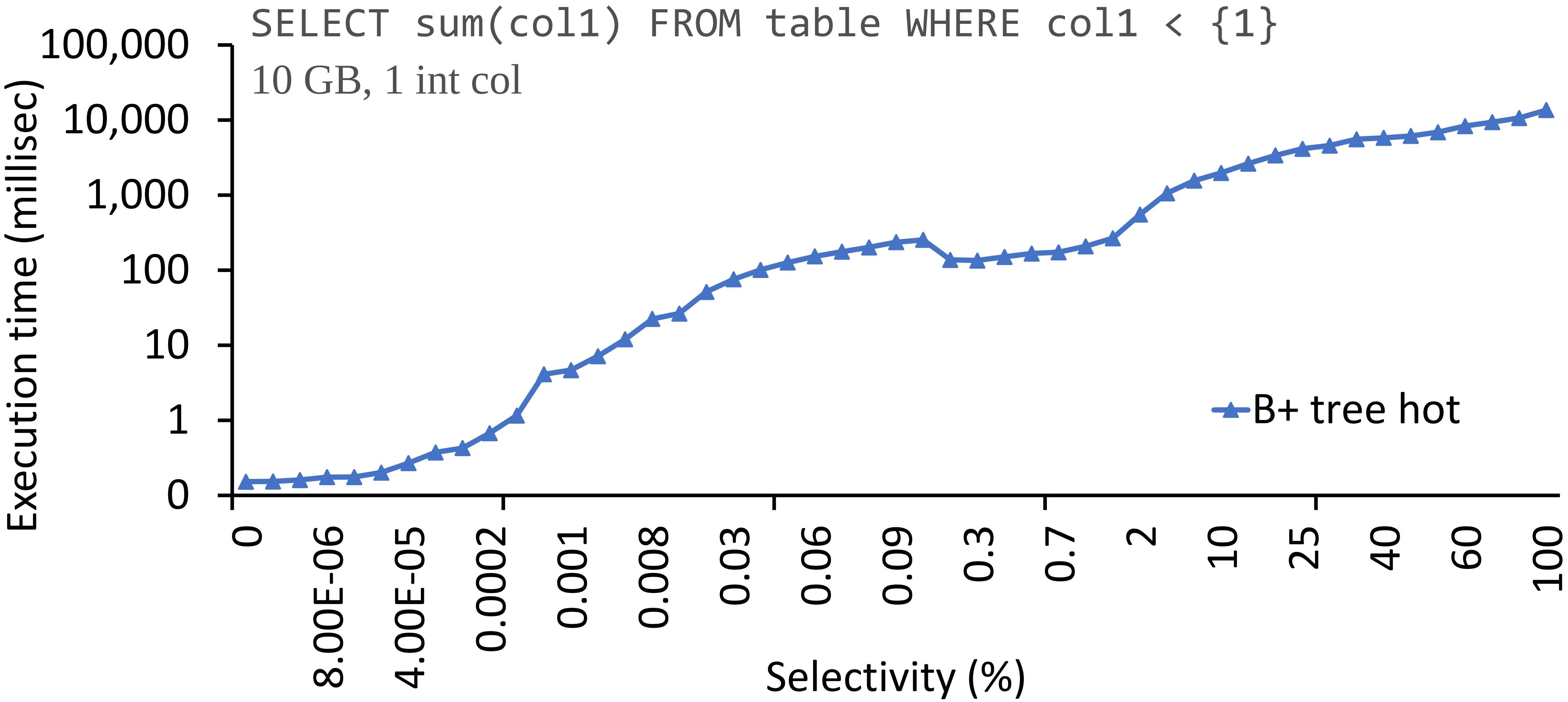
PHYSICAL DESIGNS



Experimental setup for micro-benchmarks

- Synthesized queries and data sets + TPC-H data
- Pre-release version of SQL Server 2017
- Server: on-premise
  - **Dual socket** Intel® Xeon® CPU E5−2660v2, **10 cores per socket**, 2 threads per core, clocked at 2.20 GHz, 64 KB L1 cache per core, 256 KB L2 cache per core, and 25 MB L3 cache shared
  - **384 GB main memory**
  - **18 TB HDD in RAID-0** configuration (throughput of ~1 GB/sec for reads and ~400 MB/sec for writes)

B+ tree Range Scans vs. Col Full Scans



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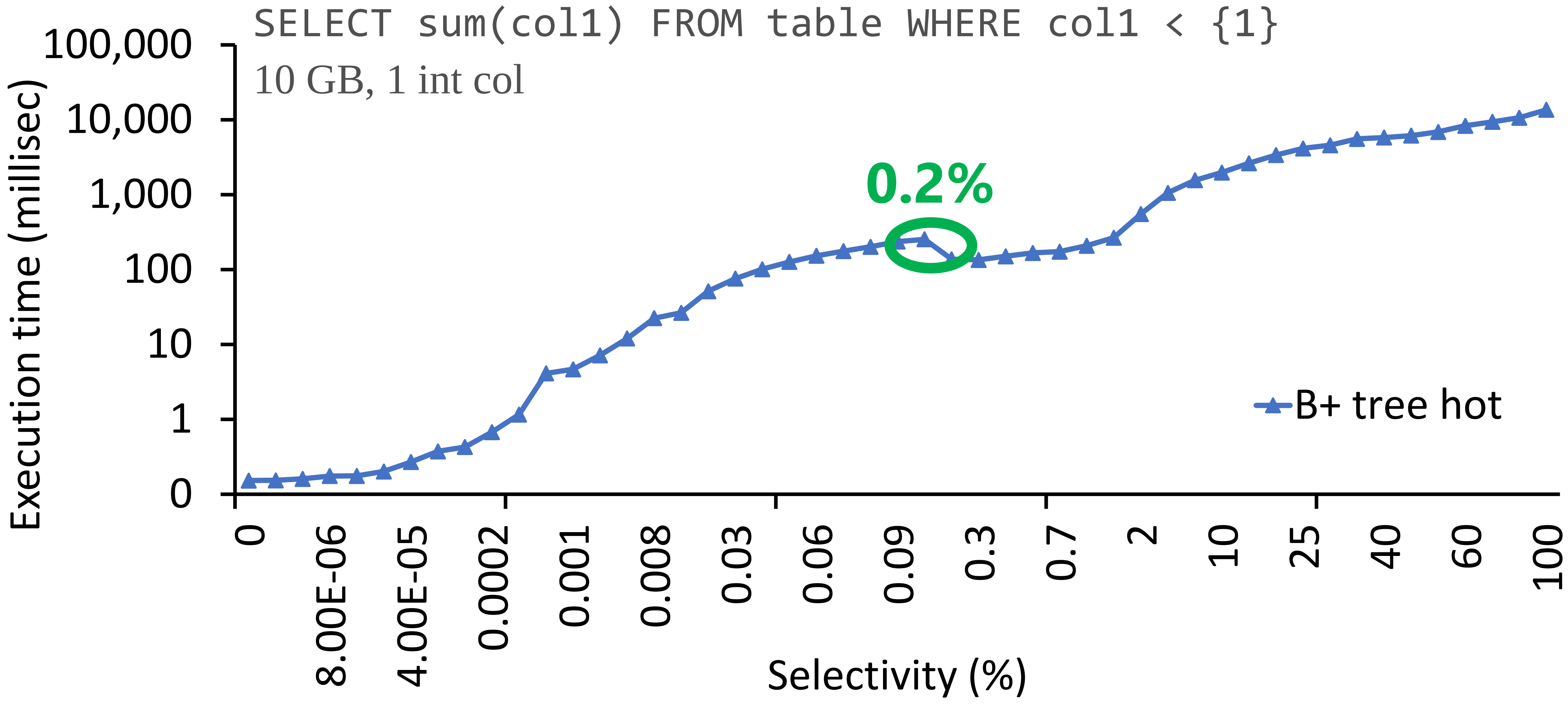
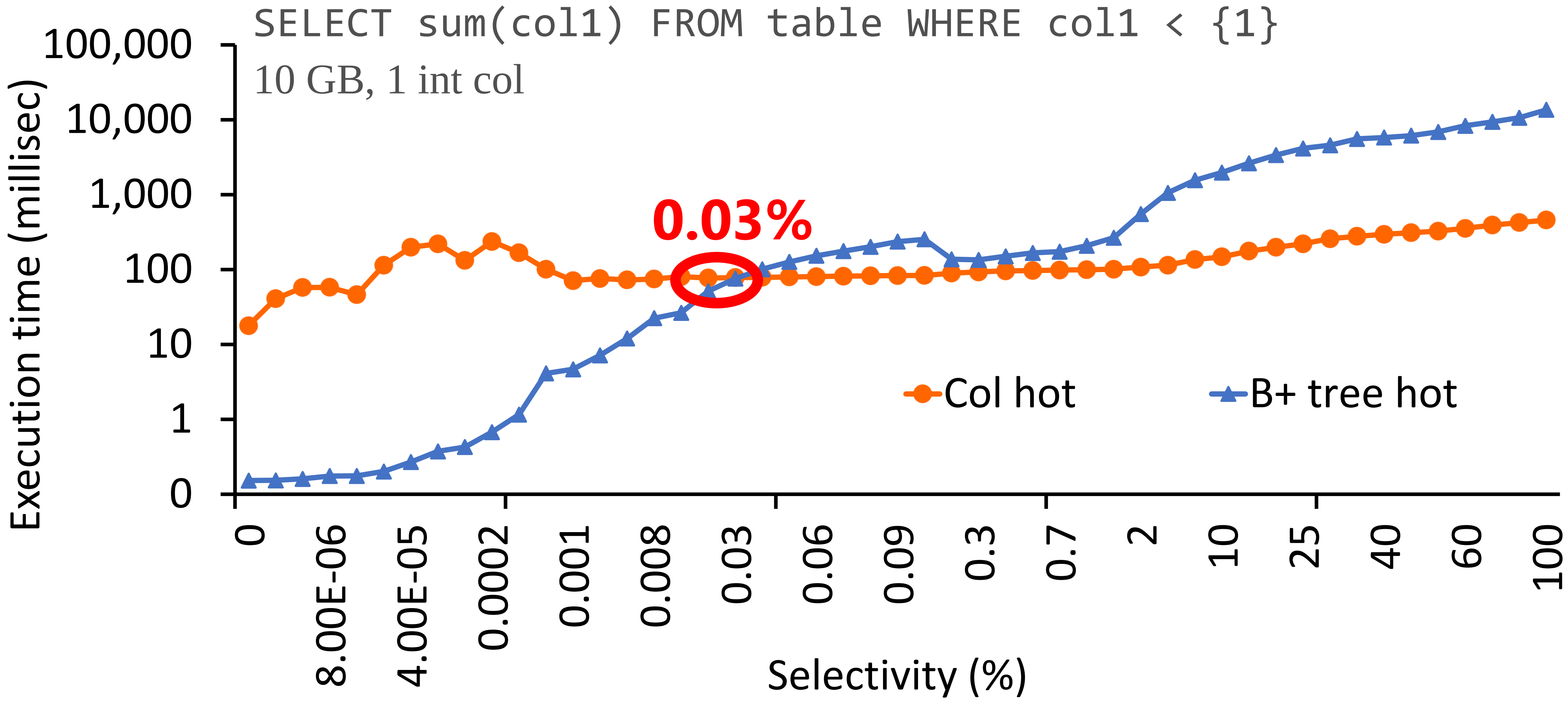


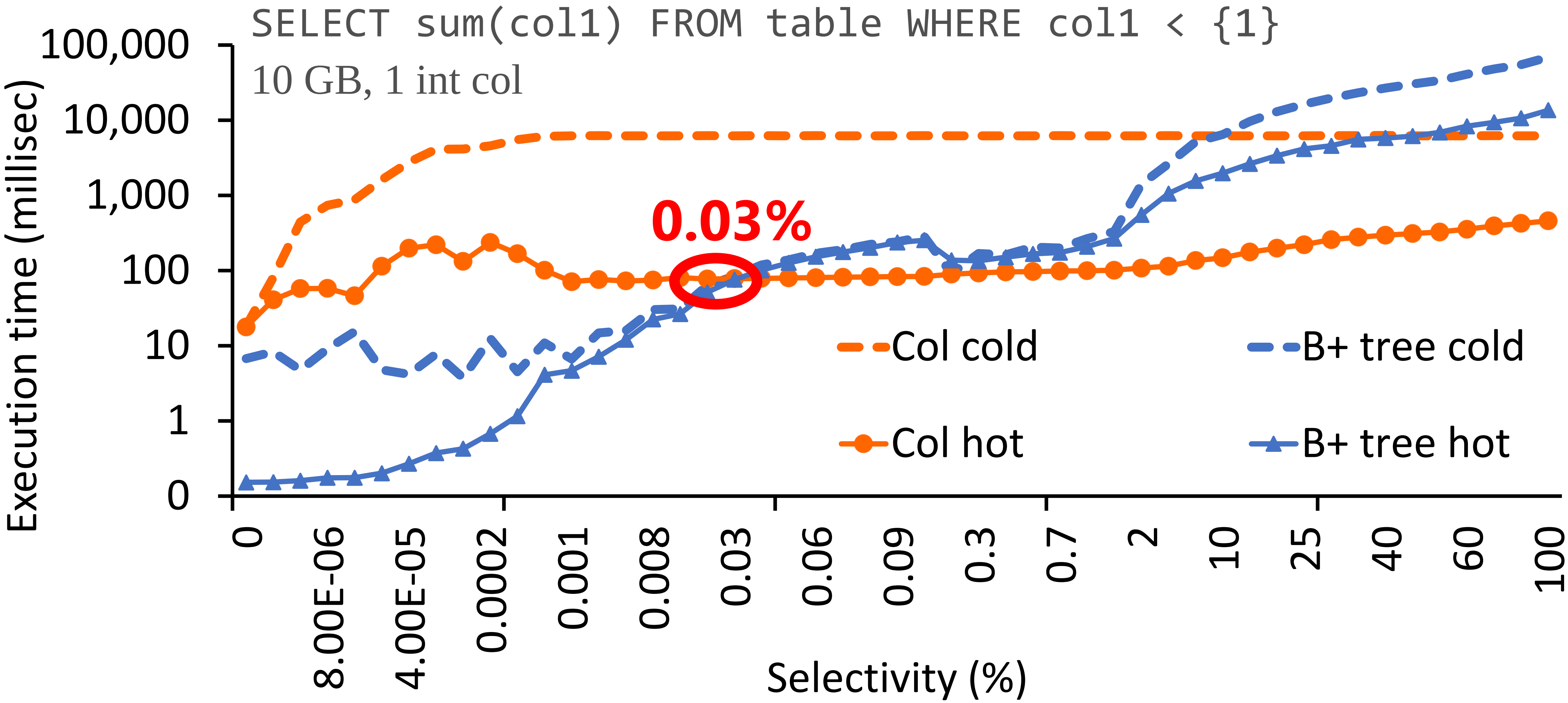
Skip data effectively & run single-threaded

B+ tree Range scans vs. Col Full scans



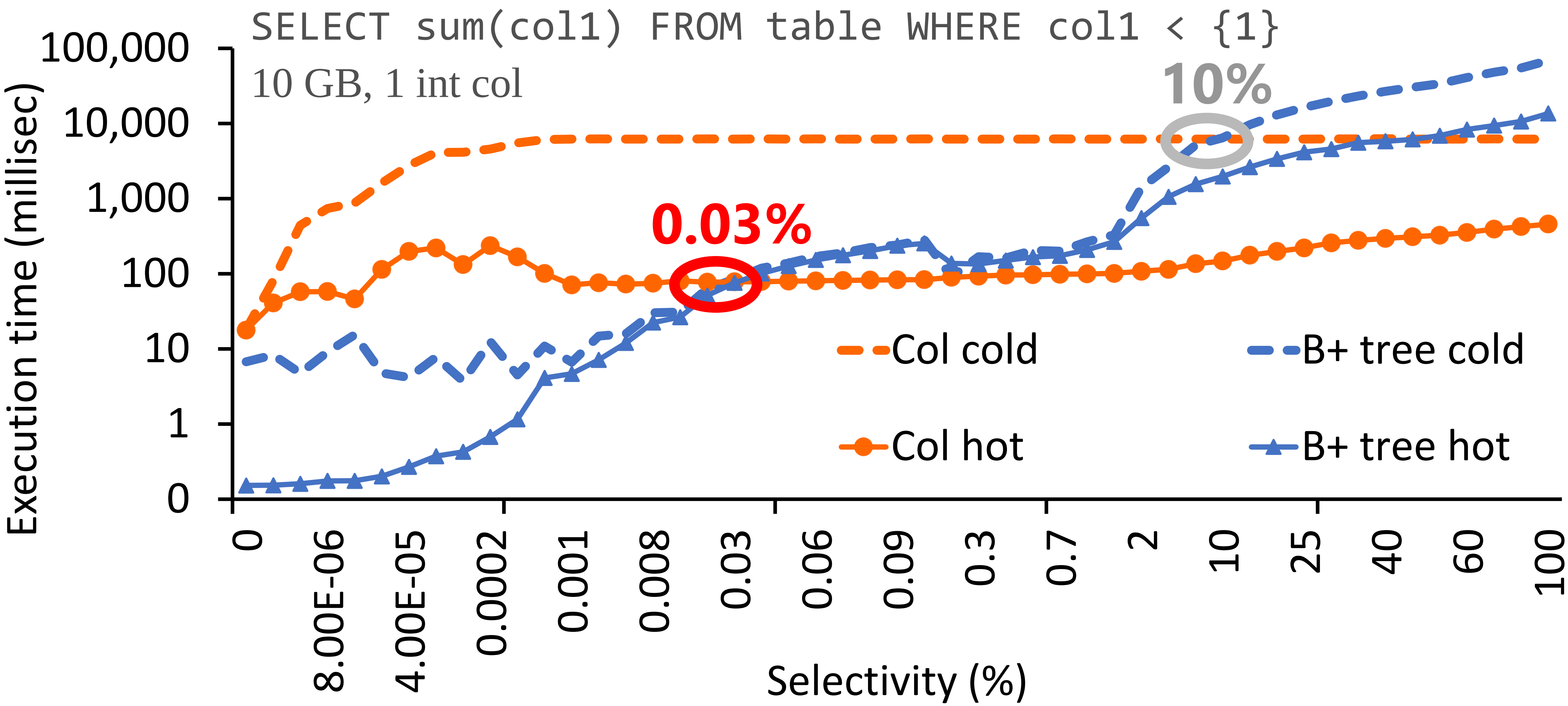
Superior performance of Columnstore scans

B+ tree Range Scans vs. Col Full Scans



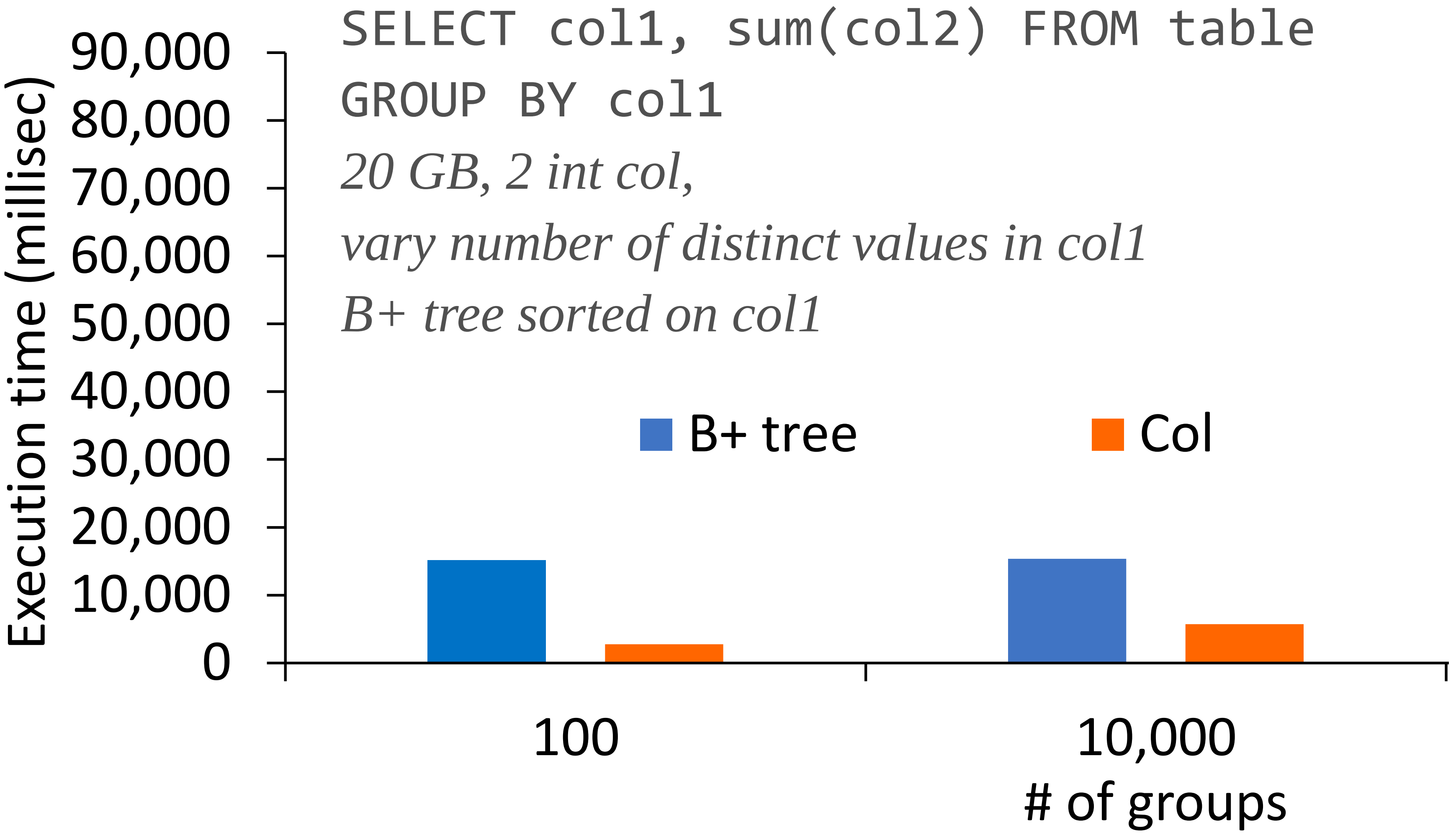
B+ tree helps for low selectivity & slower storage

B+ tree Range Scans vs. Col Full Scans

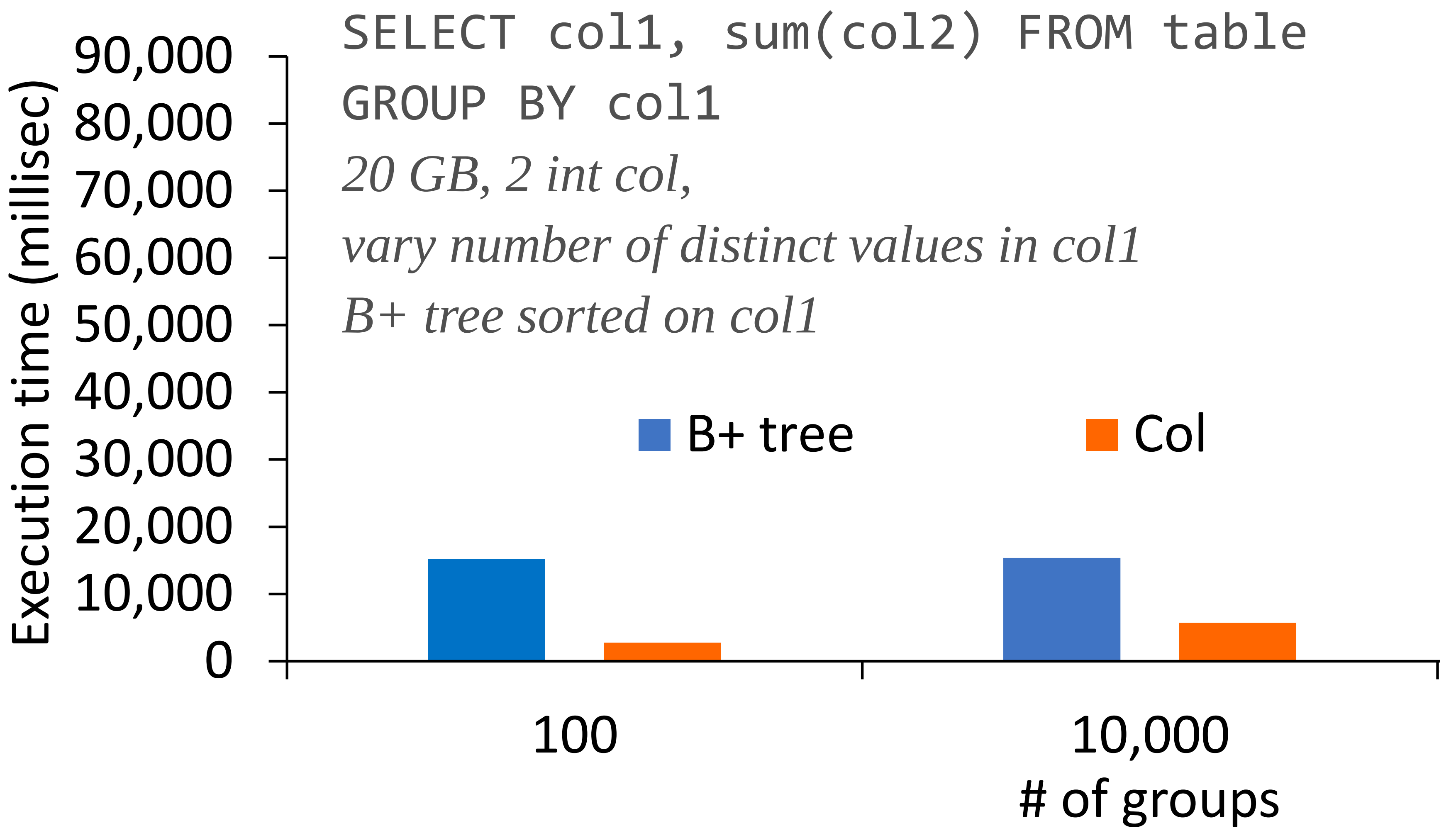


B+ tree helps for low selectivity & slower storage

Sorted B+ tree vs. Unsorted Col

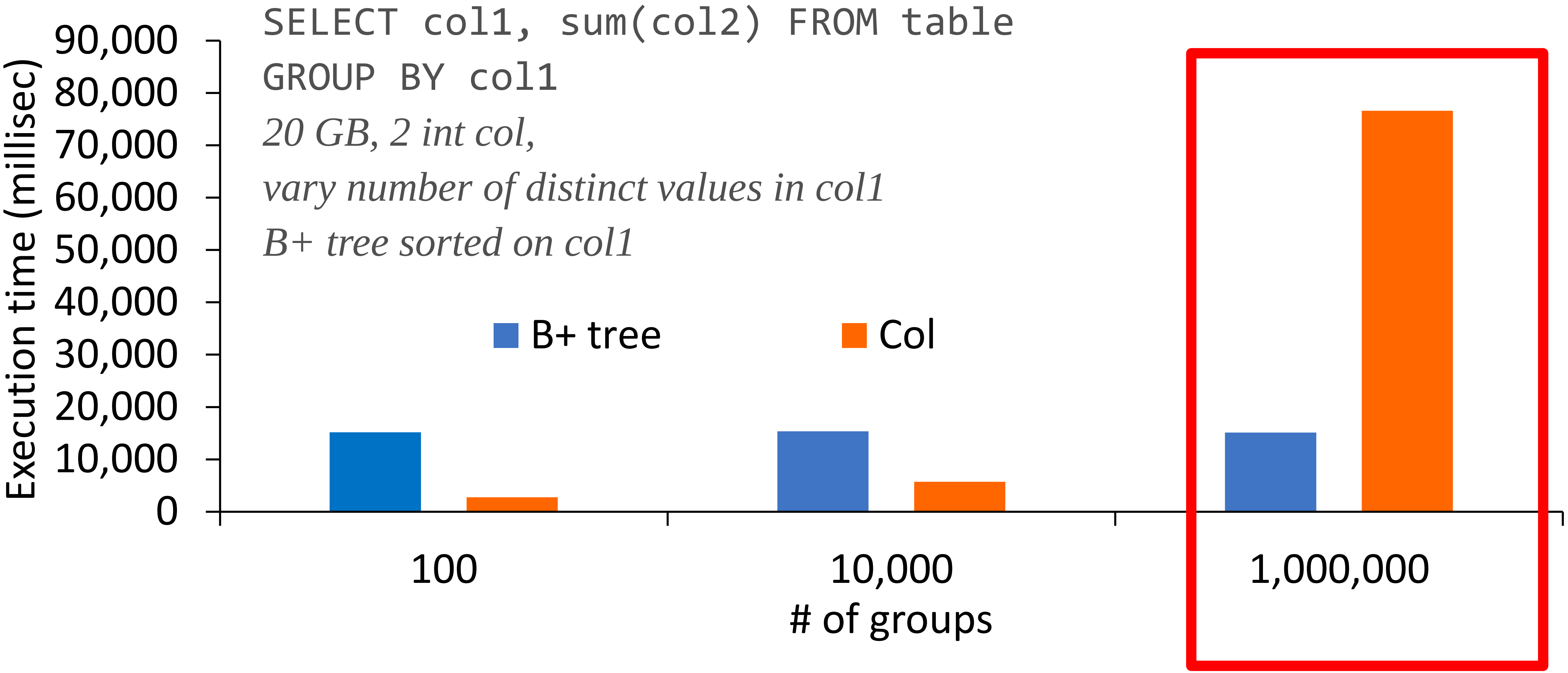


Sorted B+ tree vs. Unsorted Col



Scanning & hashing Col faster than reading sorted B+ tree

Sorted B+ tree vs. Unsorted Col

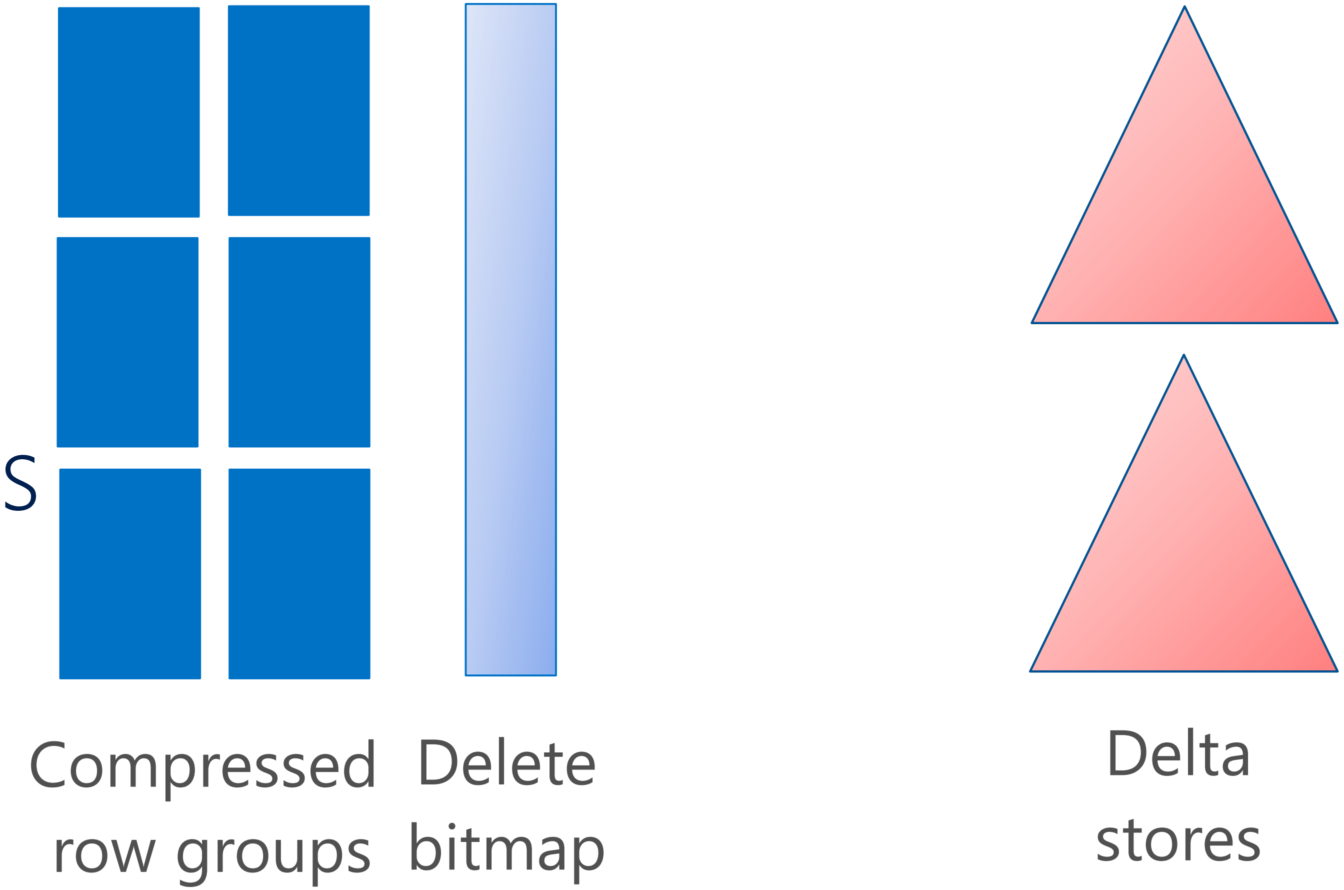


Sort order of B+ tree beneficial for scarce query memory

Two types of Columnstores in SQL Server

Primary Columnstores

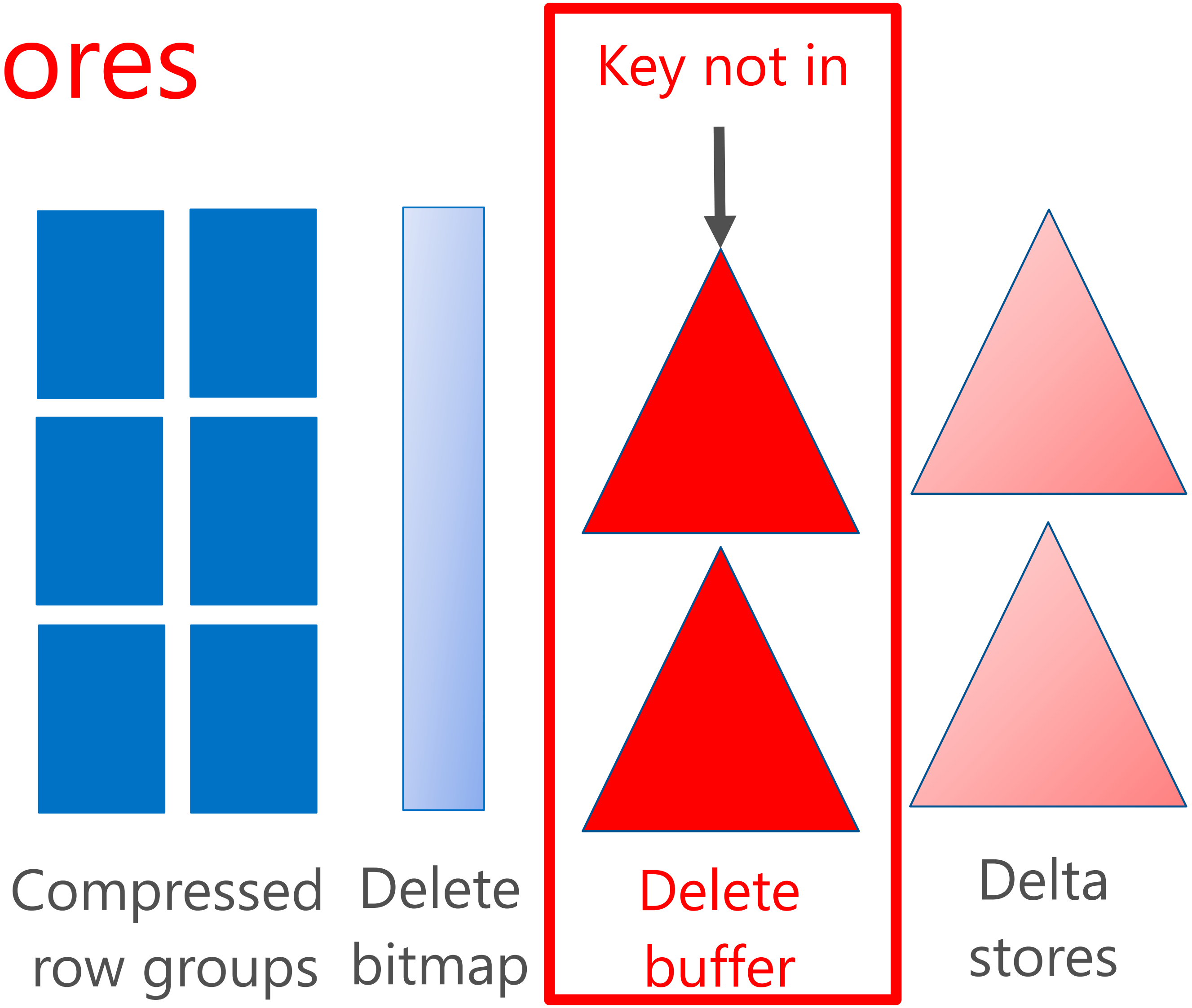
- Base table storage
- Optimize **large scans**
- **Complicated updates** on compressed columns
- **Updates** via the delete bitmap **are expensive**



Two types of Columnstores in SQL Server

Secondary Columnstores

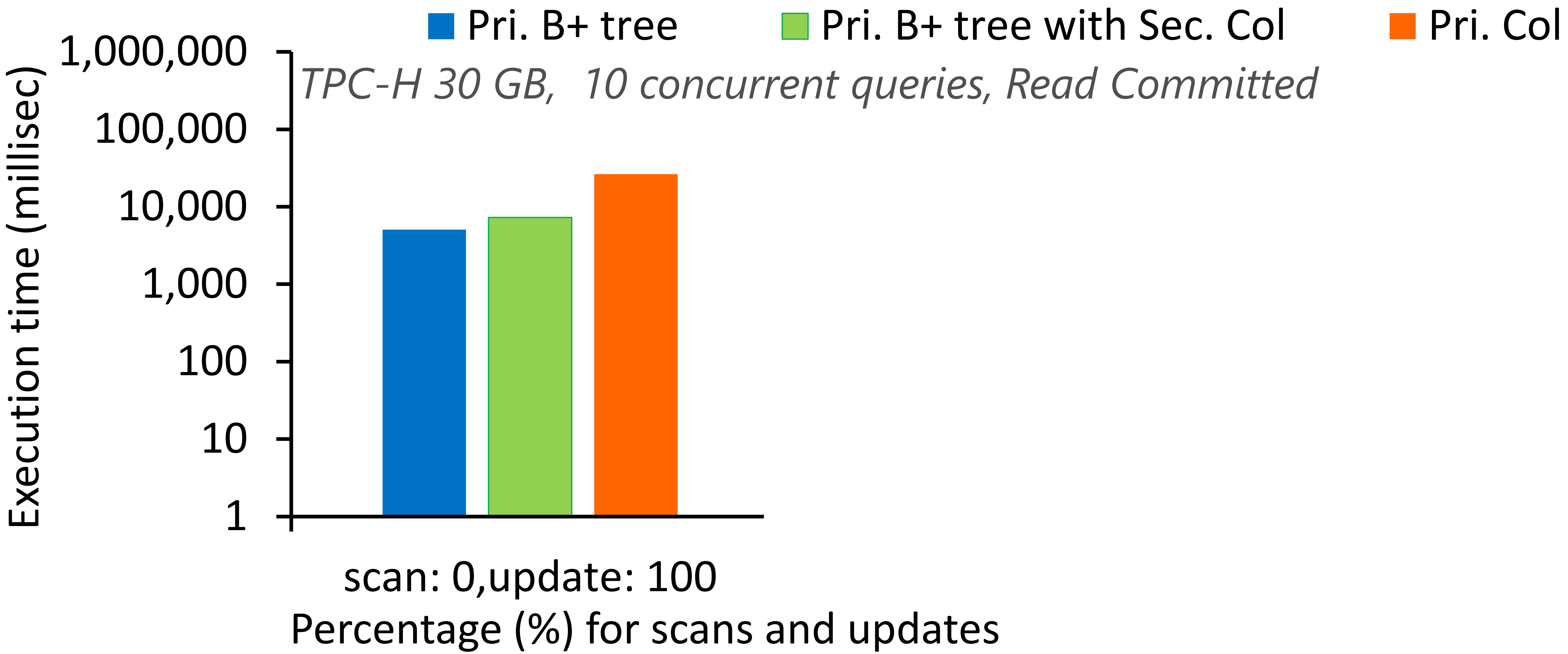
- Designed to balance performance of **long scans and updates**
- **Delete buffer** stores the logical row being deleted
- Requires anti-semi join



Mixed workload: large scans & small updates

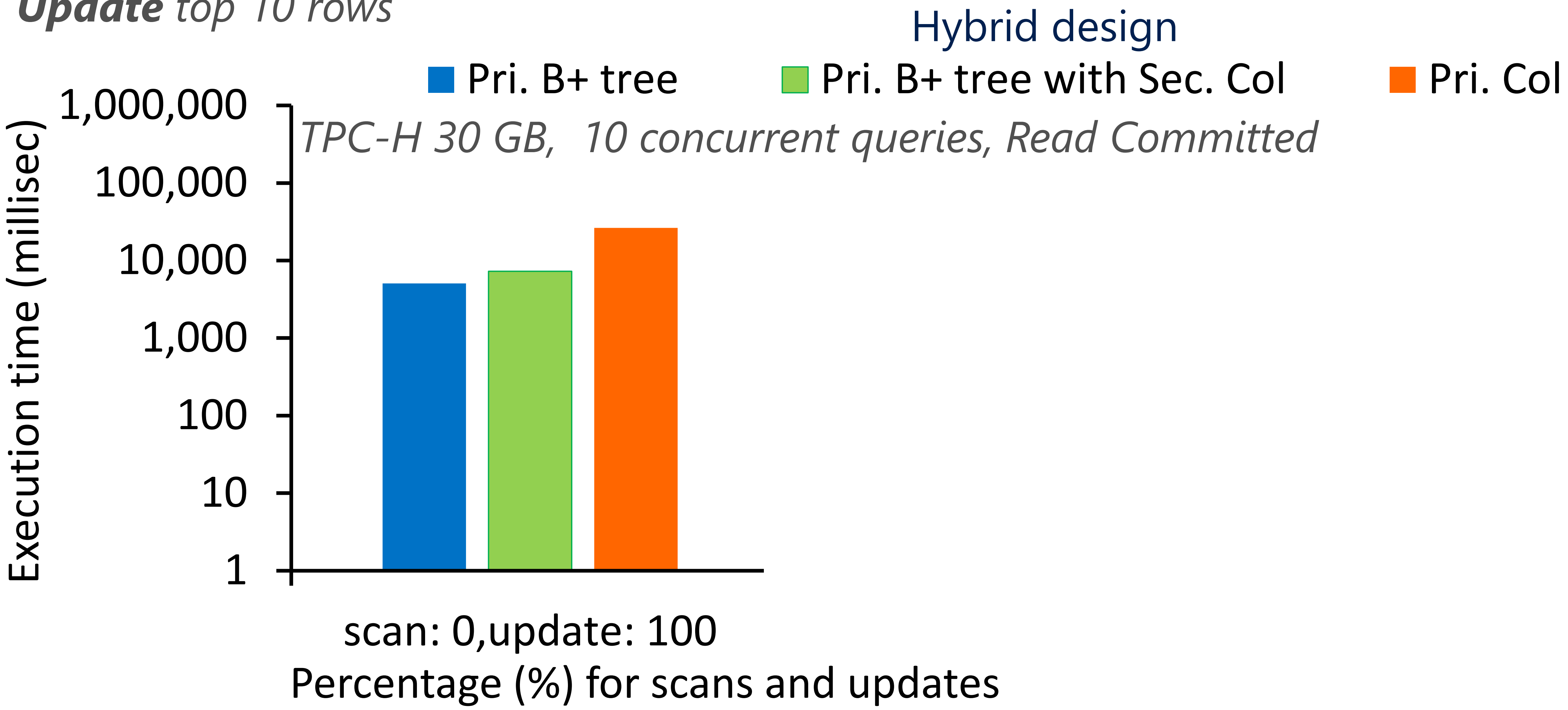
***Update** top 10 rows*

Hybrid design



Mixed workload: large scans & small updates

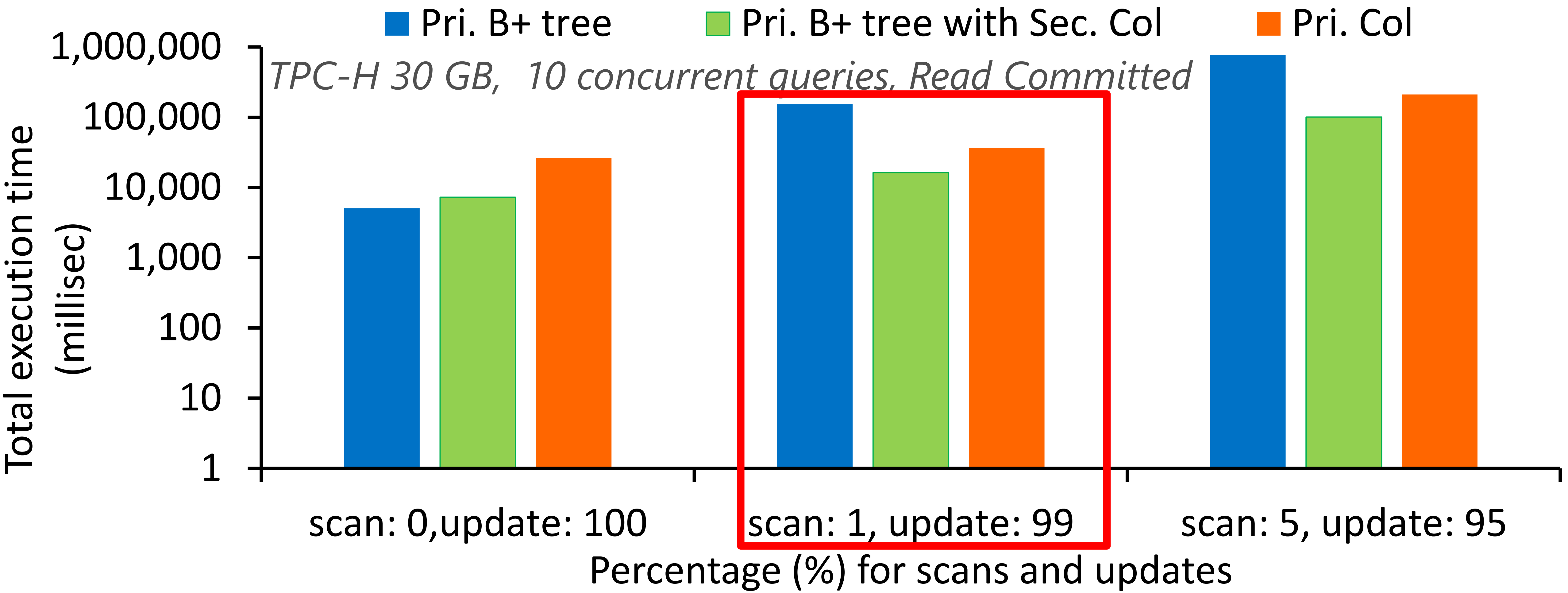
Update *top 10 rows*



B+ trees cheaper than Columnstores for pure updates

Mixed workload: large scans & small updates

Update *top 10 rows,* ***Select*** *sum of quantity & price for a single shipdate from lineitem table*

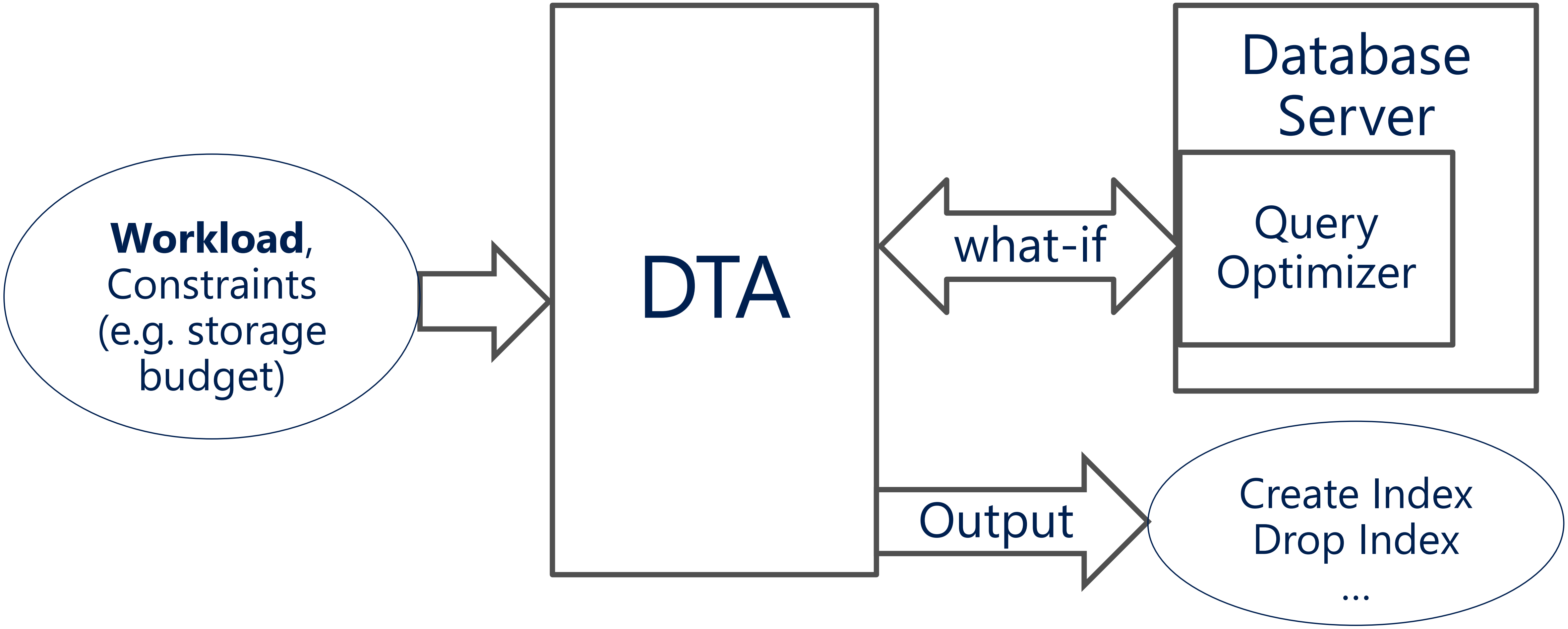


Secondary Columnstore: balance small updates & large scans

Hybrid design = B+ tree & Columnstore

1. Micro-benchmarks
2. Auto Recommend Hybrid Designs
3. End-to-end evaluation

Database Engine Tuning Advisor (DTA)



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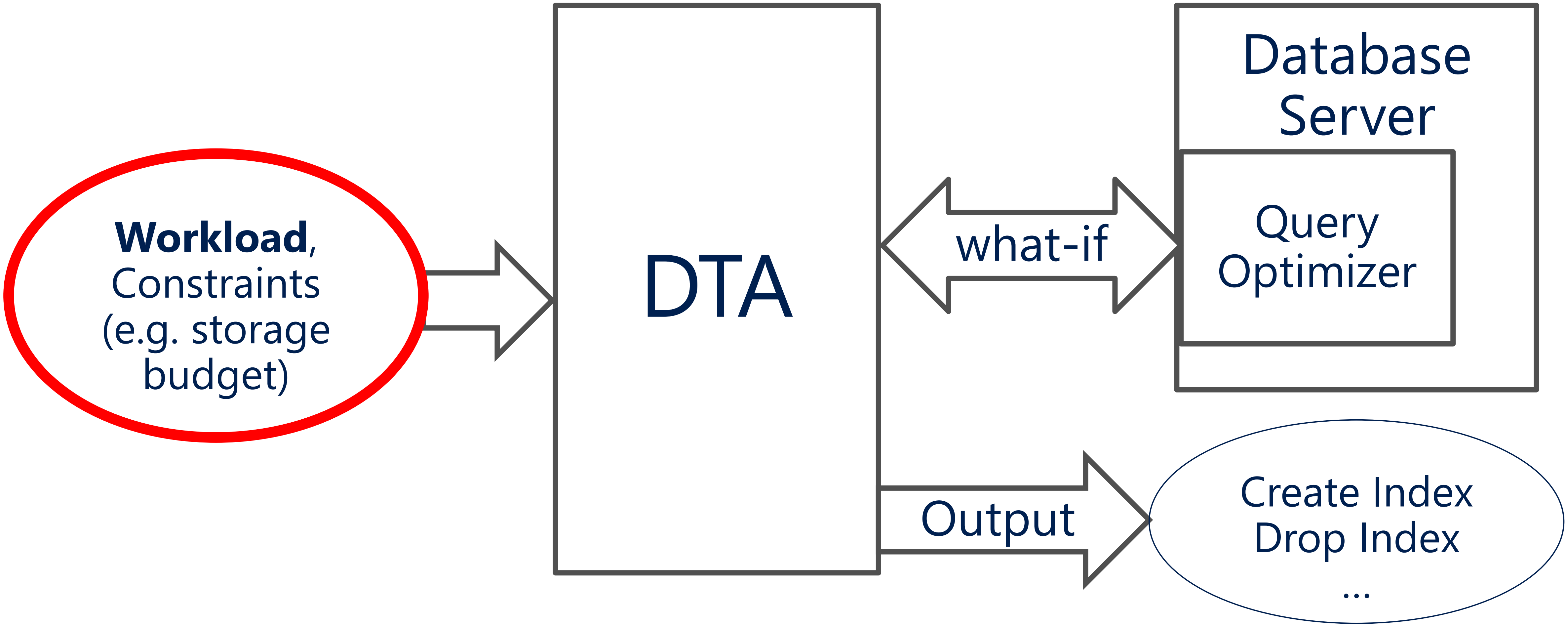

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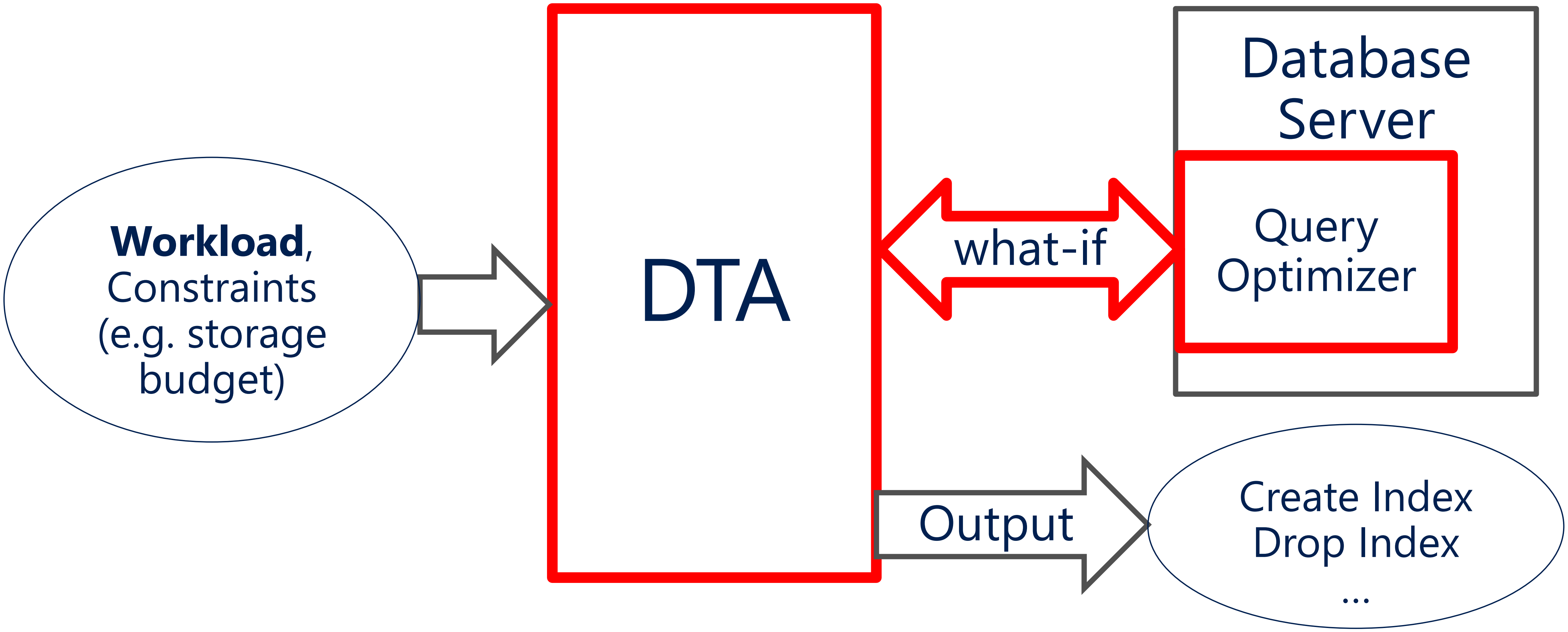

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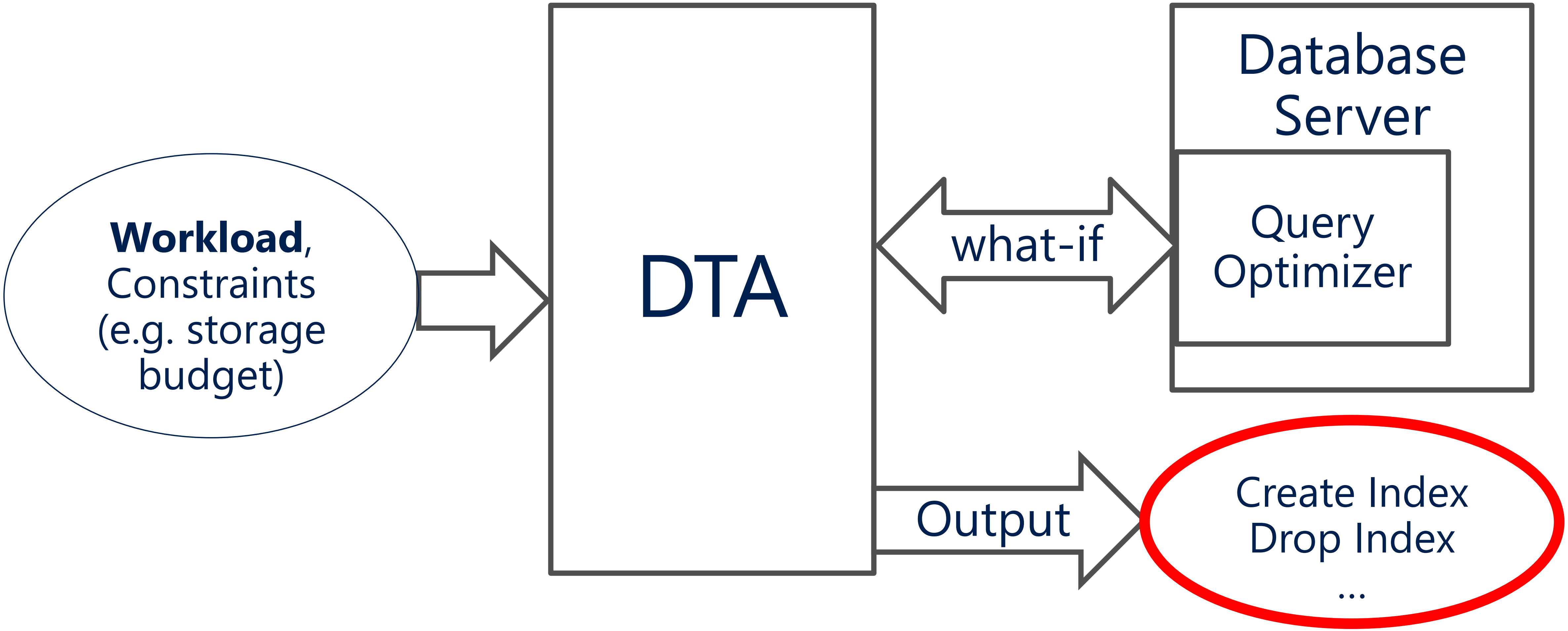

Extensions to SQL Server Query Optimizer

Augment the "what-if" API for:

1. Costing queries on Hypothetical Columnstores

Extensions to SQL Server Query Optimizer

Augment the "what-if" API for:

1. Costing queries on Hypothetical Columnstores

2. Per-column size estimation
   - stay within storage budget
   - per-column access cost
   - hard problem

DTA extensions for hybrid designs

1. Optimal designs searched over:
   combined space of
   Columnstores & B+ trees

DTA extensions for Hybrid Designs

1. Optimal designs searched over:

   combined space of

   Columnstores & B+ trees

2. Released as part of

   SQL Server 2017 CTP

Hybrid design = B+ tree & Columnstore

1. Micro-benchmarks
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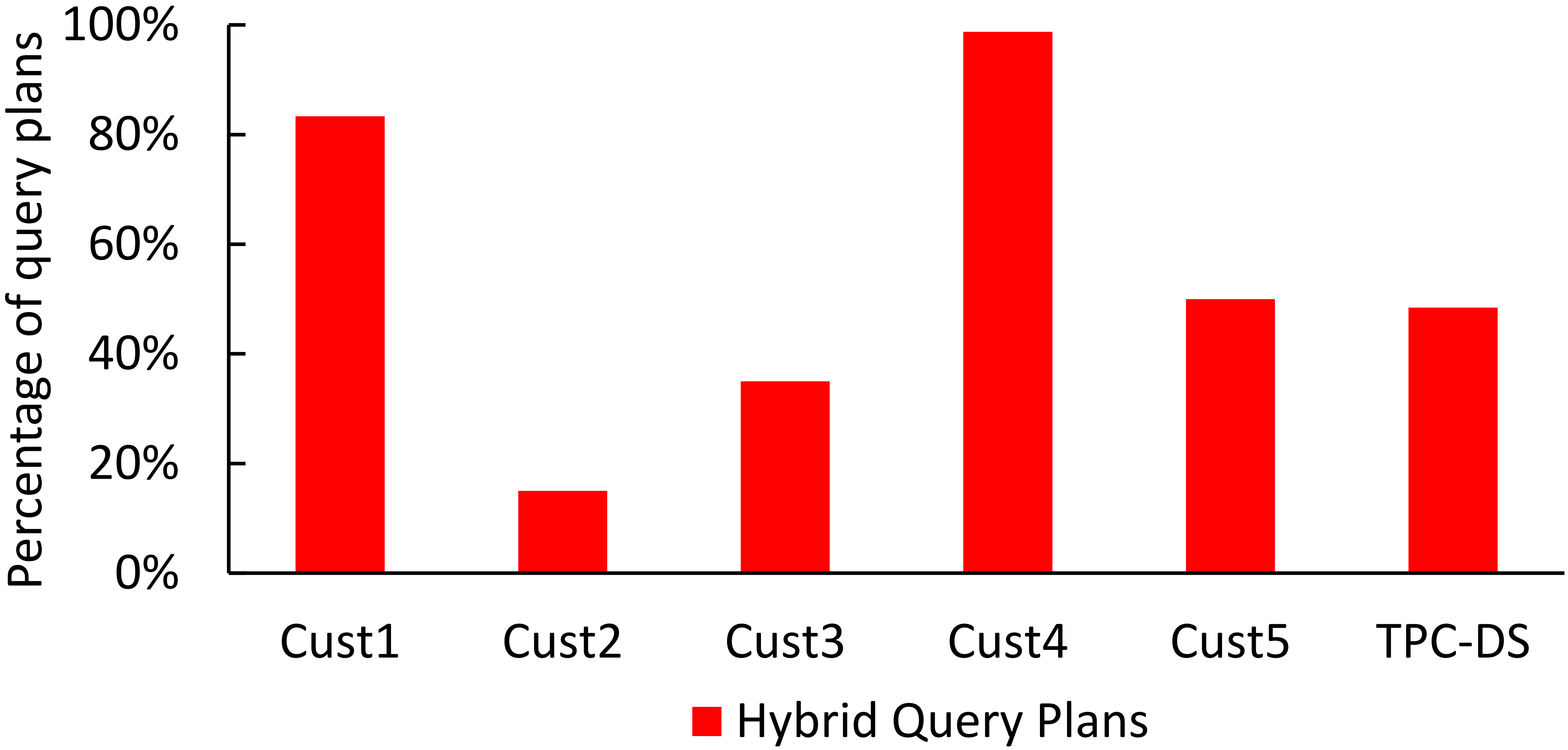
End-to-end evaluation of hybrid designs

- 5 customer workloads, TPC-DS, and CH benchmark
- Homogenous design
  - B+ tree only (for each query, tune with DTA's B+ tree index recommendations)
  - Columnstore only (secondary Columnstores on all tables for all possible columns)
- Hybrid design
  - B+ tree and Columnstore indexes recommended by **DTA** (Database Engine Tuning Advisor)
- Speedup = (time on Homogenous) / (time on Hybrid)
  - Metrics: median execution time & CPU time (per query)
  - Warm execution & working set in memory
- The same hardware & software as for micro-benchmarks

Hybrid Query Plans are common



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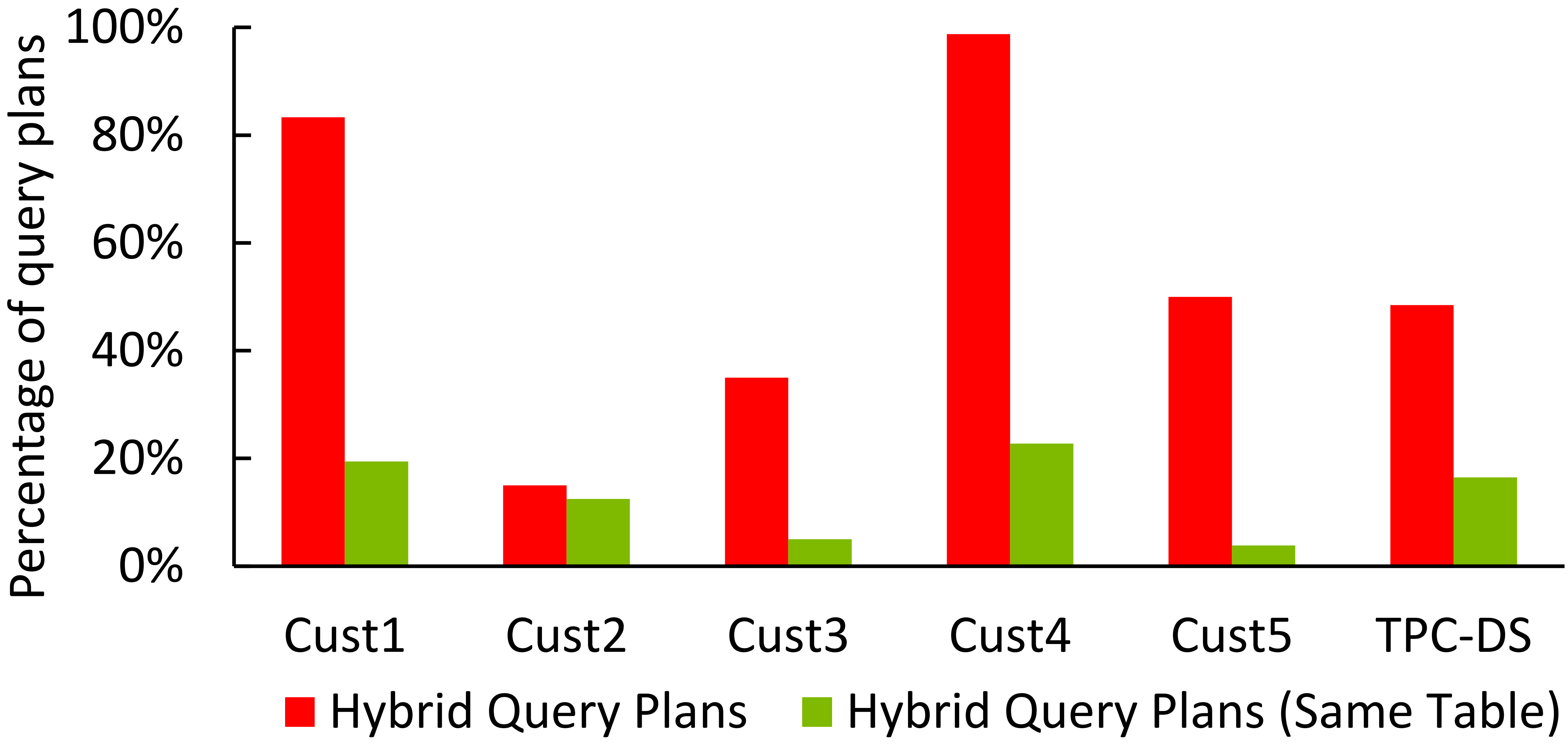
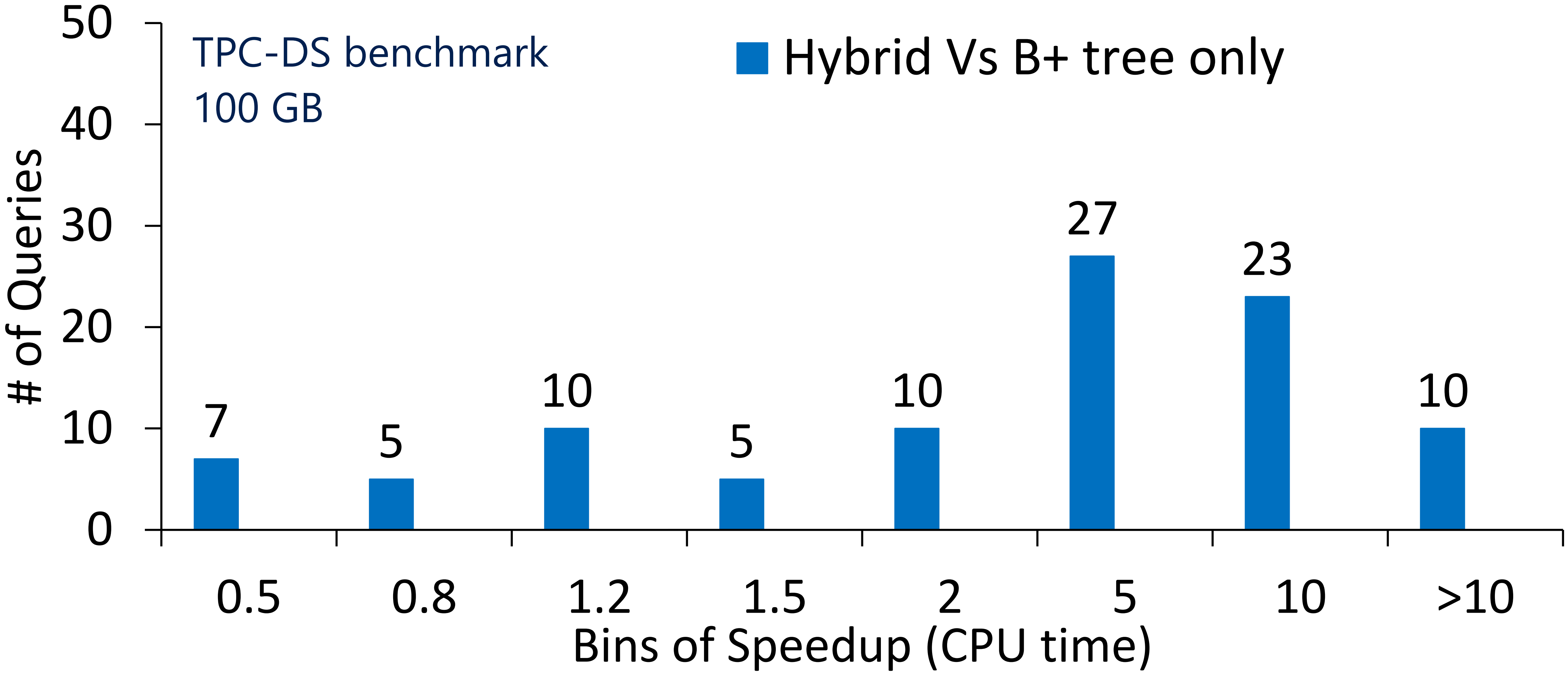


Columnstores & B+ trees selected by DTA



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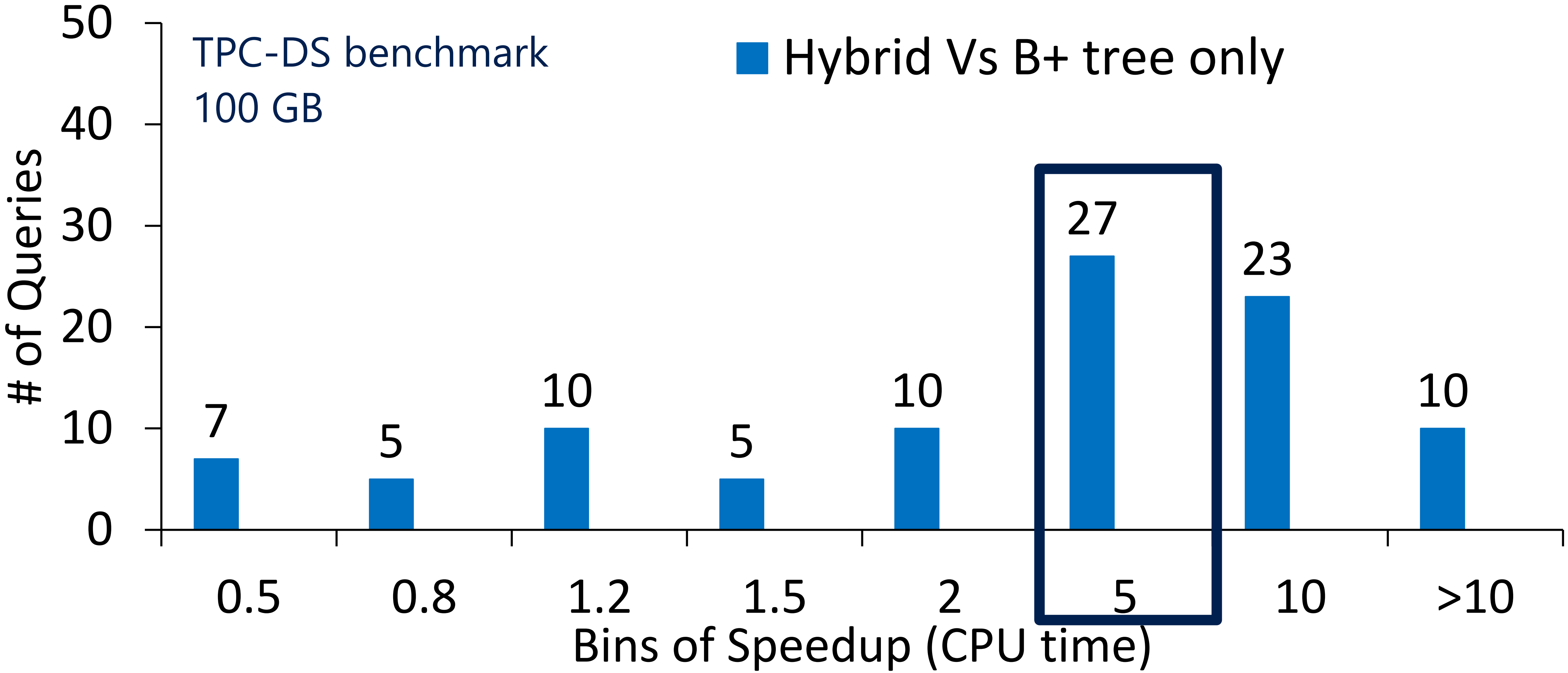

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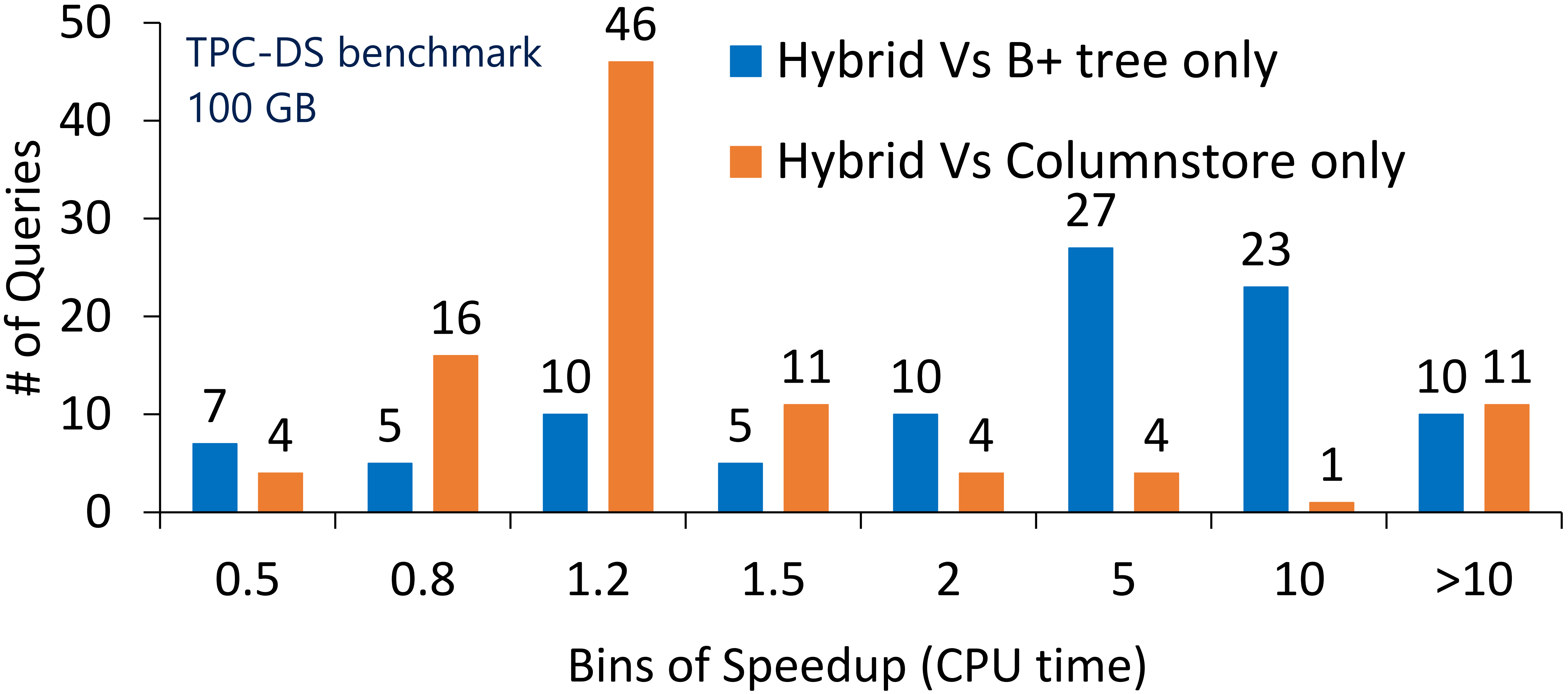

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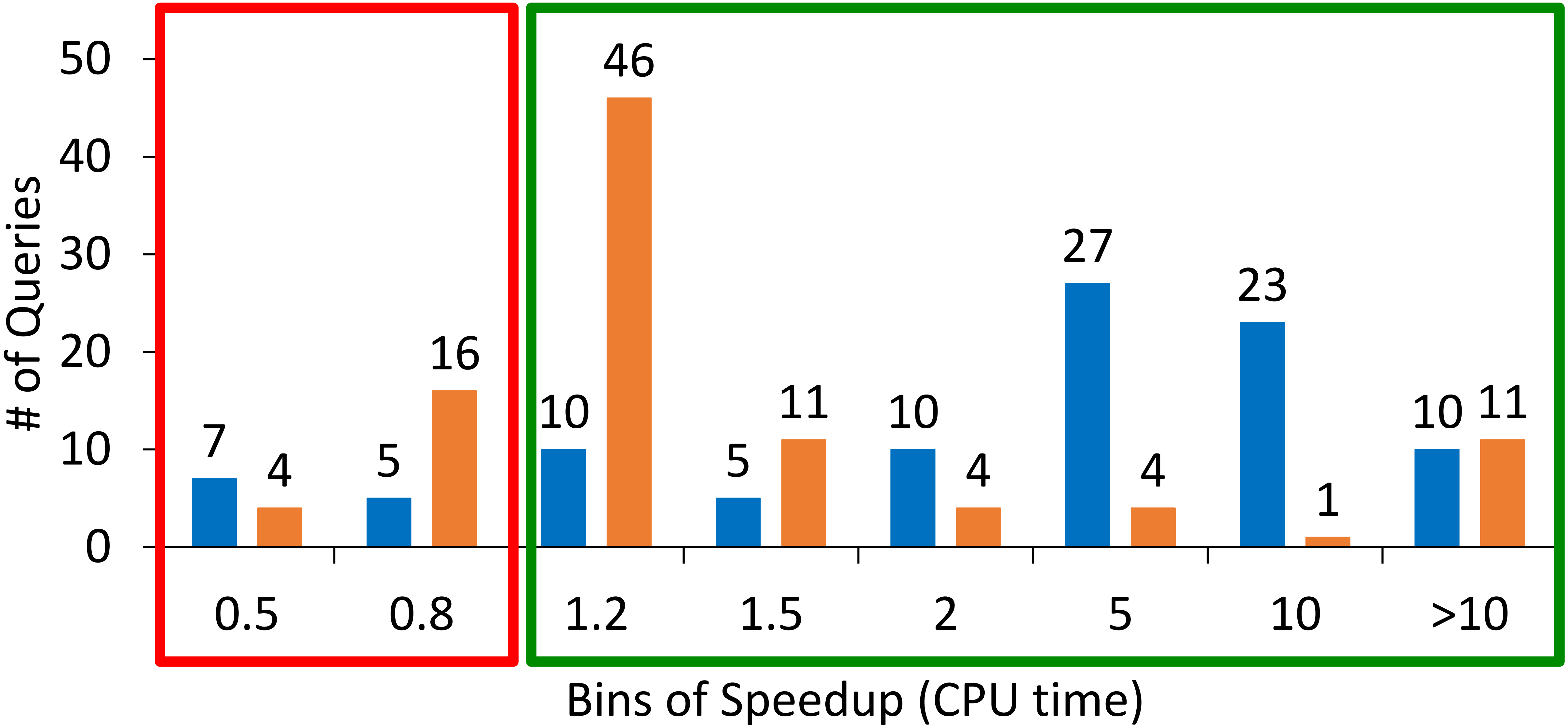
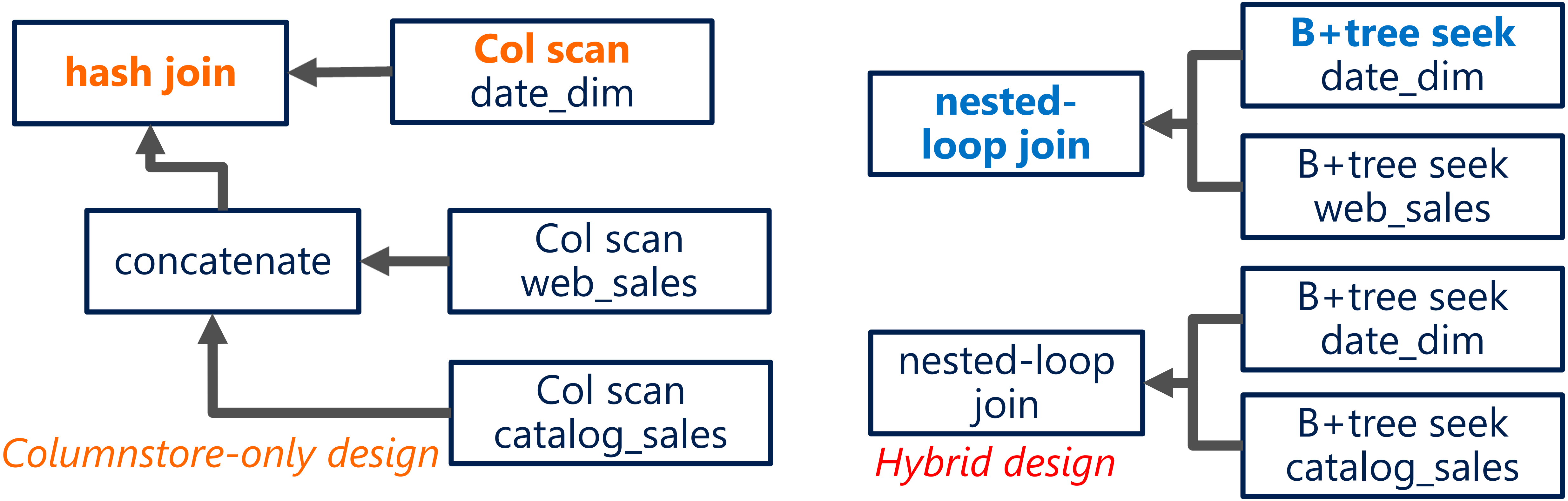


Hybrid designs significantly improve decision support workload

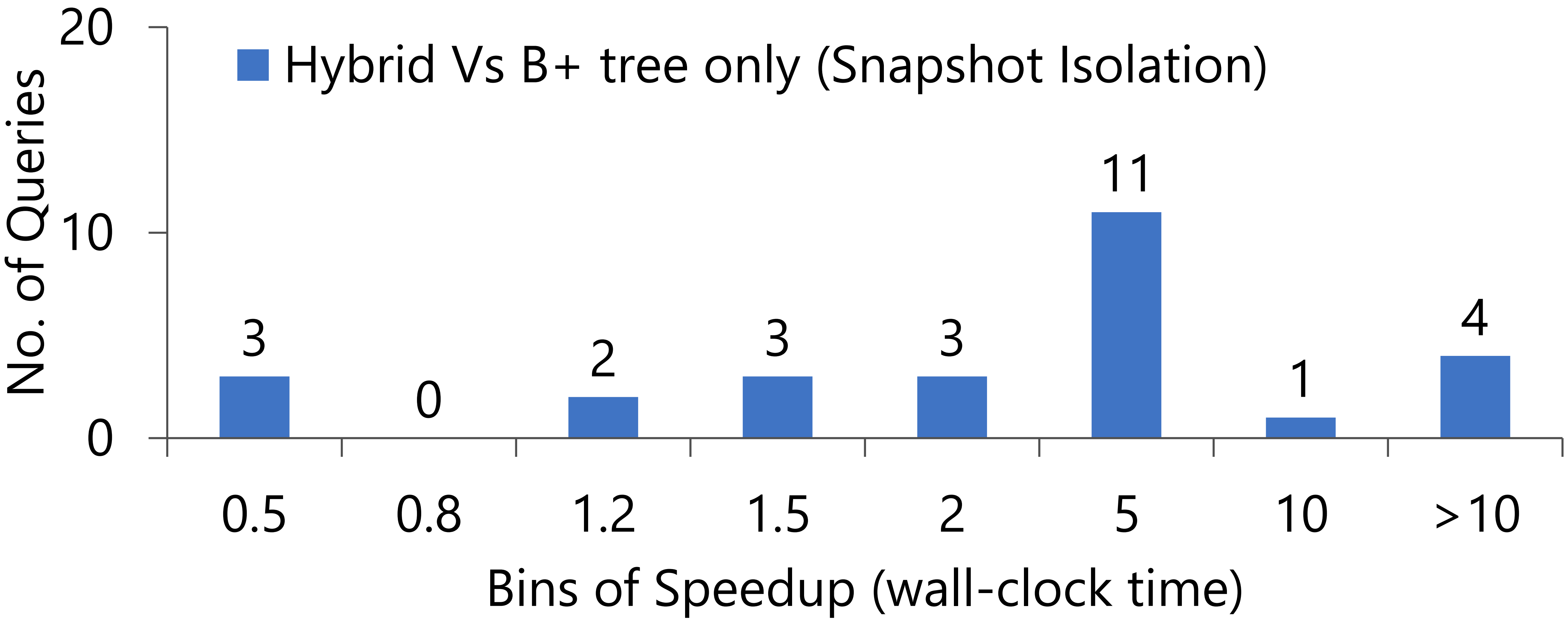
Example: Hybrid Design for TPC-DS Q54

- Q54: several selective predicates on dimension table: date_dim
- DTA: B+ tree index on date_dim as well as fact tables catalog_sales and web_sales
- **20X** reduction in execution cost of **leaf nodes** (8,000 ms to 400 ms),
- **10X** reduction in query execution cost (from 26,000 ms to 2,600 ms)



CH Benchmark: OLTP + Analytics

15 cores for analysis queries, 5 cores for transactions, workload runs 6 hours, 1K warehouses



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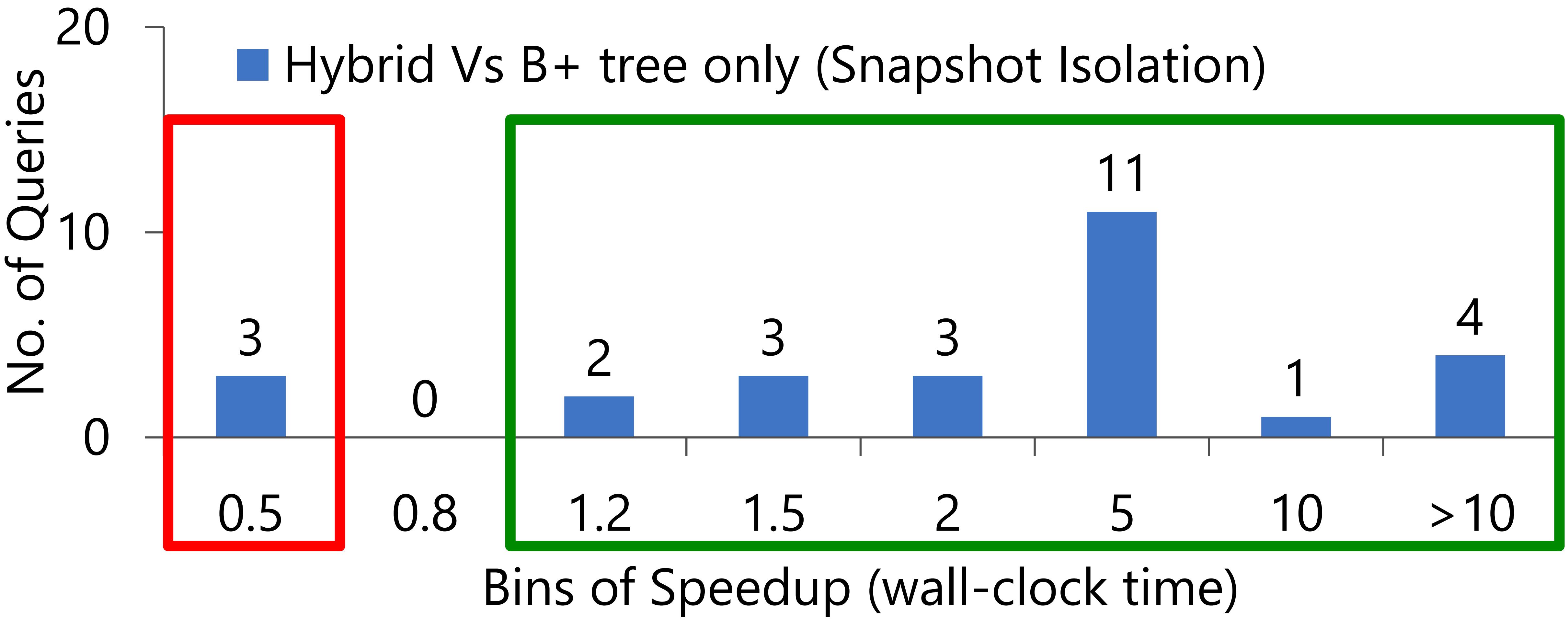

2X slowdown of transactions & 10X speed-up of analytics

Summary

Hybrid Designs: crucial for mixed workloads

- Hybrid physical designs should not be ignored!
  - Effective even for read-only queries
- Small slowdown for OLTP transactions and 10X or more speed-up of complex analytical queries
- DTA can recommend combination of Columnstores and B+ trees
- Several open challenges
  - Columnstore size estimation
  - Modeling concurrency effects

Thank you

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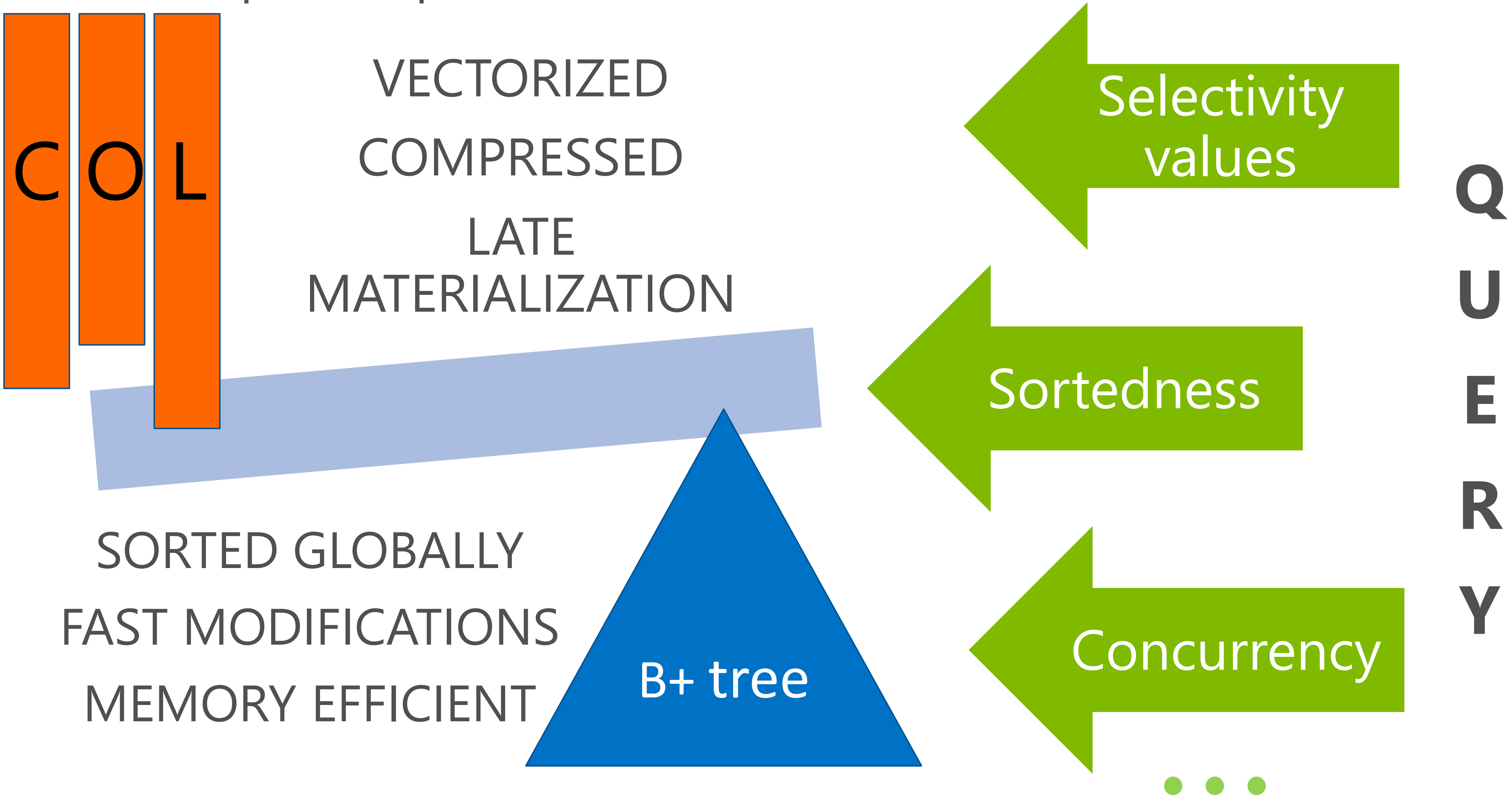
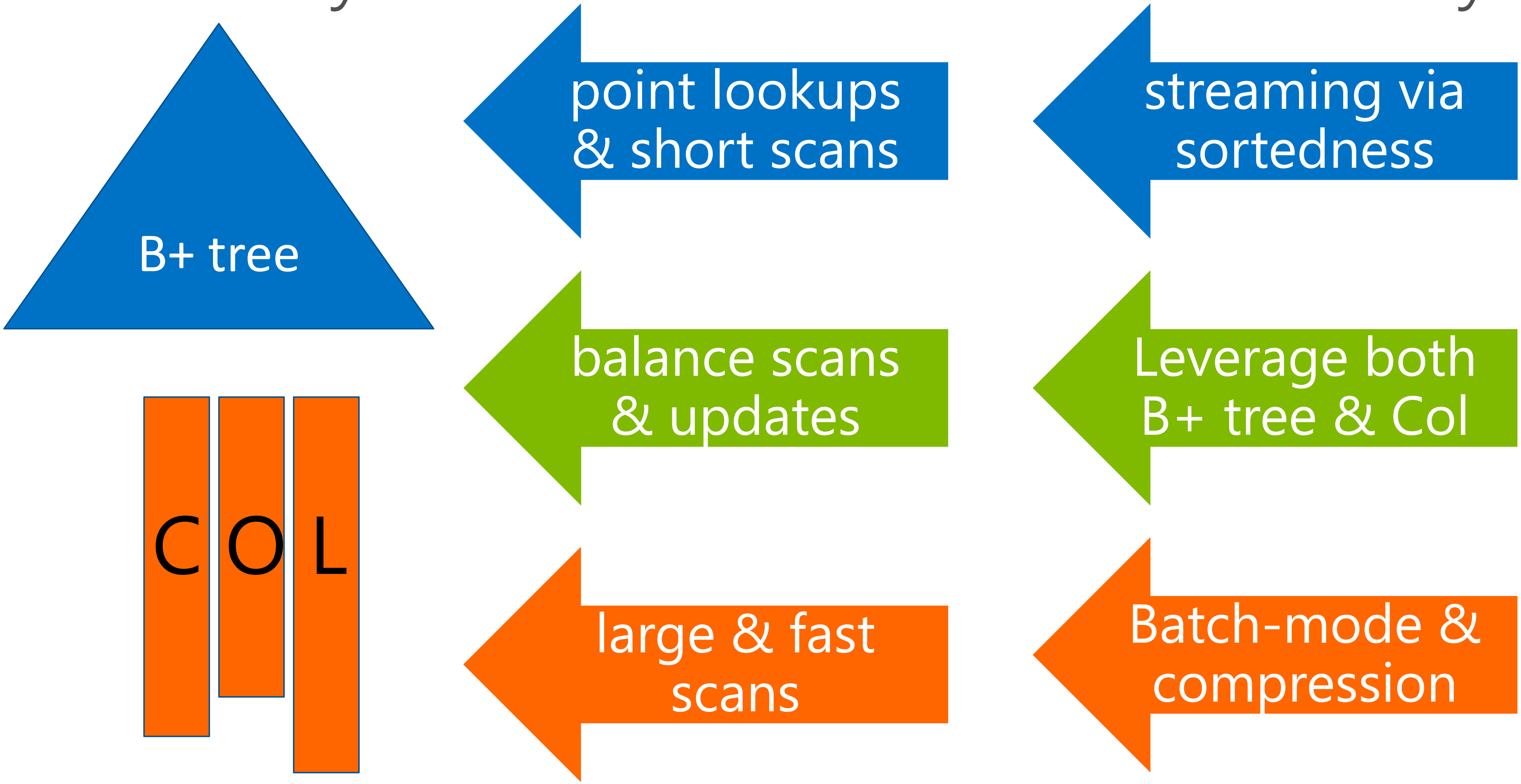
Notes

- Primary index – means that this is the main storage of the data
- Mixed workload insight: as soon as we have one big scan, the Hybrid Design provides much better performance
- Primary Columnstores not efficient for mixed workloads
- DTA – optimization tool + access to the query optimizer via the what-if API
- SQL Server Columnstore not globally ordered
- Explore when to use B+ tree or a Columnstore
- SQL supports hybrid designs (not new, already there)

Tease apart performance characteristics



Takeaways from micro-benchmark analysis



Key takeaways from end-to-end evaluation

- Hybrid designs can result in 10X to 100X improvement in execution costs compared to B+ tree or Columnstore only designs
- DTA – automated recommendation of hybrid physical designs is cost-based and workload-dependent
- Open challenges for hybrid designs in query optimization, concurrency, and locking

Compression with RLE & GEE estimator

Initial sample

A	B
30	0.0
30	0.1
0	0.0
10	0.0
30	0.1
30	0.1

Encoded

A	B
3	0
3	1
0	0
1	0
3	1
3	1

Sorted by B,A

A	B
0	0
1	0
3	0
3	1
3	1
3	1

Compressed

A
0, 1
1, 1
3, 4

B
0, 3
1, 3

GEE estimator groups that occur once in the sample are scaled by *total_size / sample_size* (e.g. [0,1] and [1,1]), other groups are counted once in total

Columnstore size estimation

- Not scalable to scan and apply encodings on the whole dataset
- Estimate per column/segment sizes using sampling
- For each column segment: 1) encode values
2) determine optimal row ordering 3) compress.
- Variety of encodings, row ordering optimization and compression techniques make size estimation hard

Customer workloads and benchmarks

Work-load	DB Size (GB)	# of tables	Max table size (GB)	Avg. # of cols per table	# of queries	Avg. # of joins	Avg. # of ops per plan
Cust1	**172**	23	63.8	14.1	36	7.2	29.1
Cust2	44.6	614	44.6	23.5	40	8.1	28.3
Cust3	138.4	**3394**	79.8	**26.3**	40	8.7	24.1
Cust4	93	22	54.8	20.3	24	6.9	24.4
Cust5	9.83	474	1.52	5.5	47	**23.1**	**57.7**
TPC-DS	87.7	24	34.9	17.2	**97**	7.9	28.2
TPC-CH		11			27		

Motivation

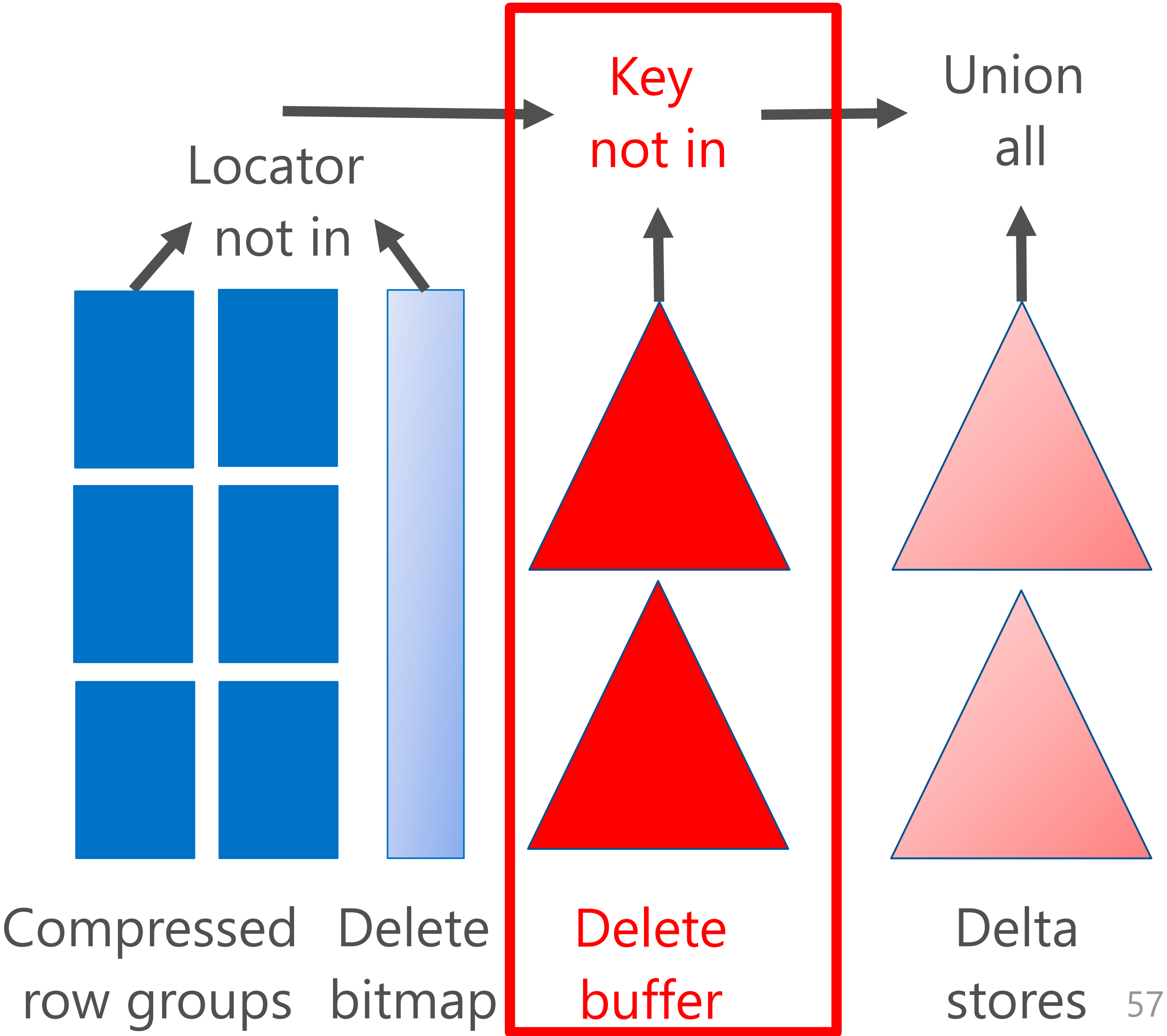
- *Wide variety of workloads* with different usage characteristics: OTLP, OLAP, Mixed workloads (e.g. real-time analytics)
- Mixed workloads imply need for Hybrid Physical Designs to achieve good performance
- SQL Server supports a wide variety of Physical Design options
- What are the ramifications of Hybrid Designs for auto-indexing in SQL Server?

Major Questions

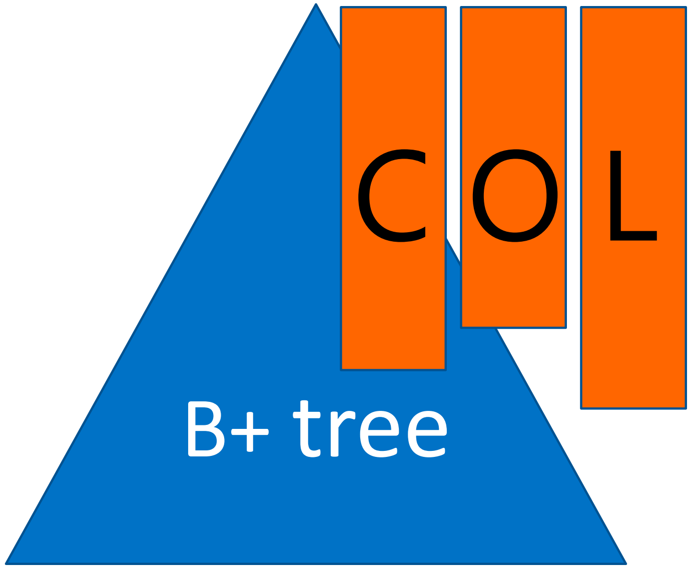
- Efficient data skipping and sort order of B+ tree vs. efficient vectorized processing of Columnstores
  - What are the trade-offs?
    - **Data skipping**
    - Concurrency
    - **Memory constraints**
- Impact of updates on B+ trees & Columnstores
  - Primary (clustered) and secondary (non-clustered) have different designs
- Performance of Hybrid Designs for Mixed Workloads - short updates and reporting queries scanning data

Two types of Columnstore Indexes (CSIs)

- CSI updatable via auxiliary structures
- Primary CSI designed to optimize scan performance in DW
  - No delete buffer in primary CSI, making small updates expensive



Characteristics: B+ tree, Col & hybrid

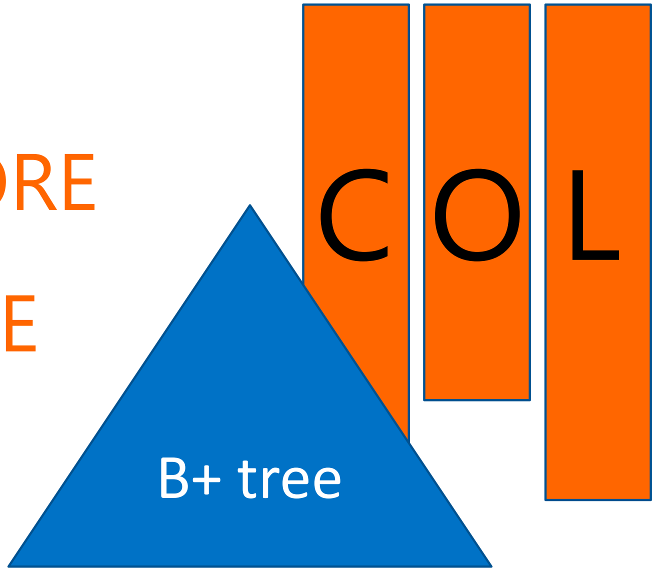


SORTED B+ TREE

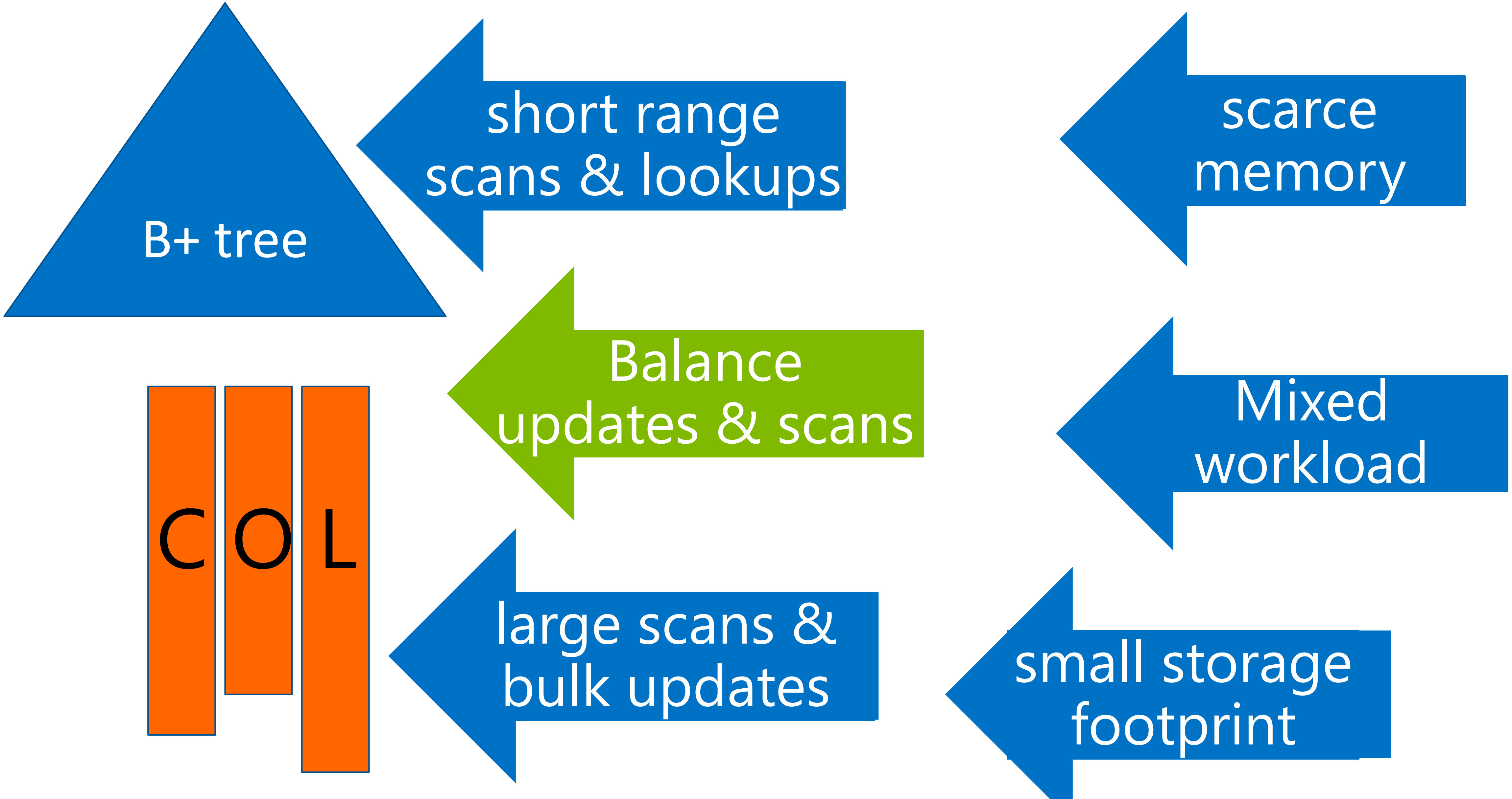
PRIMARY B+ TREE
&
SECONDARY COLUMNSTORE

NOT SORTED GLOBALLY COLUMNSTORE

COLUMNSTORE PRIMARY STORAGE
&
SECONDARY B+ TREE

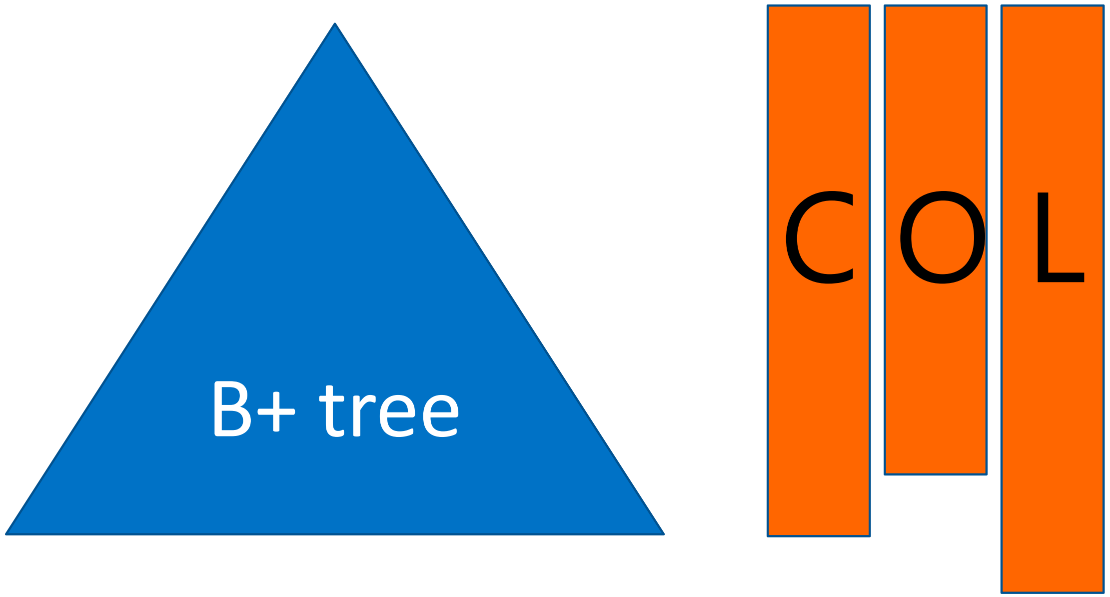


Takeaways from micro-benchmark analysis



Takeaways from Microbenchmark analysis

- B+ trees: suitable for point lookups, short range scans, update-only
- Sortedness of B+ trees only help when memory is insufficient
- Secondary CSIs strike a right balance between scans and updates
- Hybrid physical designs are essential for many mixed workloads where updates often have selective predicates

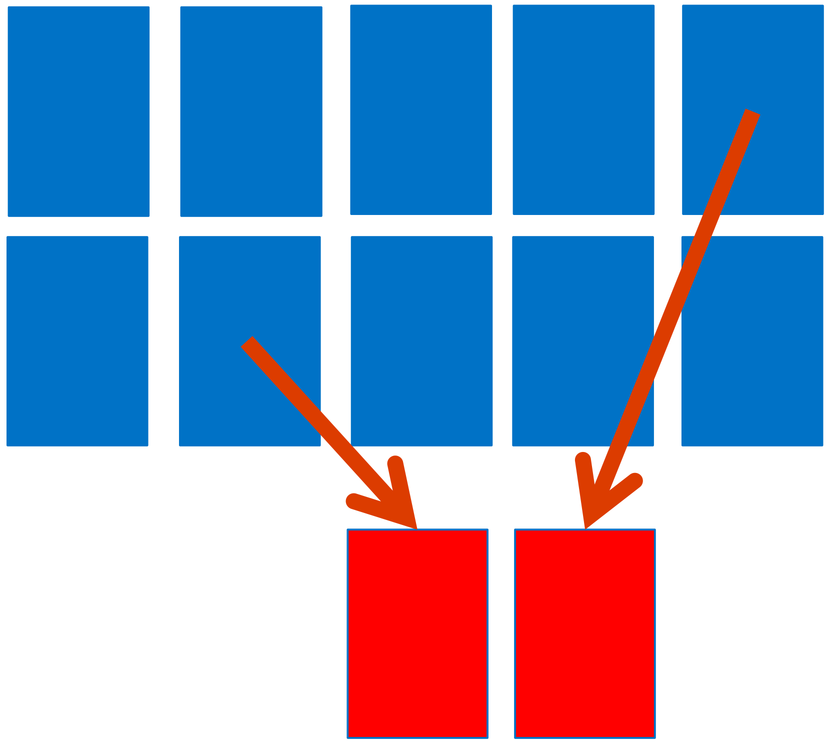


Mixed Workload: CH BenCHmark

- A join between TPC-C benchmark with the analytical H component from TPC-H
- **C component**: unmodified TPC-C schema and 5 transactions
- **H component:** 3 additional tables and adapted 22 queries which mimic TPC-H queries
- Concurrent queries compete for resources & locks
- Affinitize component C & H to different cores

Why is Columnstore size estimation hard?

Large data & design space



Sample based techniques

Complex storage

A
0.03
0.02
0.02
0.03
0.02

Input

A
3
2
2
3
2

Encode

A
2
2
2
3
3

Sort

A
2, 3
3, 2

Compress

1) Build index on samples
2) Model full index

Hypothetical Columnstore size estimation

Build index on samples

+ Simple
+ No changes required when index storage modified
- Low accuracy
- High overhead (run algorithms and store index)

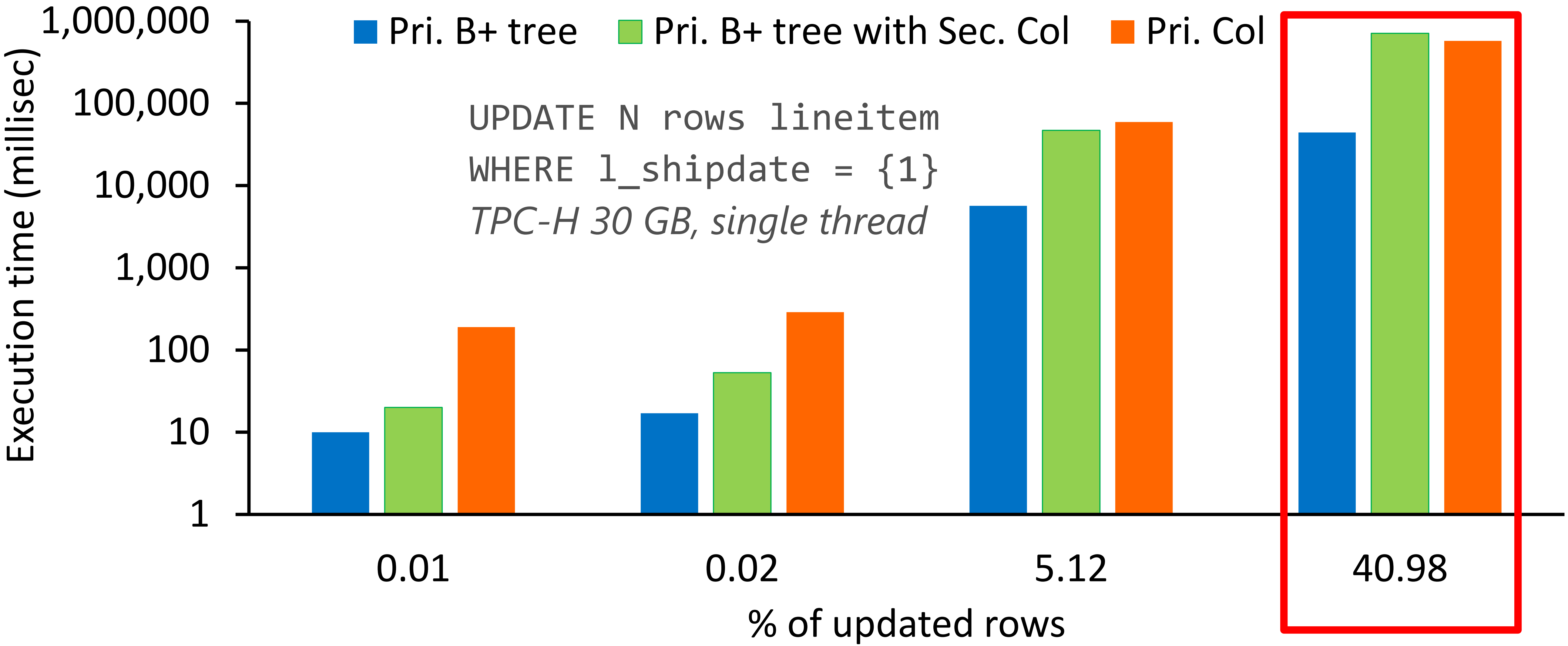
Model full index

+ More accurate
+ No overhead of sorting or writing index to disk
- High maintenance cost
- Complex (uses GEE estimator)

Hypothetical Columnstore size estimation

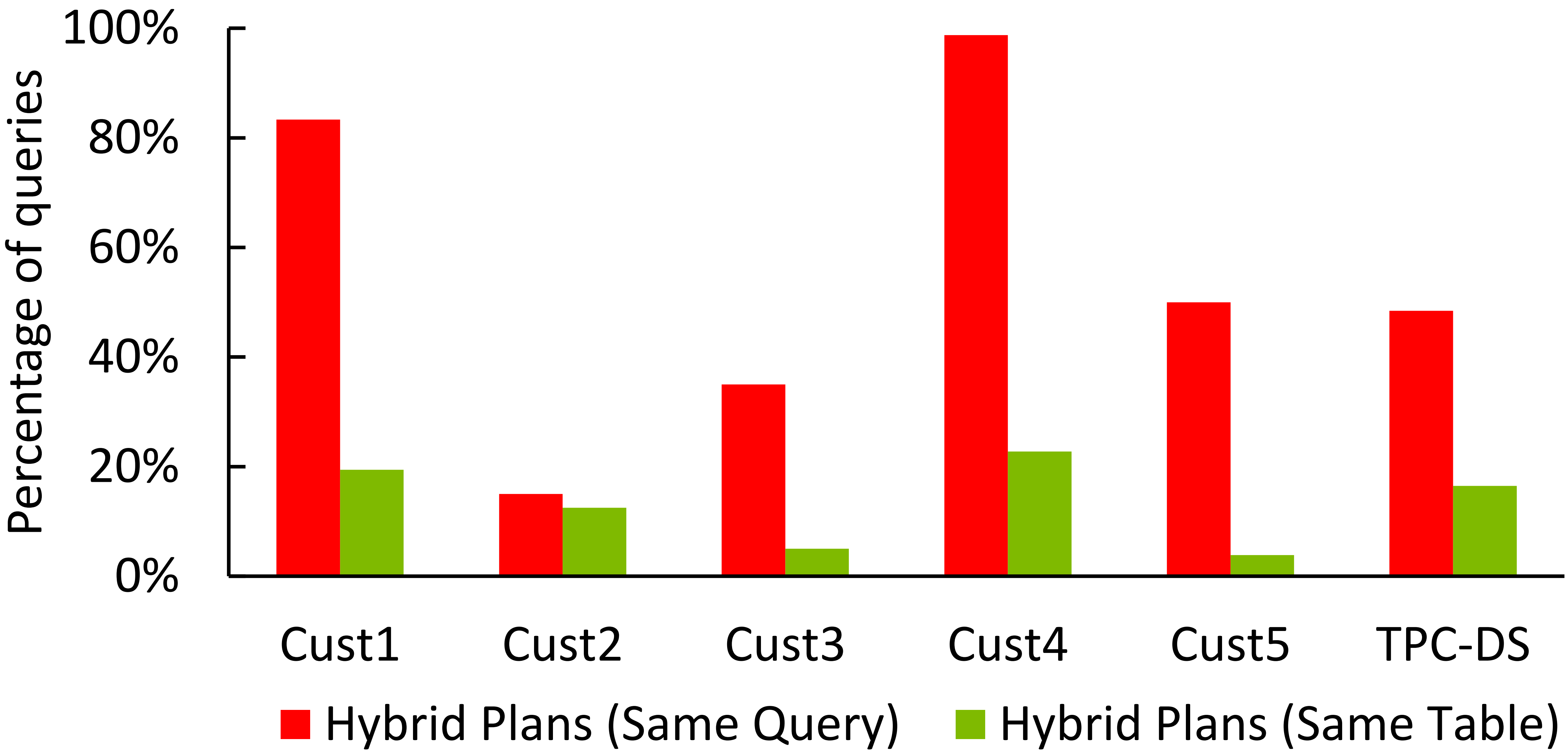
- Correctness: do not go over storage budget
- Efficiency: cannot afford to build the whole index
- Accuracy:
  - estimate the size on samples of data
  - model complex storage involving encoding, sorting and compression

Update performance



Primary & Secondary Columnstores comparable for large updates

Hybrid Query Plans are common



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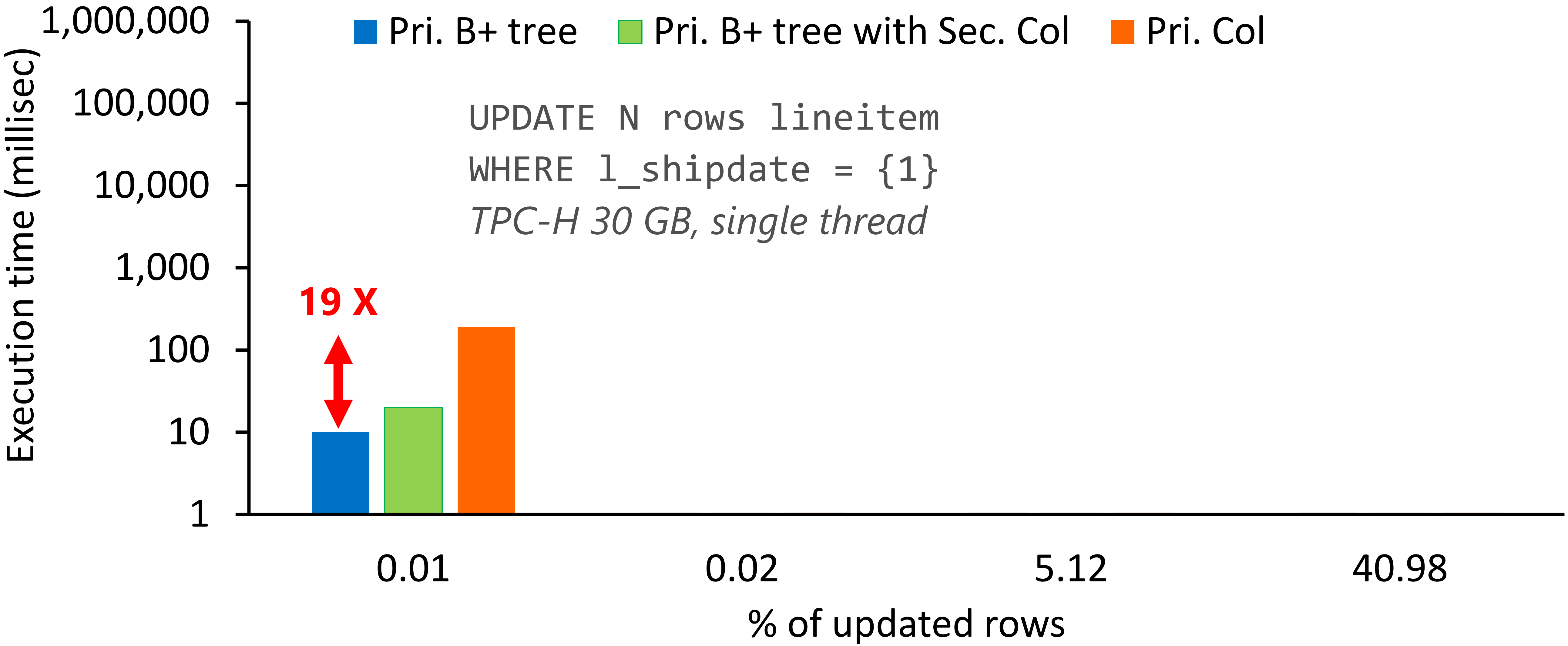
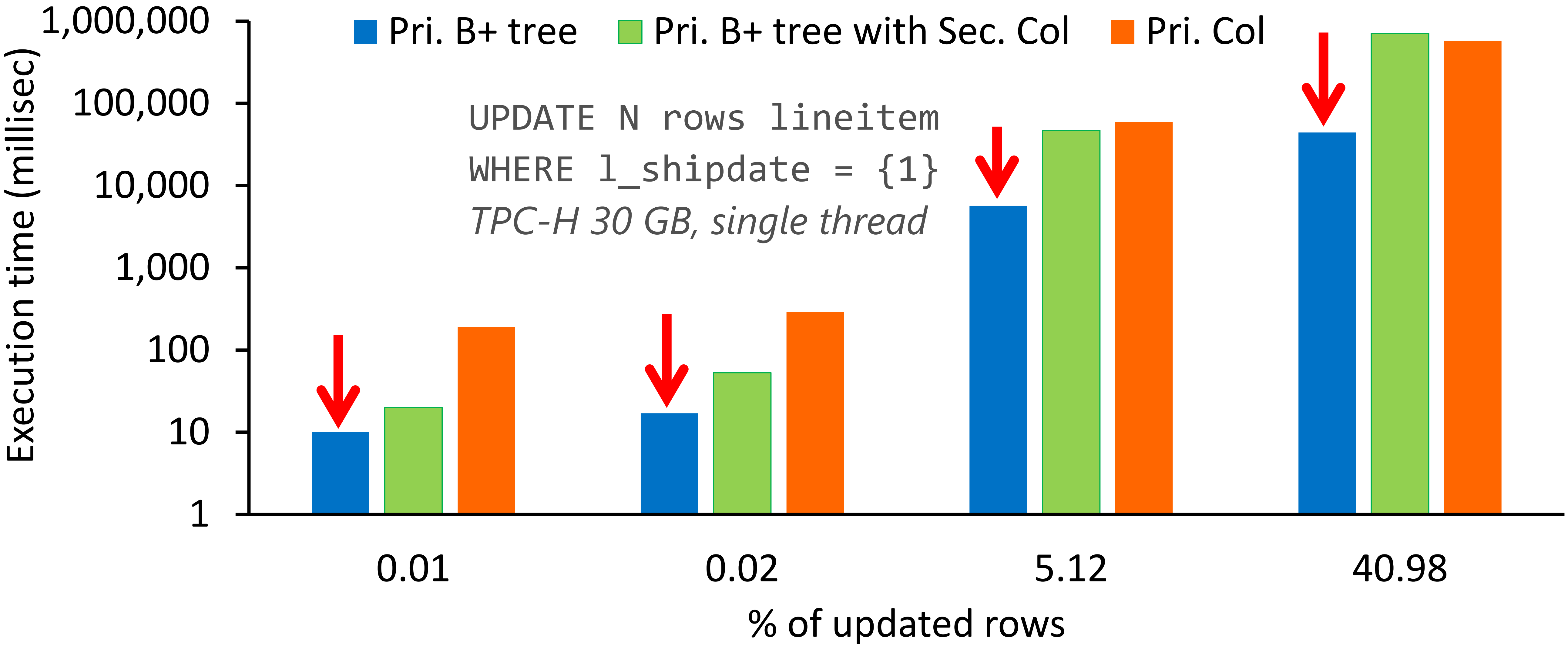


Primary Columnstores incur high cost for small updates

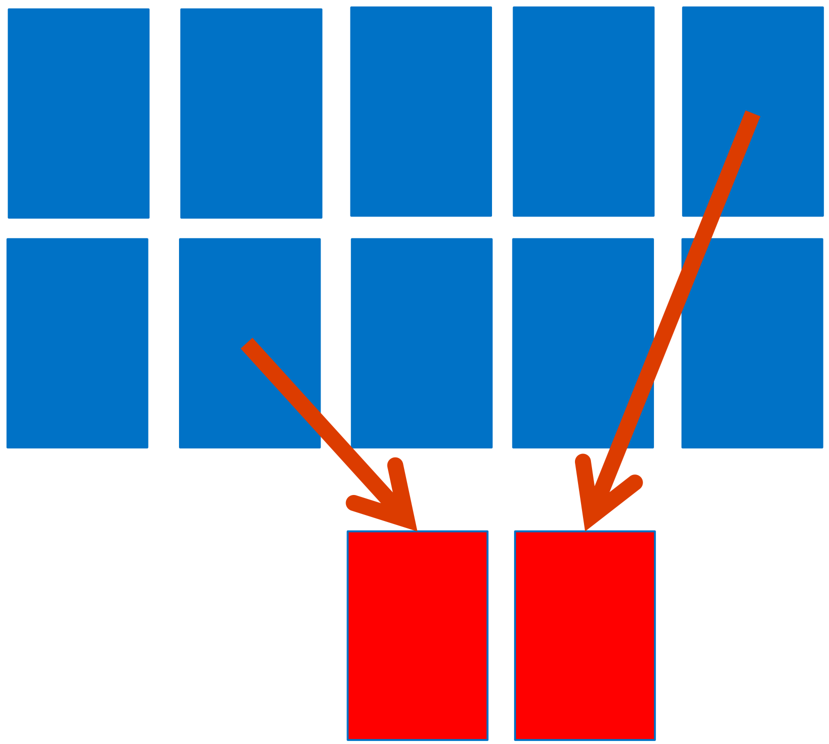
Update performance



Cheaper updates for B+ trees than for Columnstores

Why is Columnstore size estimation hard?

Large data & design space



Sample based techniques

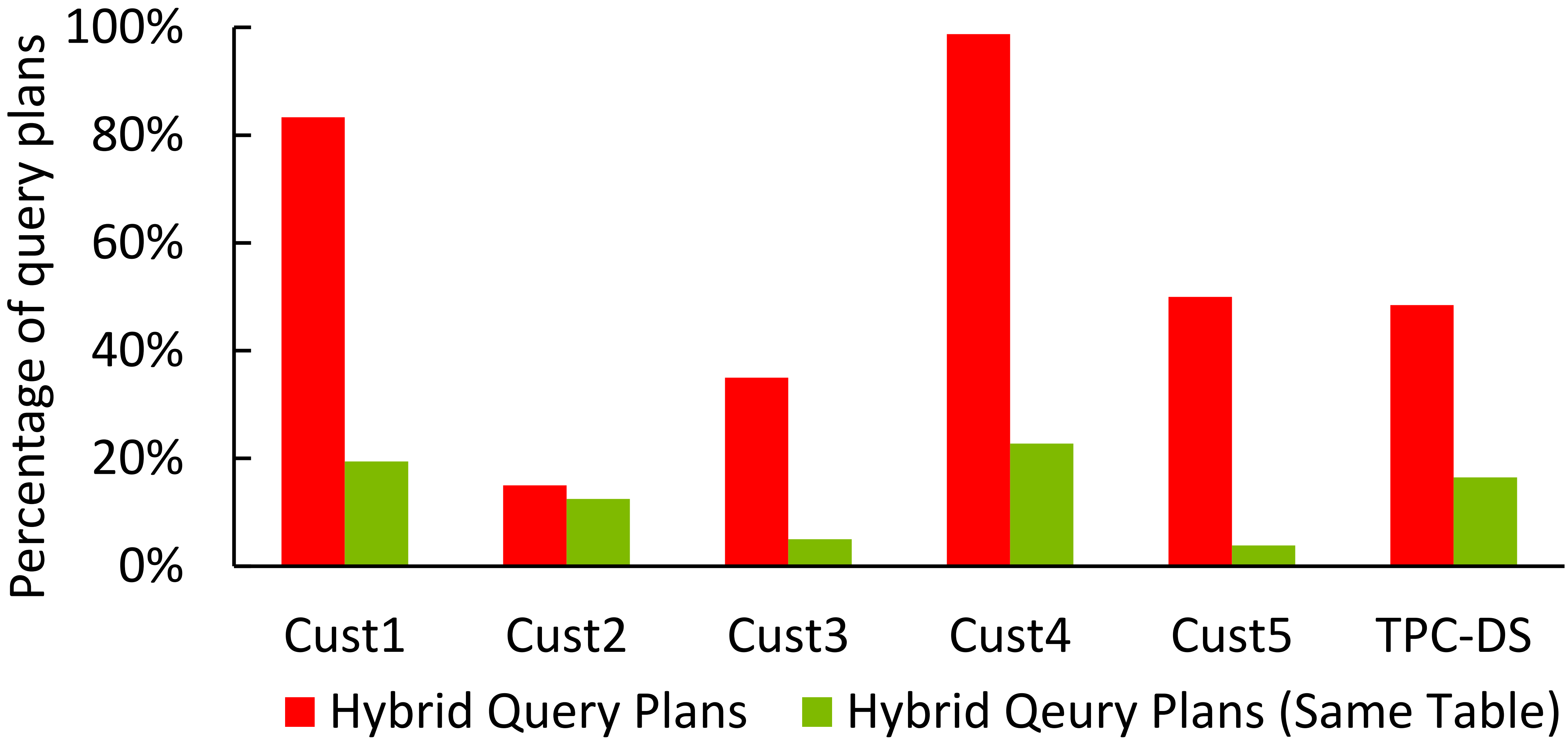
Complex Columnar storage

A	A	A
0.03	3	2
0.02	2	2
0.02	2	2
0.03	3	3
0.02	2	3
Input	**Encode**	**Sort**

A
2, 3
3, 2
Compress

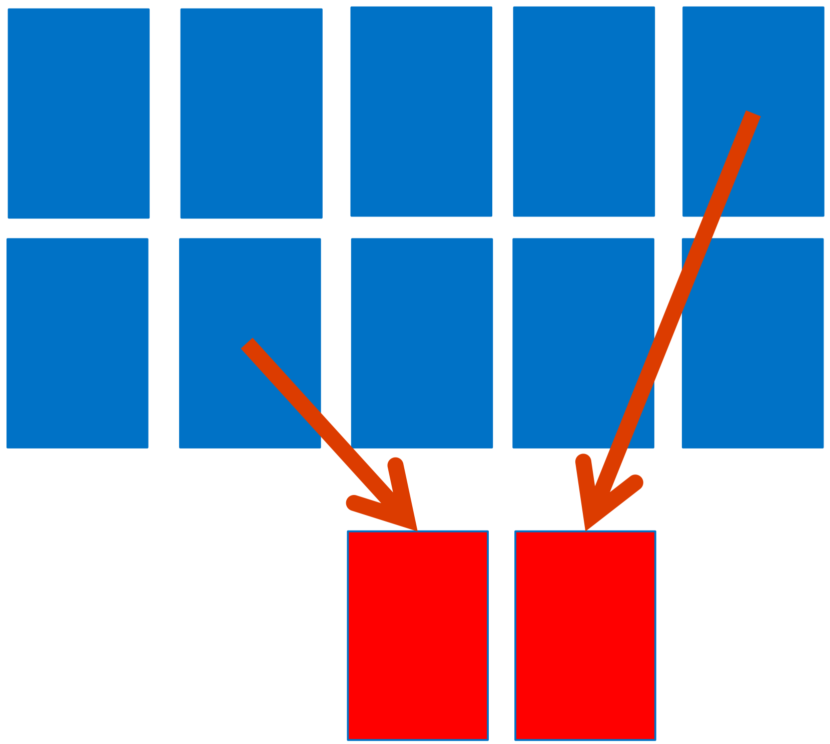
At least as hard as distinct value estimation

Hybrid Query Plans are common



Why is Columnstore size estimation hard?

Large data & design space



Sample based techniques

Complex Columnar storage

Input: A	Encode: A	Sort: A
0.03	3	2
0.02	2	2
0.02	2	2
0.03	3	3
0.02	2	3

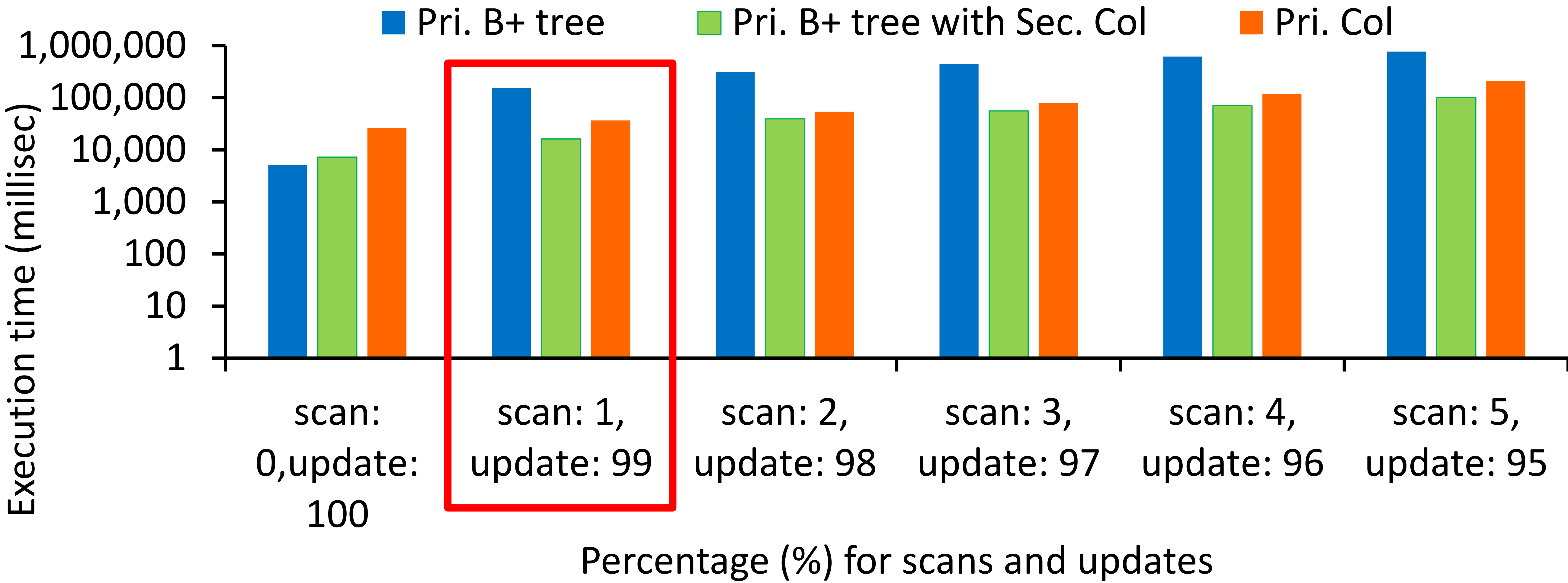
Compress: A
2, 3
3, 2

Input **Encode** **Sort** **Compress**

At least as hard as distinct value estimation

Mixed workload: large scans & small updates

Update *top 10 rows,* ***Select*** *sum of quantity & price for a single shipdate from lineitem table*



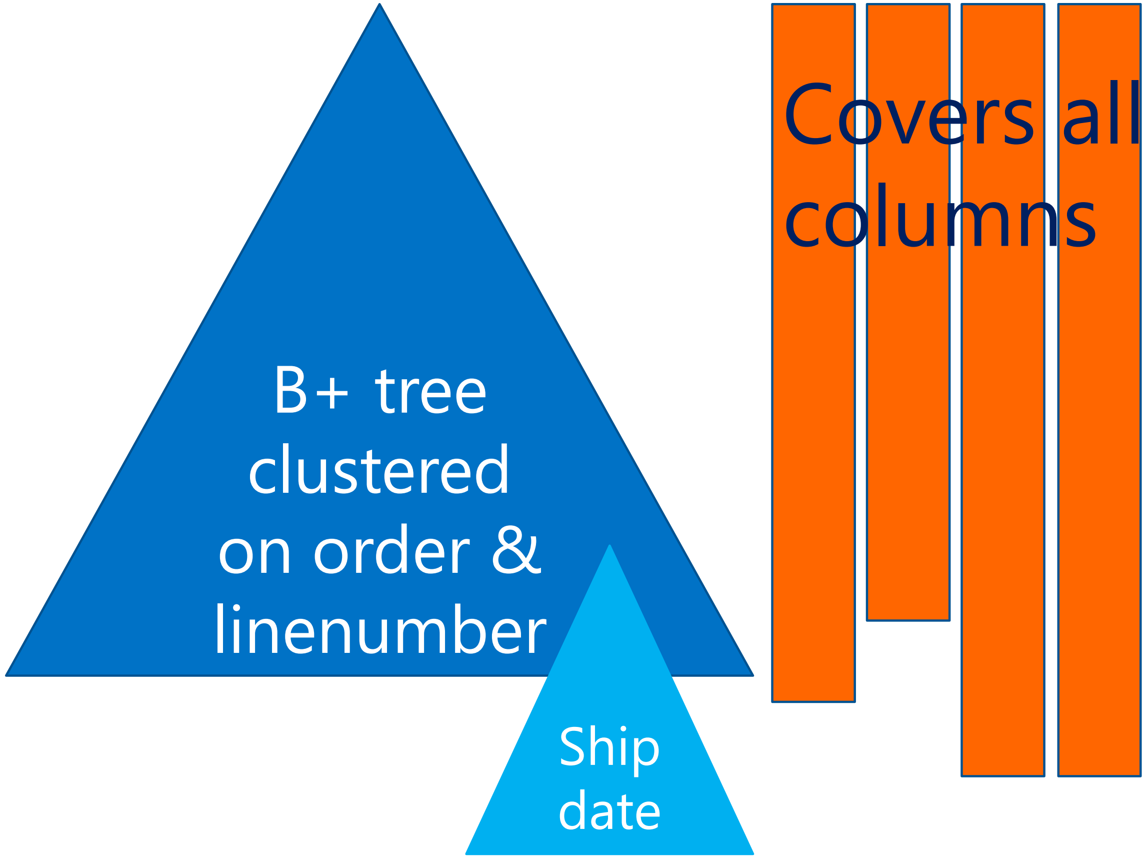
Secondary Columnstore: balance small updates & large scans

Differences to Kester et al. (sections 2.4 & 4)

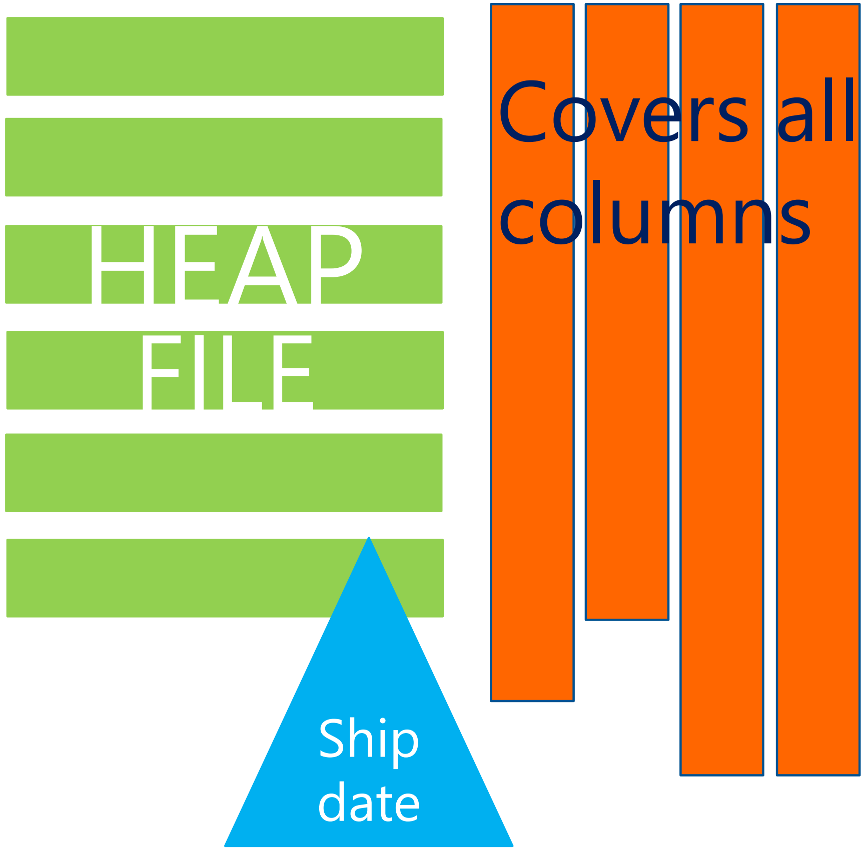
Concept	Access Path Selection	Hybrid designs
B+ tree	Main memory optimized	General (disk-based)
Scans	Shared	Non-shared
DB engine	Prototype	SQL Server
Main focus	Model Concurrency	DTA and many workloads
Physical designs	Columnstore and Secondary B+tree	Hybrid Physical Designs

Hybrid Designs

Primary B+ tree (base table)
Secondary Columnstore
Secondary B+tree on ship date

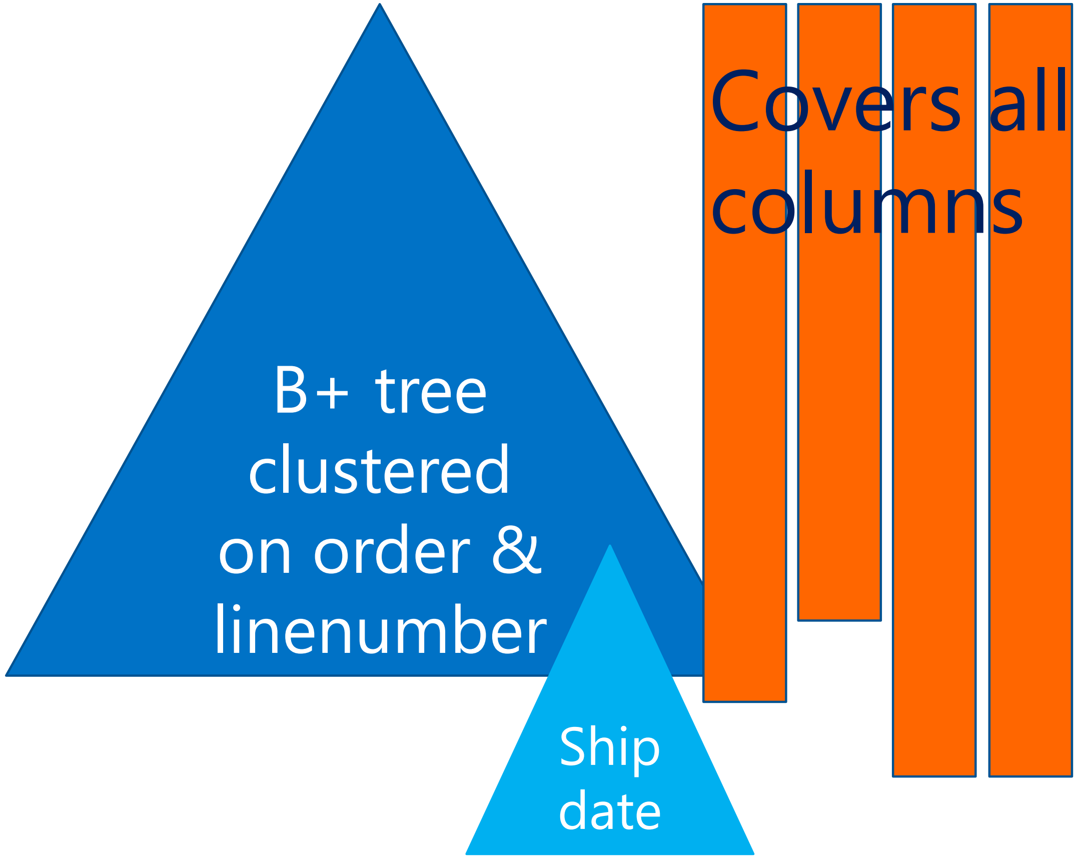


Heap file base table
Secondary Columnstore
Secondary B+tree on ship date

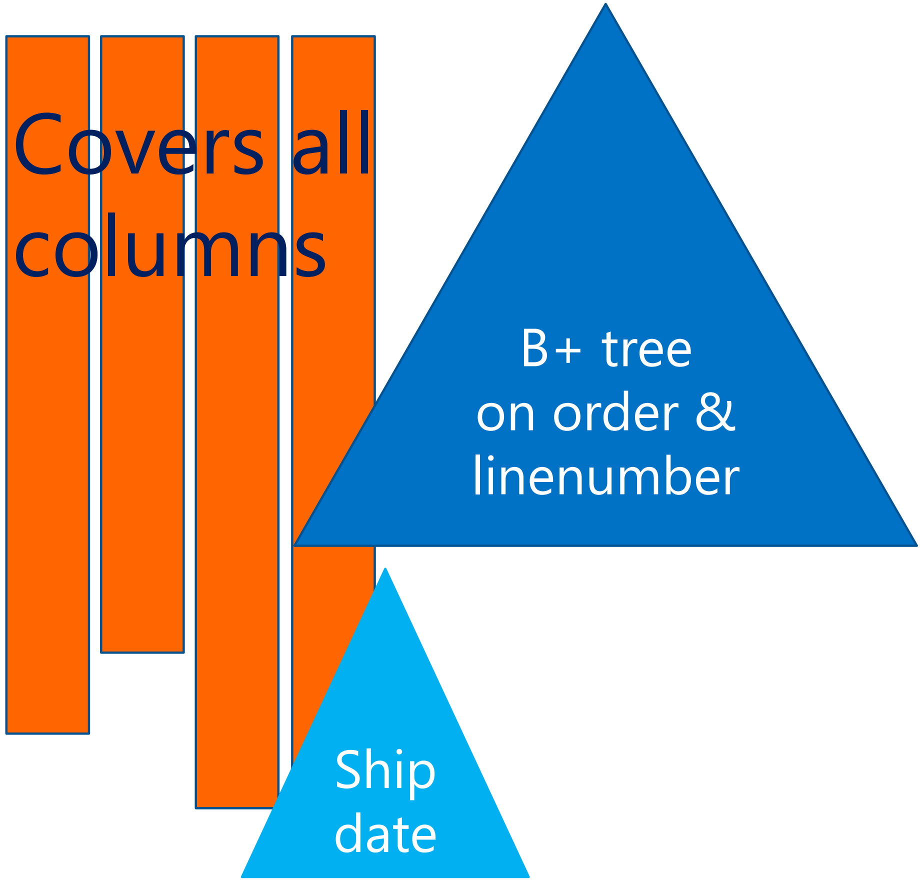


Hybrid Designs

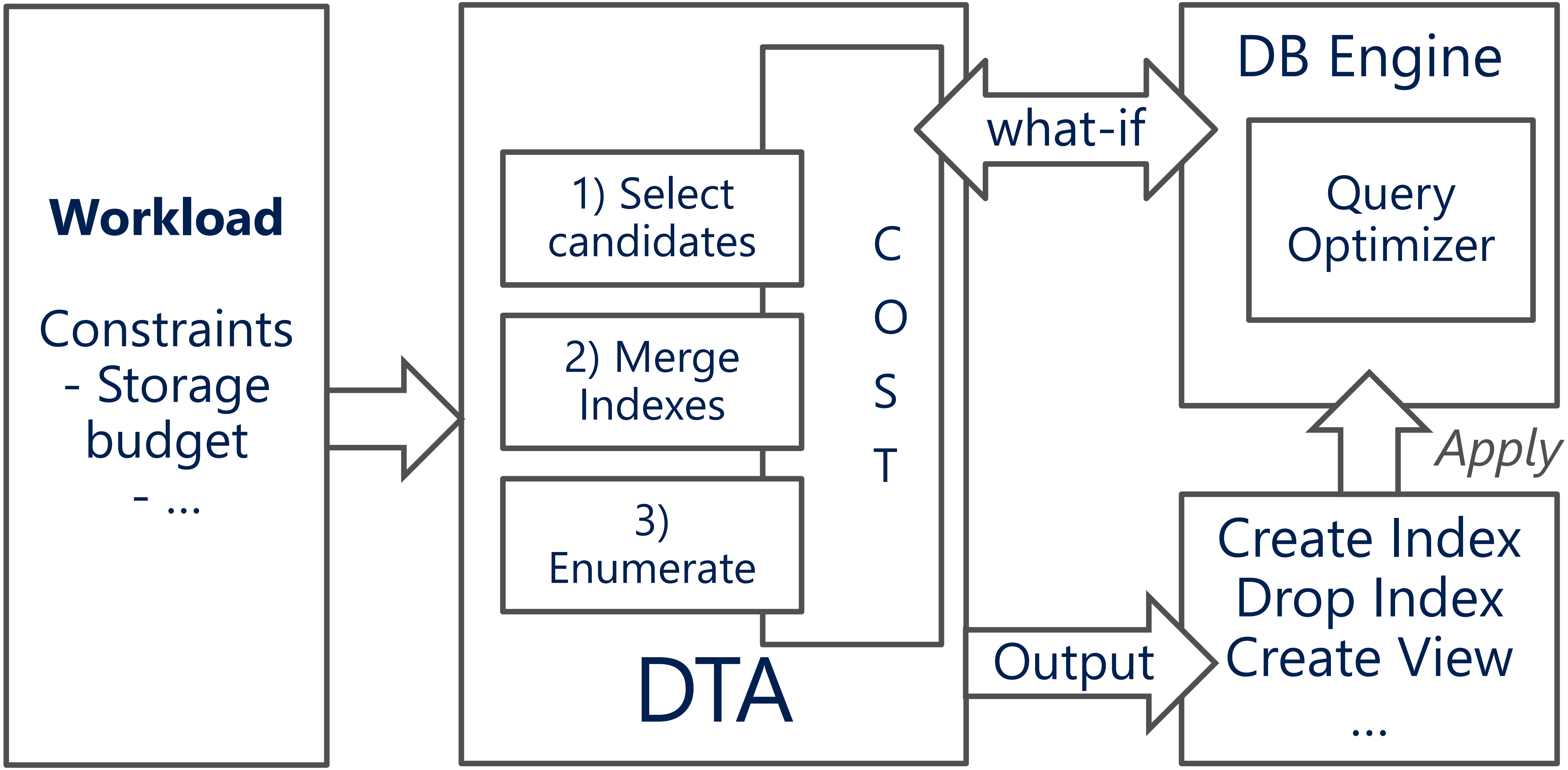
Primary B+ tree (base table)
Secondary Columnstore
Secondary B+ tree on ship date



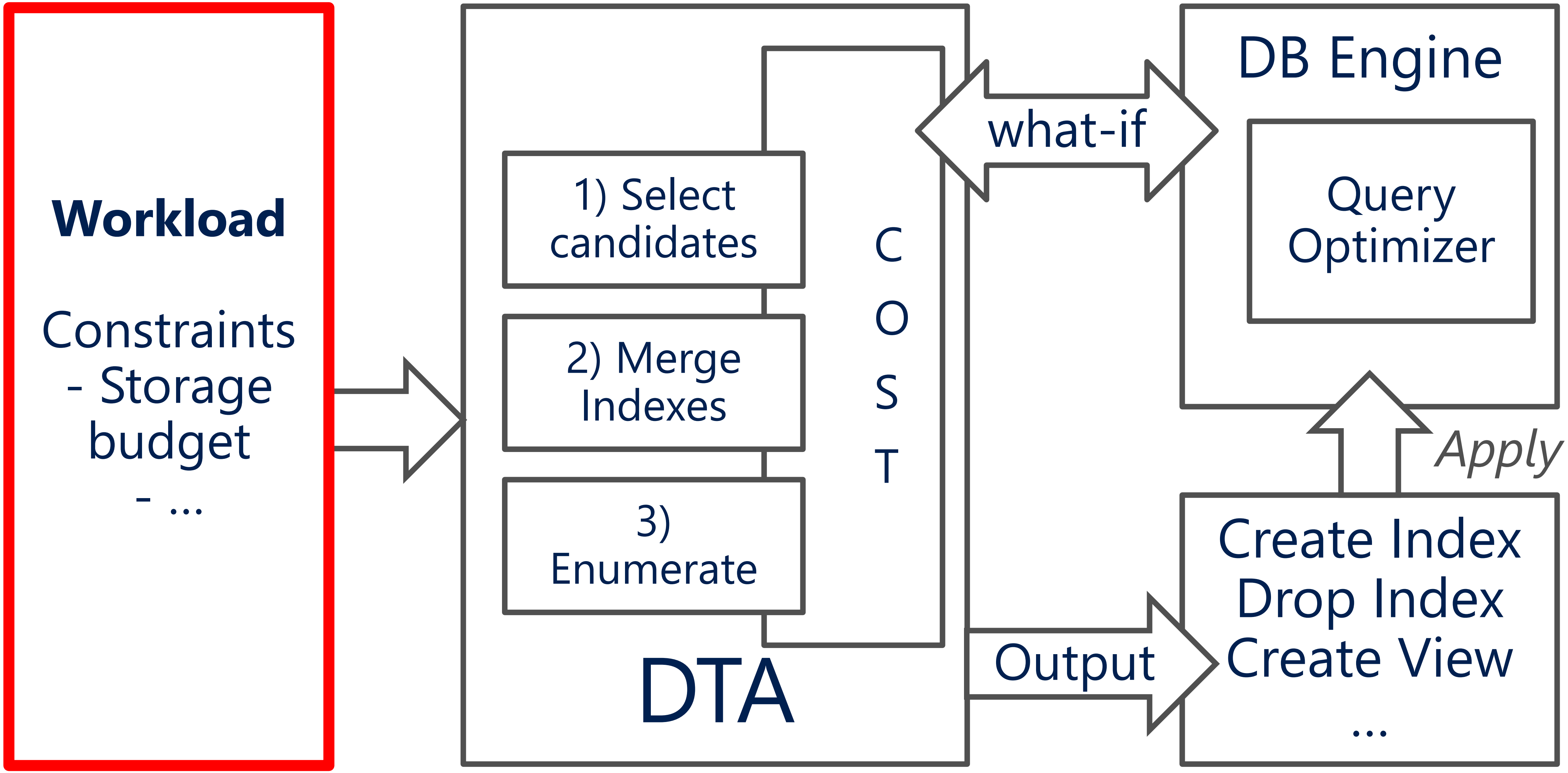
Primary Columnstore
Secondary B+ tree on order/line
Secondary B+ tree on ship date



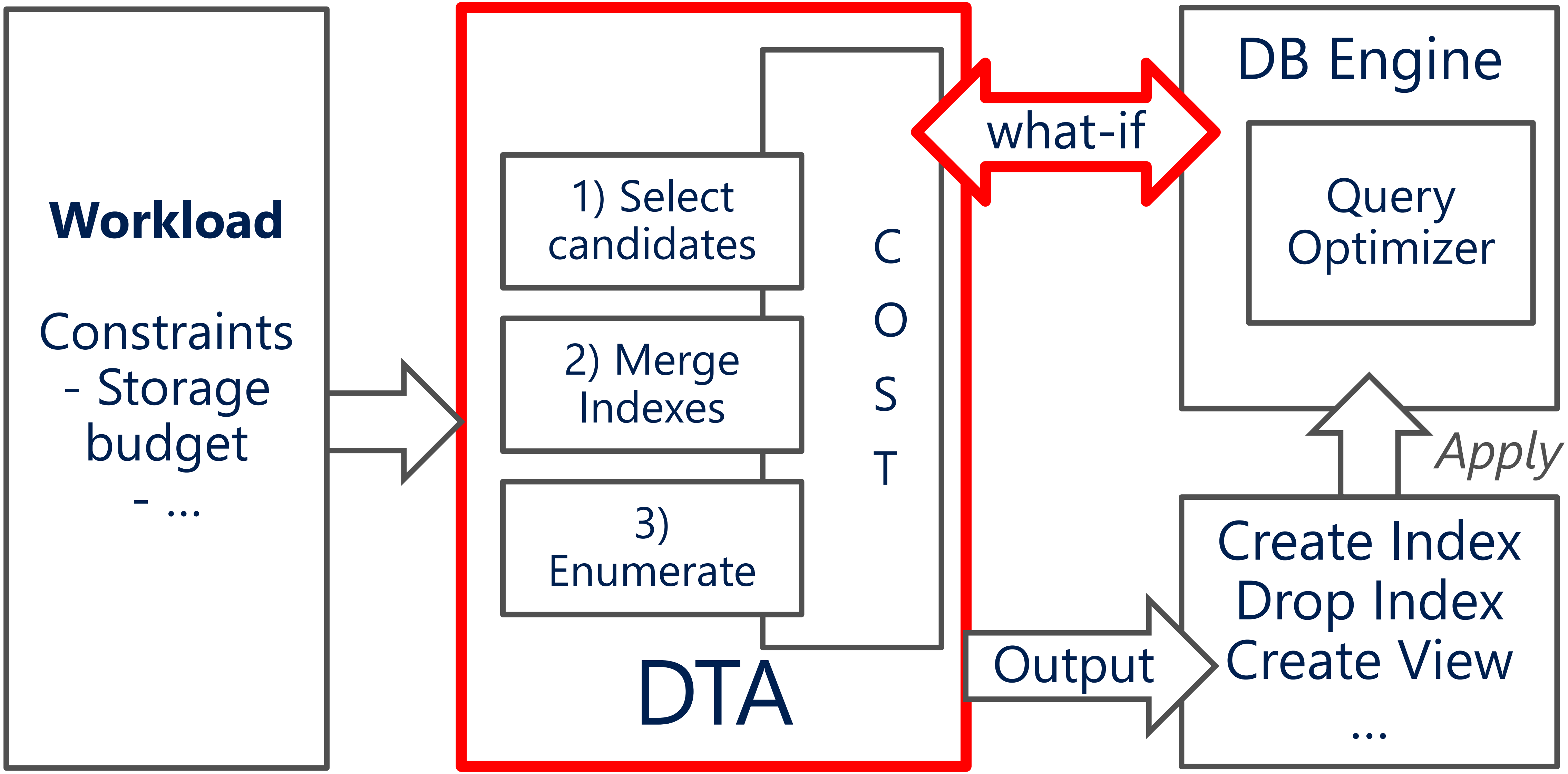
Database Engine Tuning Advisor (DTA)



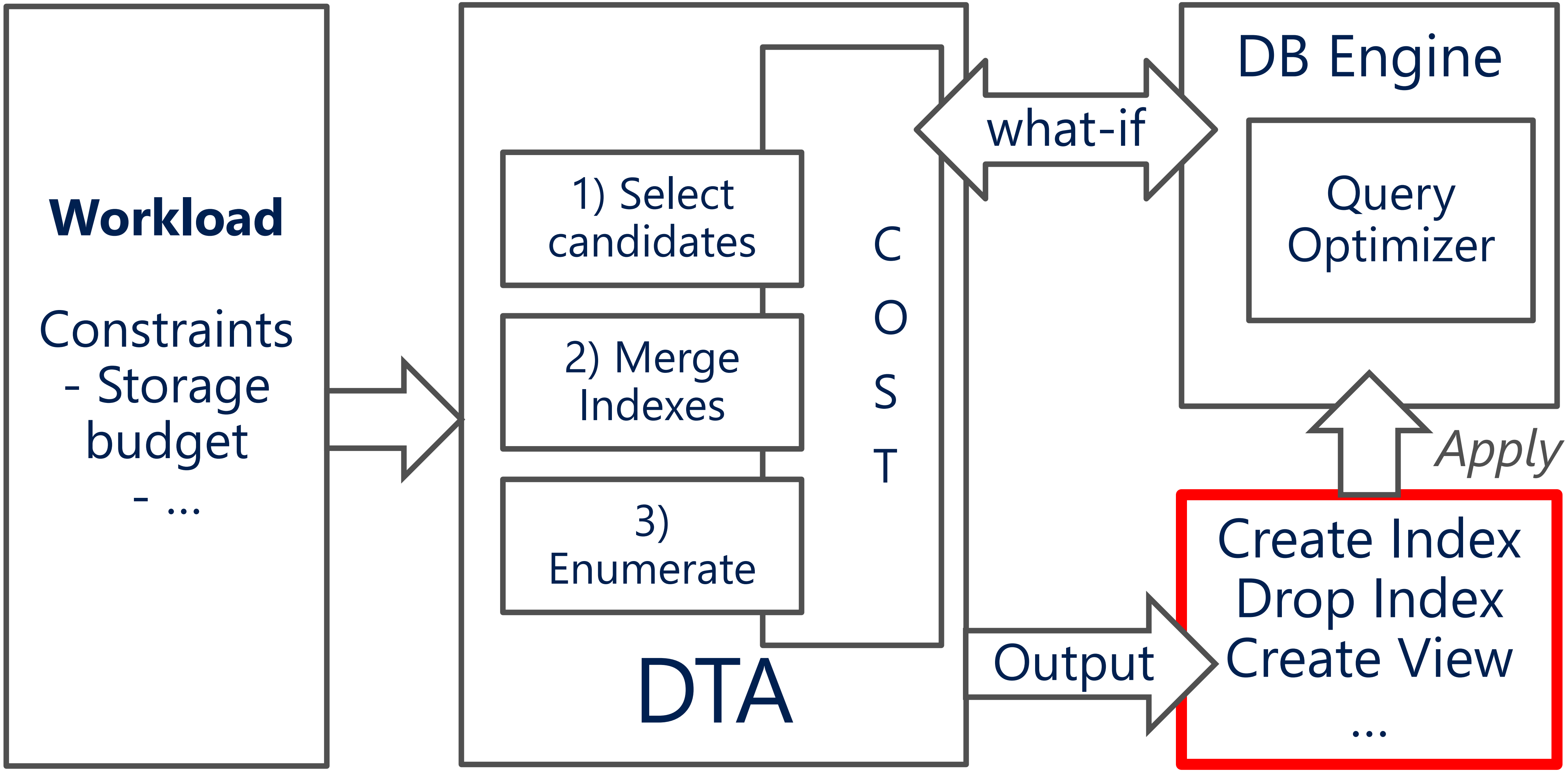
Database Engine Tuning Advisor (DTA)

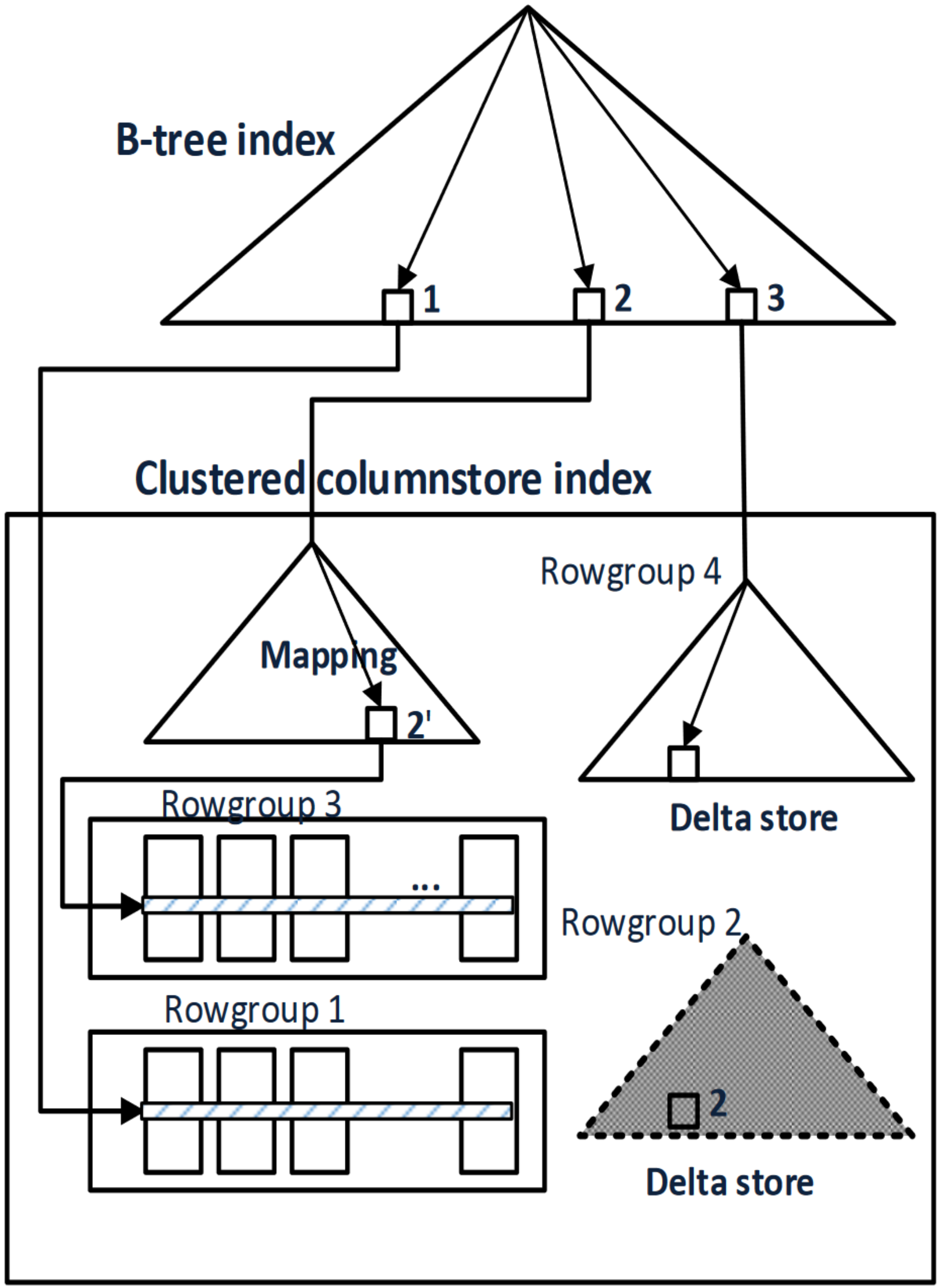


Database Engine Tuning Advisor (DTA)



Database Engine Tuning Advisor (DTA)





Primary Columnstore & Secondary B+ tree index:

- Efficient point-lookups and small range scans \w B+ tree
- enforce constraints efficiently (e.g. Primary Key)

<u>Source: </u>Real-Time Analytical Processing with SQL Server *– Paul Larson, Adrian Birka, Eric Hanson, Weiyun Huang, Michal Novakiewicz, Vassilis Papadimos (Microsoft)*