# A GPU Multiversion B-Tree

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AMD

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# Outline

1. Fully concurrent GPU data structure example
2. Challenges with GPU data structures (and how we address them)
3. Results
4. Summary and future research directions

# Data analytics on GPUs

blazingSQL

HEAVY.AI

ARESDB

RAPIDS

VOLTRON DATA

# Can we write code like this?

```
data_structure_0 edges;
data_structure_1 graph;

std::for_each(std::execution::par,  // in parallel
                std::begin(edges),  // from the first element
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**Fully concurrent GPU data structure**

Support for **concurrent** read-only and update operations

My dissertation topic

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# What will be the output on the GPU?

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Thread$_0$ Thread$_1$

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Execution order

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Thread$_0$ ← (a)

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**Our paper addresses the semantics of concurrent operations on GPUs using *snapshots***

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              [&](const auto e) {   // perform this lambda function
                  graph.insert(e);
                  auto timestamp = graph.take_snapshot();
                  auto neighbors = graph.get_neighbors(e.first, timestamp);
                  for(n in neighbors) printf("%i, ", n);
              });
```

Execution order

Thread$_0$ ← Success

Thread$_1$ ← Success

Thread$_0$ ← (a,b)

Thread$_1$ ← (b)

😊

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# Challenges with GPU data structures

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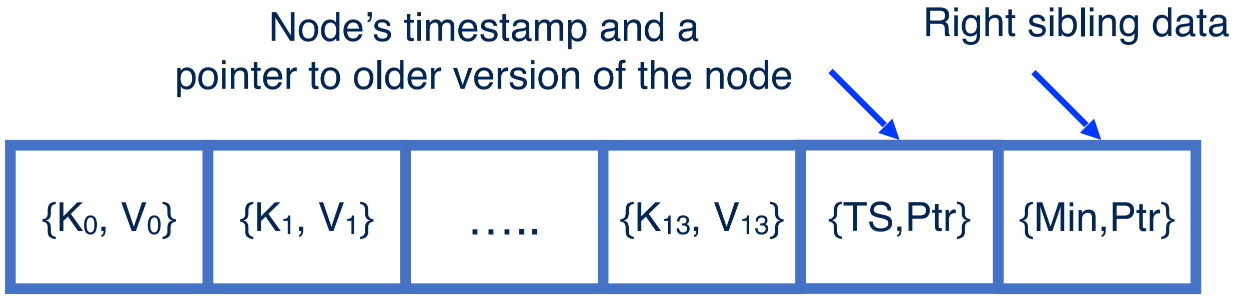


**Multiversion B-Tree node**

Node size = 128 bytes or B = 14
(assuming 32-bit key-value (or pivot-pointer) pairs)

**Our solution: use cache-line-sized nodes and WCWS**

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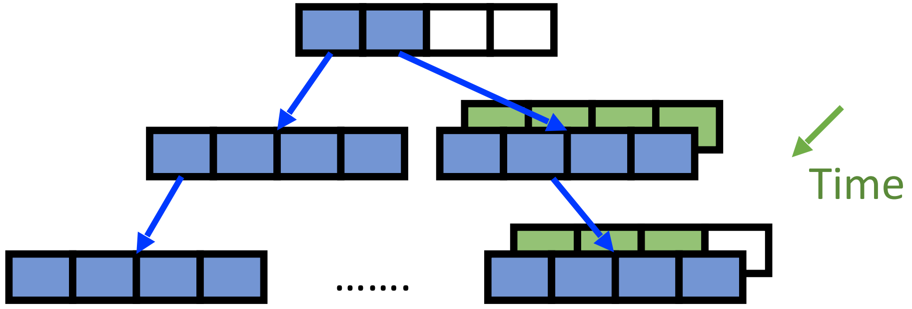
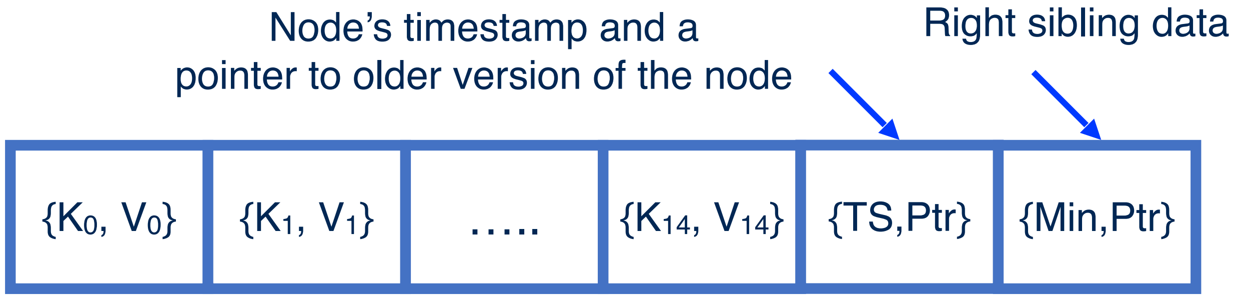



**Multiversion B-Tree**

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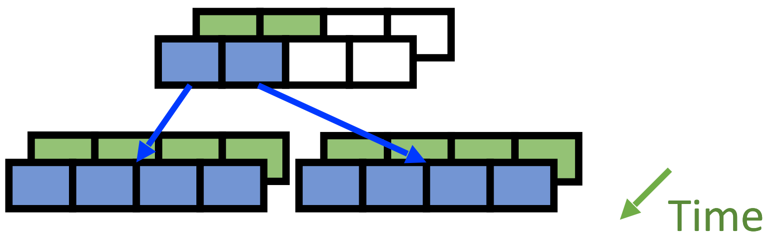


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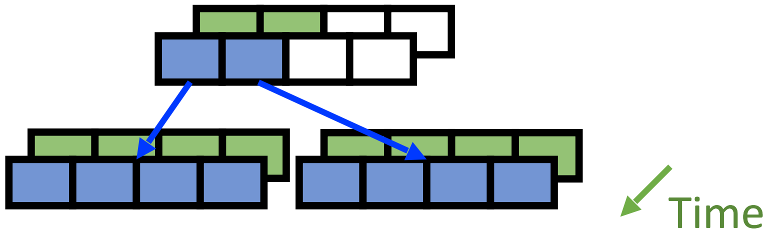


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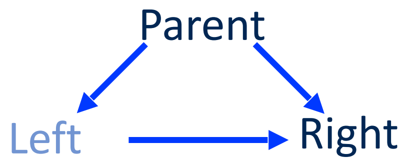

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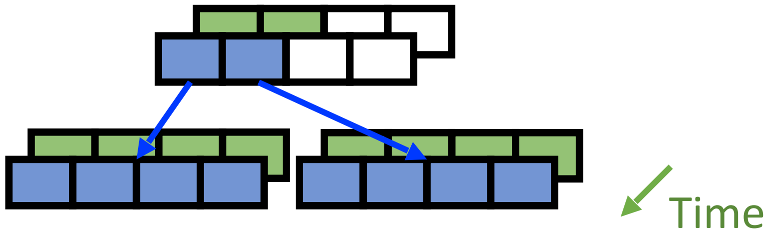


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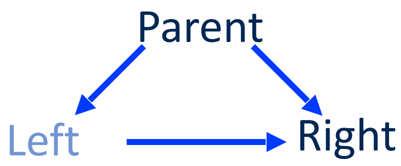


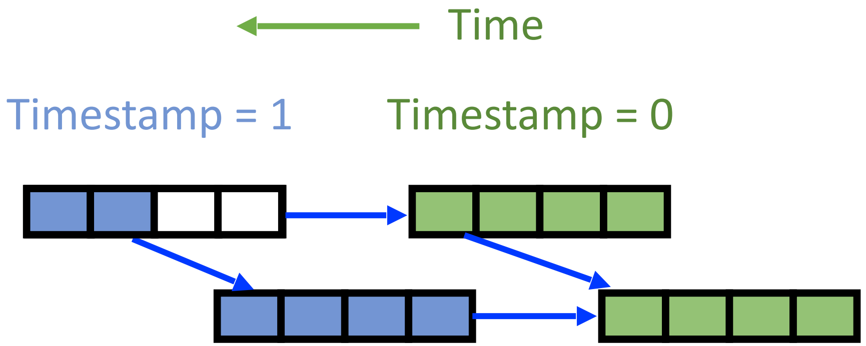


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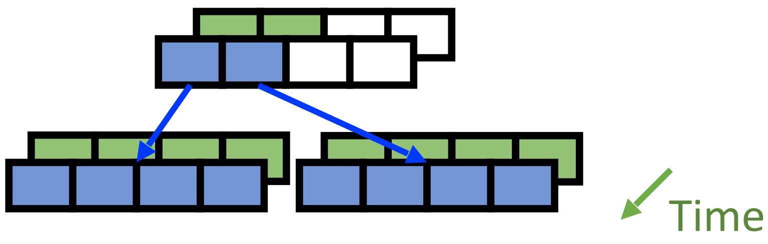
## 2. Contention during updates

- Relaxing the data structure invariants

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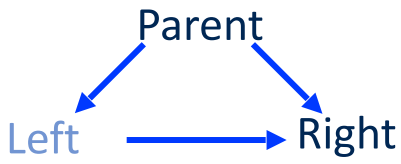


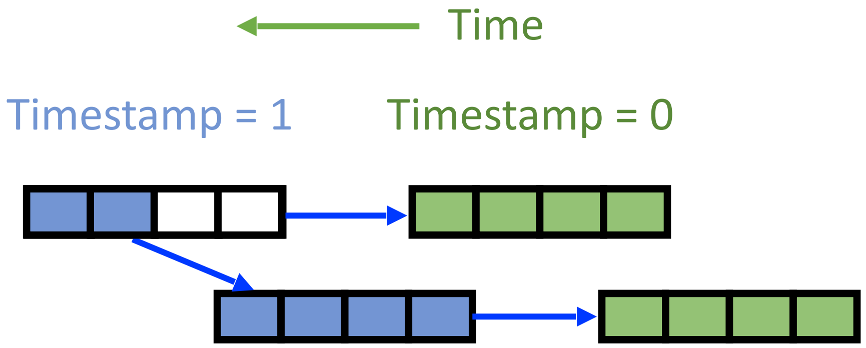


**Our solution: use single entry-point version lists**

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# Challenges with GPU data structures

2. Contention during updates
   - Relaxing the data structure invariants
   - Restarts (aborts)
     - Instead of spin locks
   - Proactively perform operations (e.g., splitting)

**Our solution: use single entry-point version lists, use restarts and proactive splitting**

# Challenges with GPU data structures

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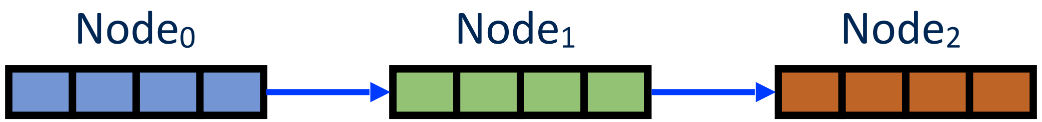


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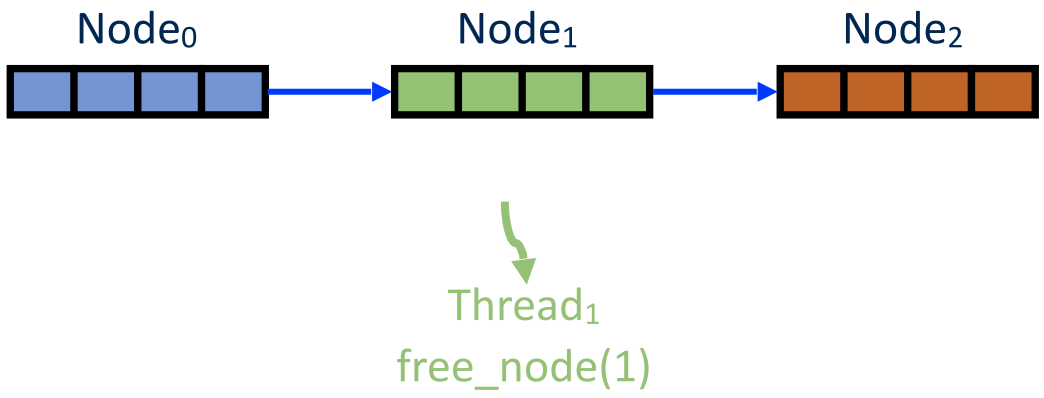

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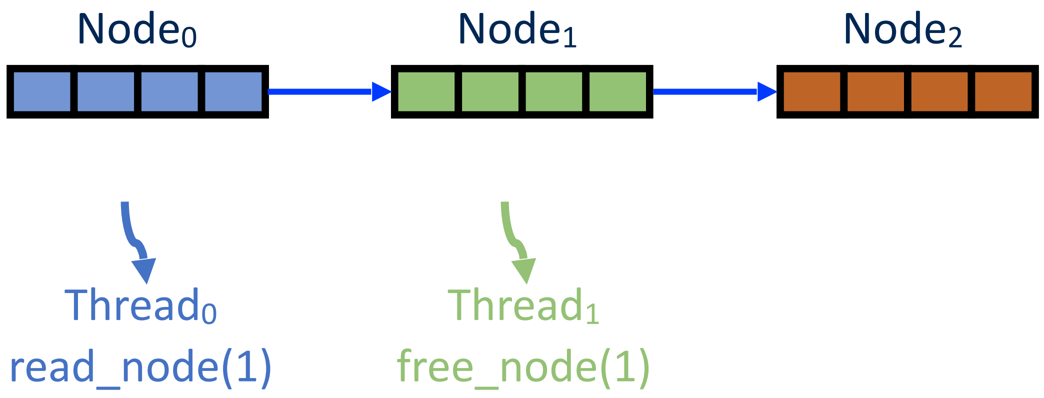

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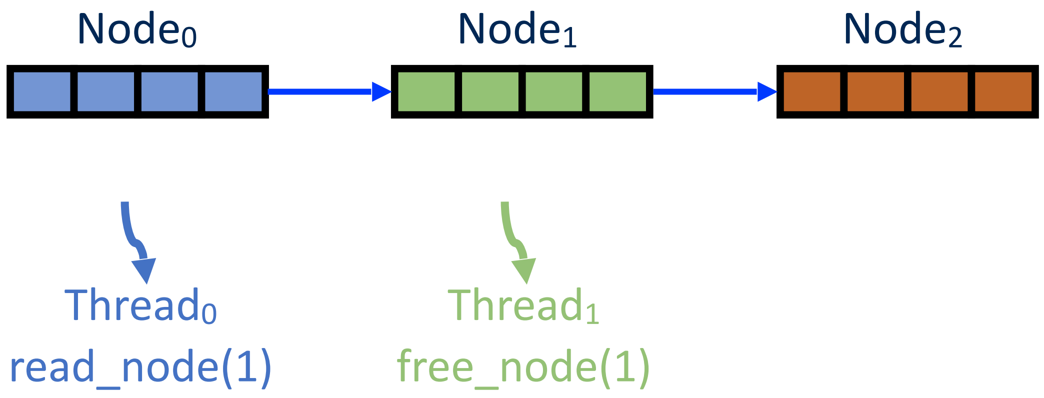


Data structure

Memory allocator

Lifecycle of a pointer (p)

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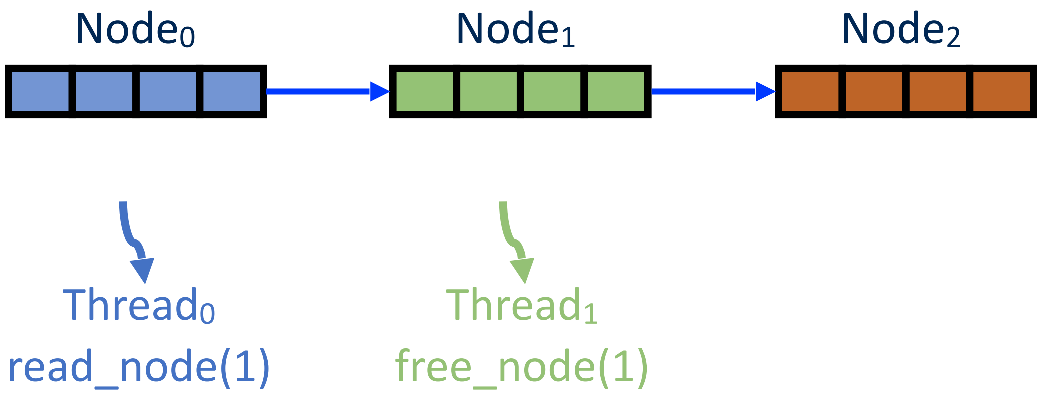


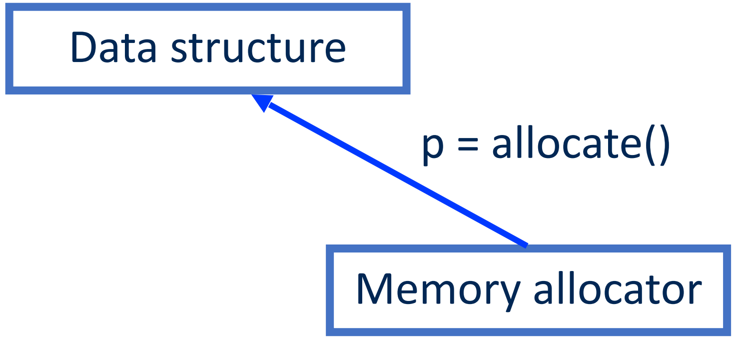


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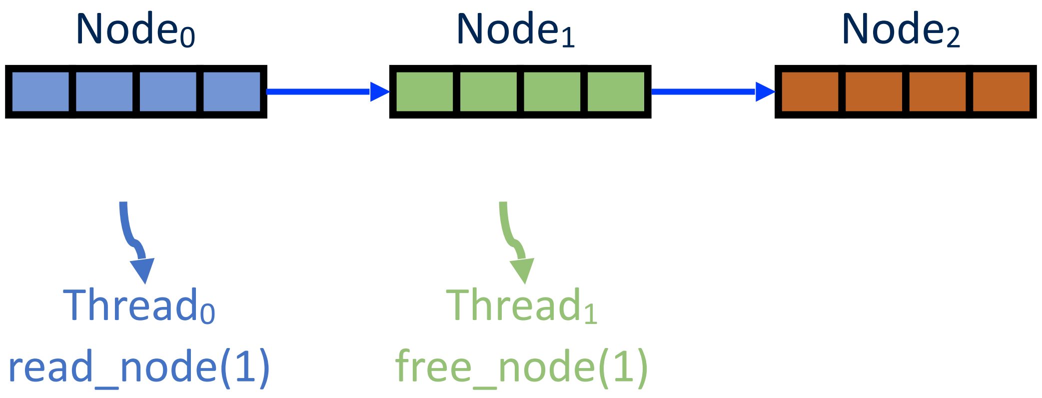


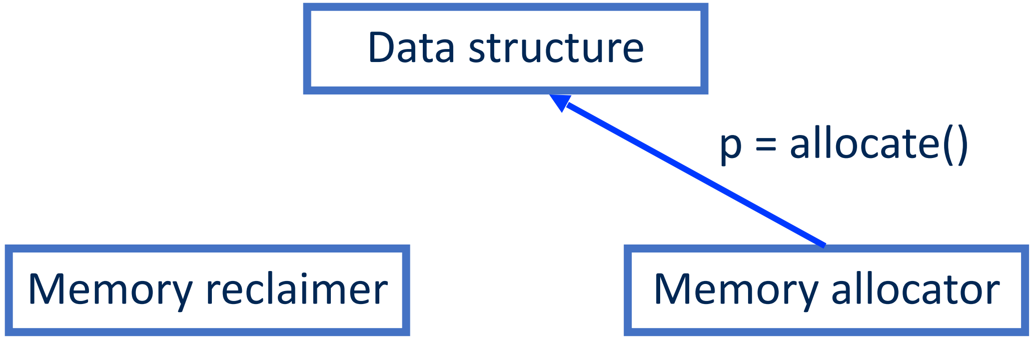


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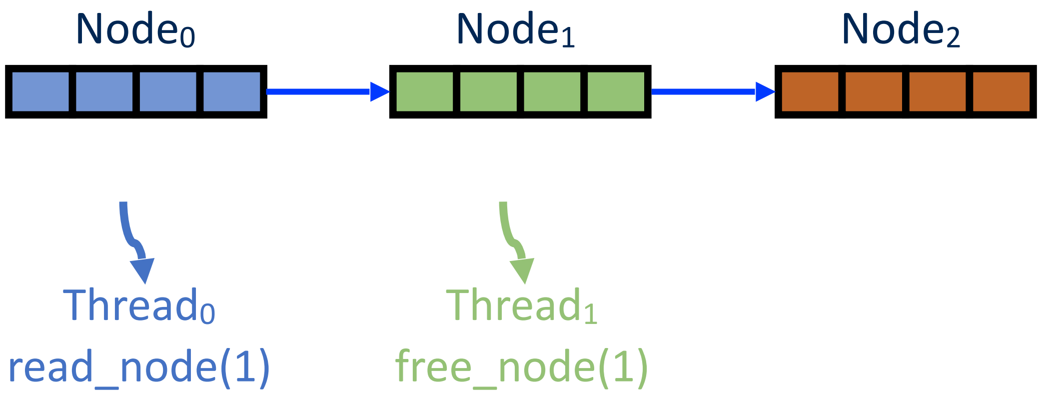


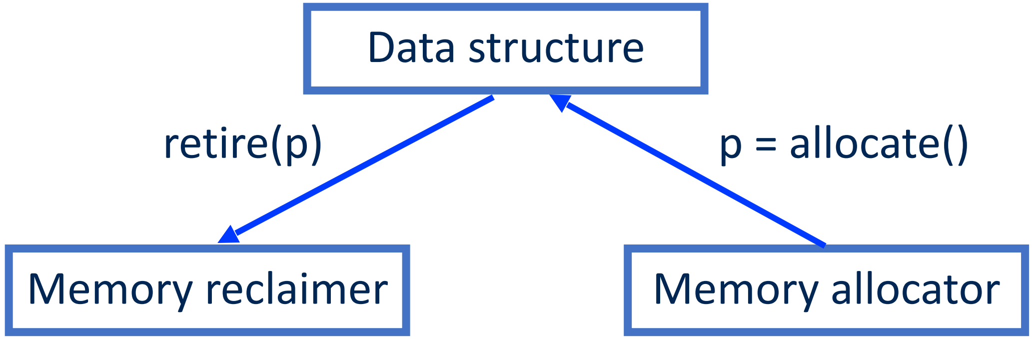


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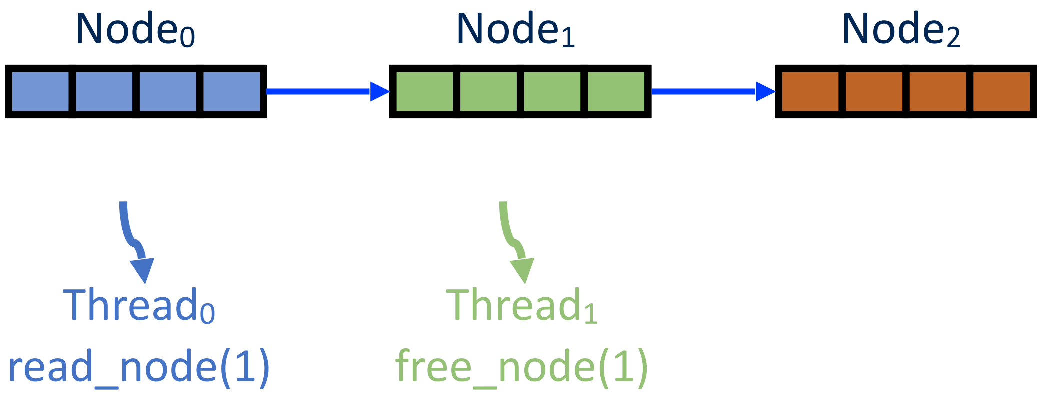


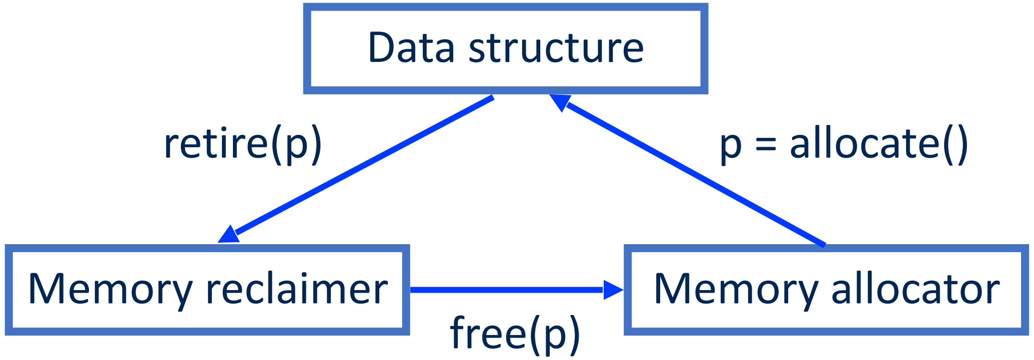


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# Challenges with GPU data structures

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Limbo bags

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Limbo bags

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|---|---|---|
| | | |

Observed Epoch number

| | | |
|---|---|---|
| 4 | 5 | 5 |

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What is a suitable GPU granularity for a process?

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**CUDA Block**

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Epoch number 5

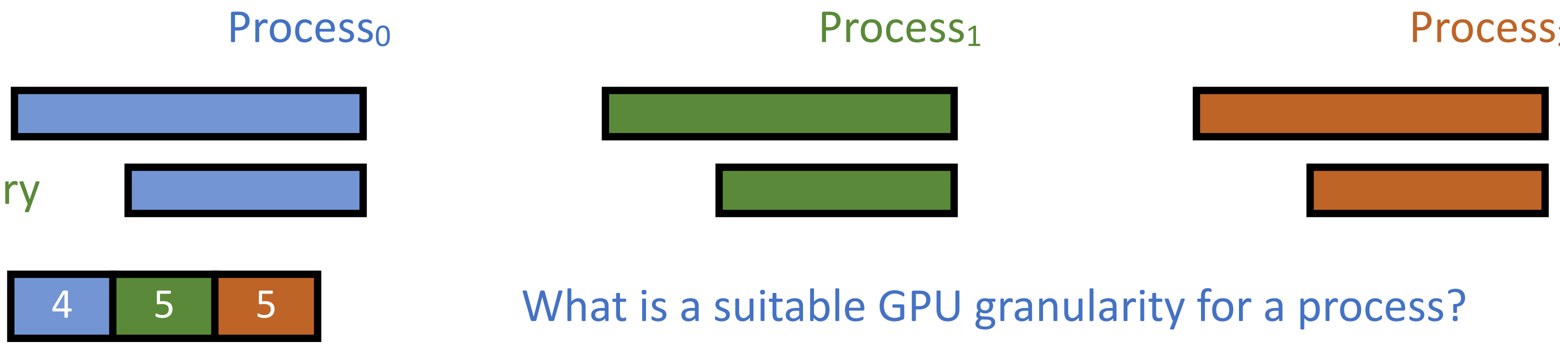
Limbo bags

DRAM

Shared memory

Observed

Epoch number




What is a suitable GPU granularity for a process?

**CUDA Block**

**Scan 80x16 states (80 SMs with 16 resident blocks)**

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# Challenges with GPU data structures

**Our solution: block-wide EBR**

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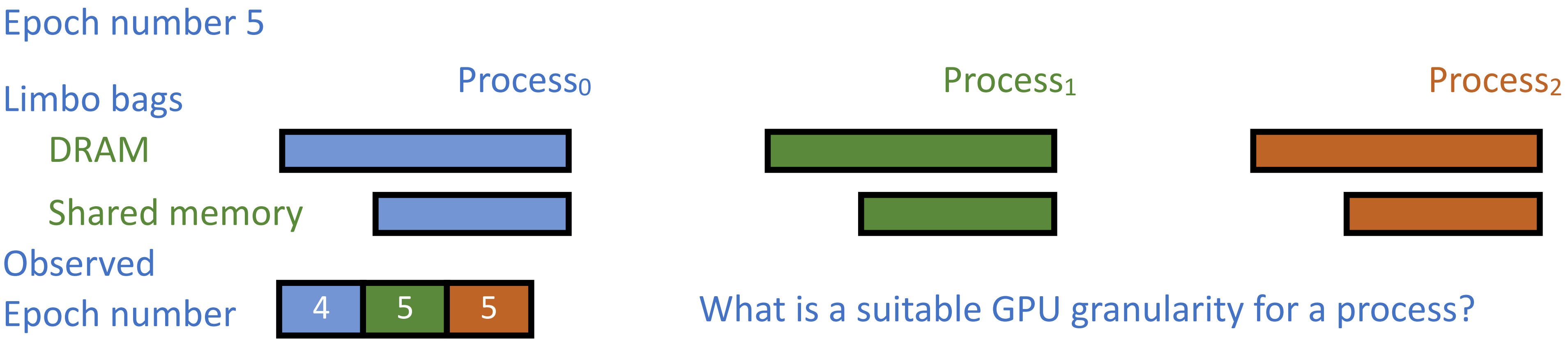


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# Challenges with GPU data structures

5. Semantics

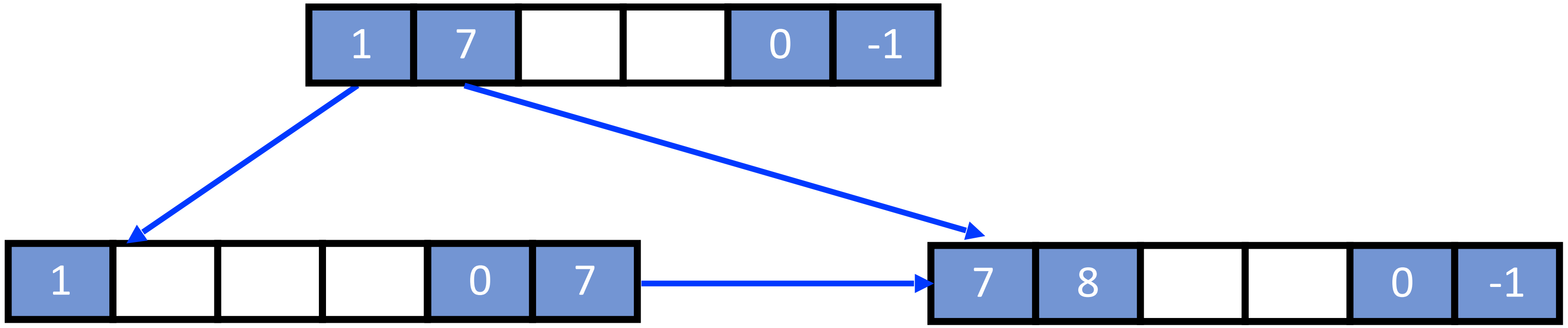
# Challenges with GPU data structures

5. Semantics
    - Meaningful results of concurrent operations
        - We achieve linearizability using snapshots

# Challenges with GPU data structures

5. Semantics
    - Meaningful results of concurrent operations
        - We achieve linearizability using snapshots

Global timestamp = 0




-1 = nullptr

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# Challenges with GPU data structures

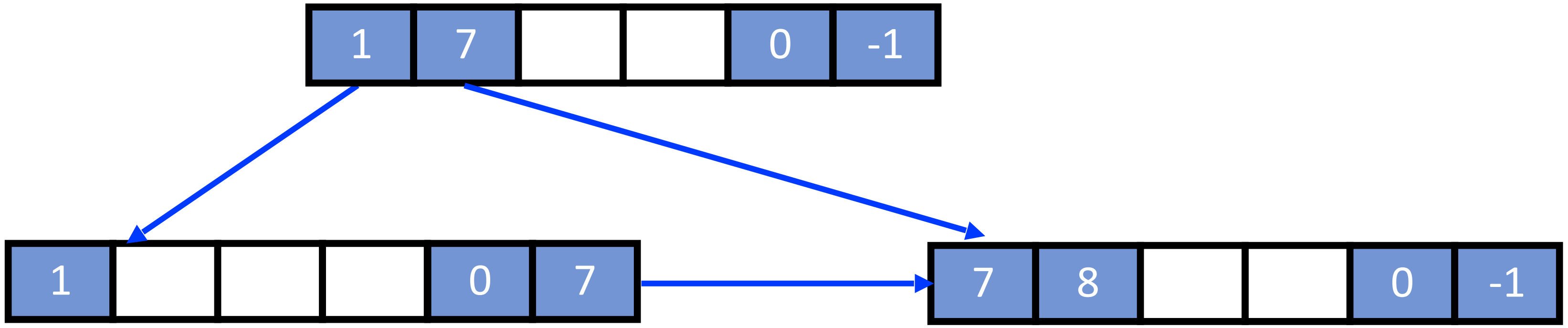
## 5. Semantics

- Meaningful results of concurrent operations
  - We achieve linearizability using snapshots

Thread performing query

```
auto timestamp = btree.take_snapshot();
```

Global timestamp = 0




-1 = nullptr

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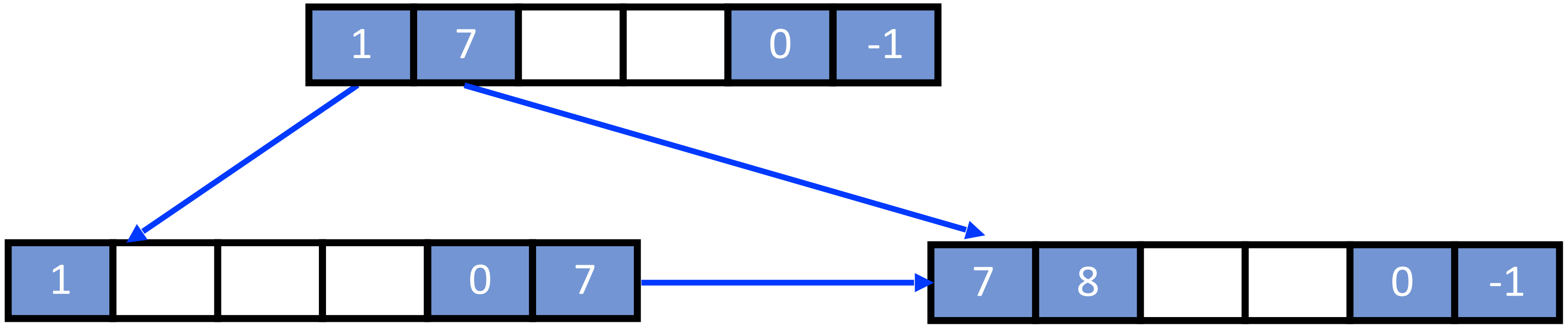
# Challenges with GPU data structures

5. Semantics
    - Meaningful results of concurrent operations
        - We achieve linearizability using snapshots

Thread performing query

```
auto timestamp = btree.take_snapshot();
```

Global timestamp = 1




-1 = nullptr

# Challenges with GPU data structures

## 5. Semantics

- Meaningful results of concurrent operations
  - We achieve linearizability using snapshots

Thread performing query

```
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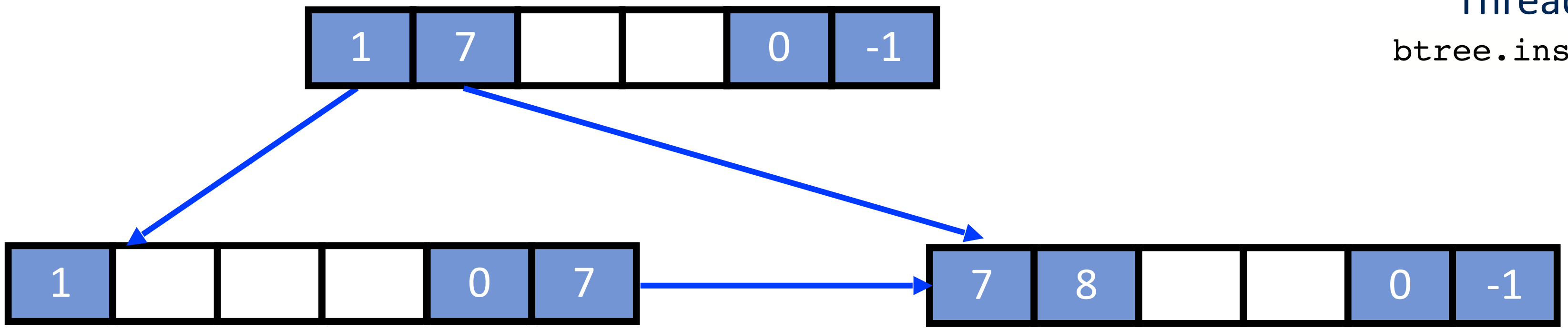


Thread performing insertion

```
btree.insert({5});
```

-1 = nullptr

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# Challenges with GPU data structures

5. Semantics
   - Meaningful results of concurrent operations
     - We achieve linearizability using snapshots

Thread performing query

```
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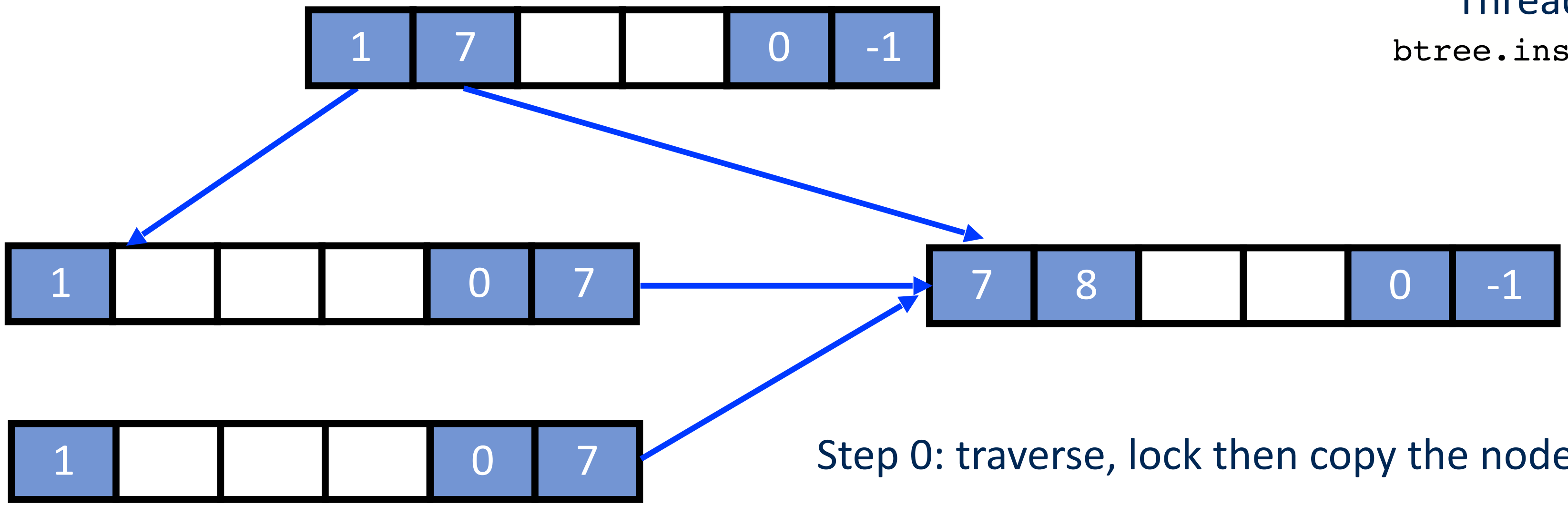


Thread performing insertion

```
btree.insert({5});
```

-1 = nullptr

Step 0: traverse, lock then copy the node

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# Challenges with GPU data structures

## 5. Semantics

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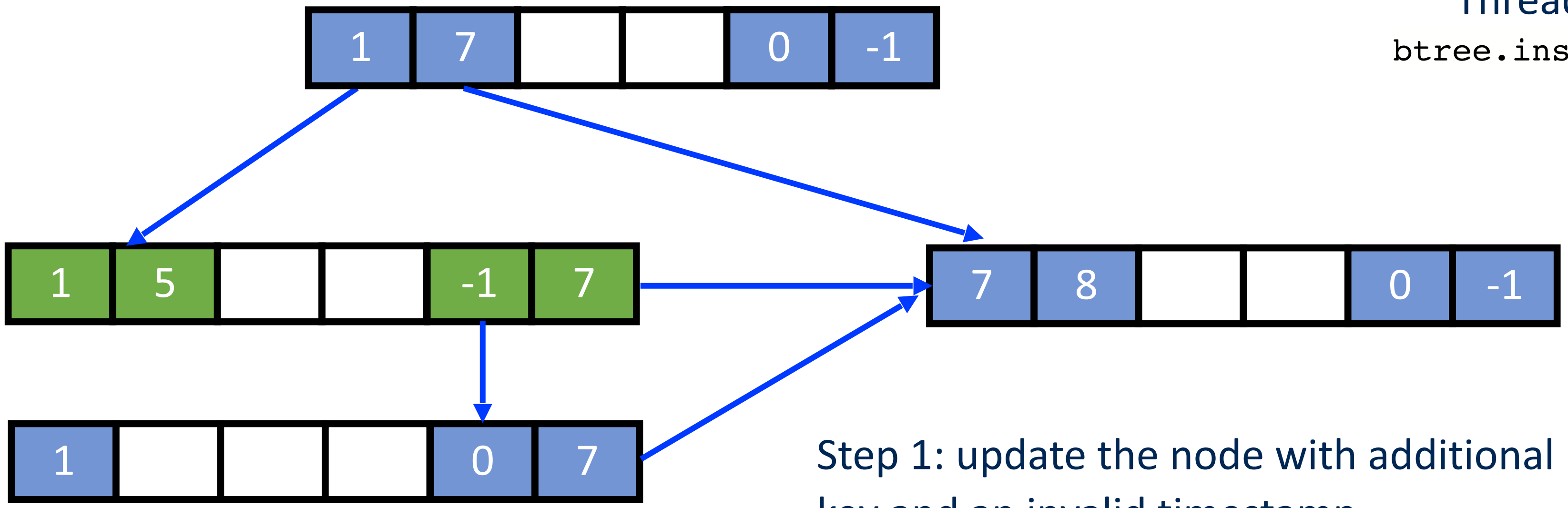


Thread performing insertion

```
btree.insert({5});
```

-1 = nullptr

Step 1: update the node with additional key and an invalid timestamp
(Node is still locked)

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# Challenges with GPU data structures

## 5. Semantics

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Thread performing query

```
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```

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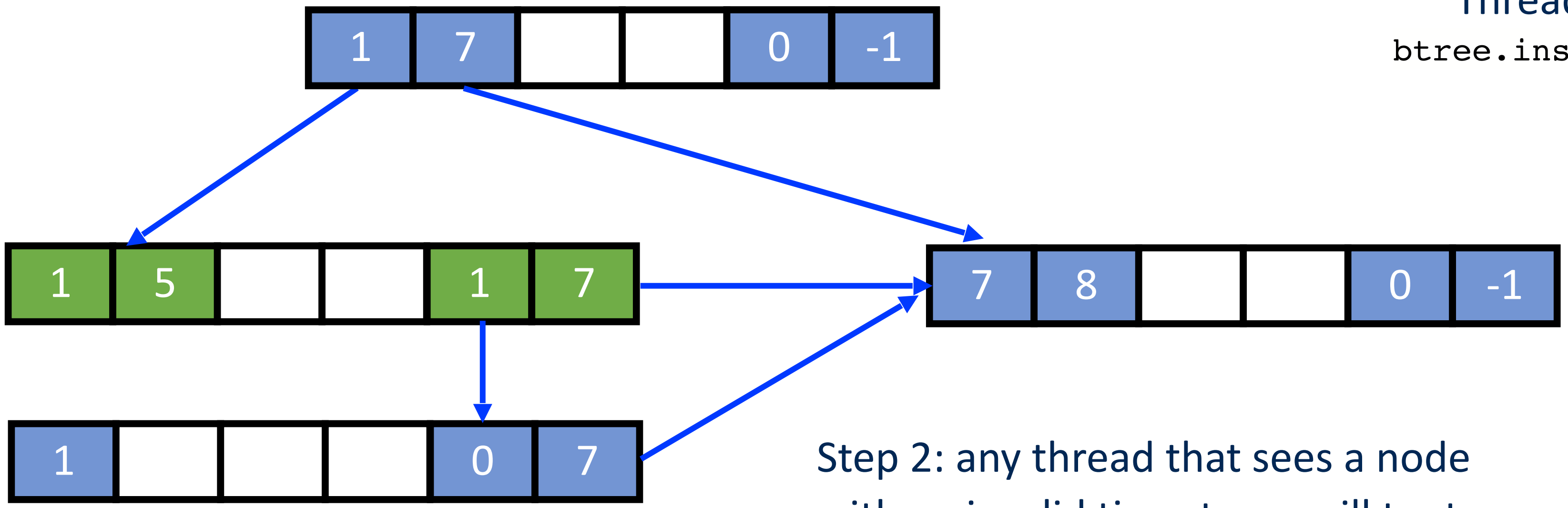



Thread performing insertion

```
btree.insert({5});
```

-1 = nullptr

Step 2: any thread that sees a node with an invalid timestamp will try to set the timestamp with the most recent one

# Challenges with GPU data structures

## 5. Semantics

- Meaningful results of concurrent operations
  - We achieve linearizability using snapshots

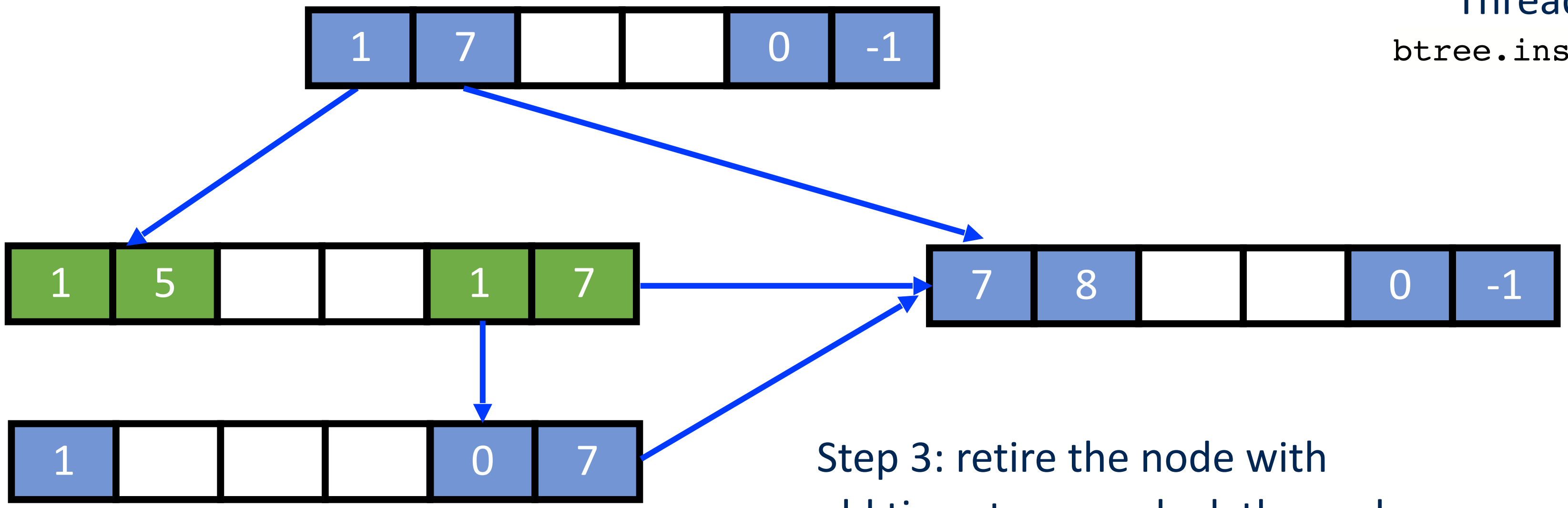
Thread performing query

```
auto timestamp = btree.take_snapshot();
```

Global timestamp = 1

Thread performing insertion

```
btree.insert({5});
```




-1 = nullptr

Step 3: retire the node with
old timestamp, unlock the node

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# Challenges with GPU data structures

5. Semantics
   - Meaningful results of concurrent operations
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```
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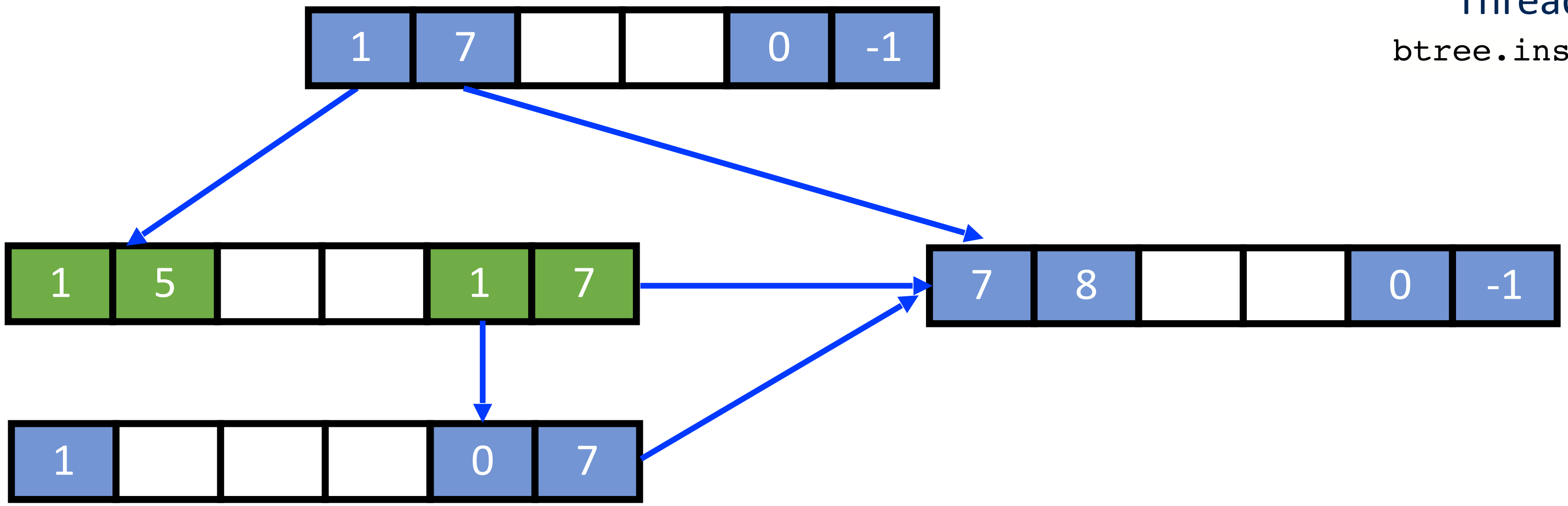


Thread performing insertion

```
btree.insert({5});
```

-1 = nullptr

Snapshot algorithm based on:
*Wei et al., Constant-Time Snapshots with Applications to Concurrent Data Structures*

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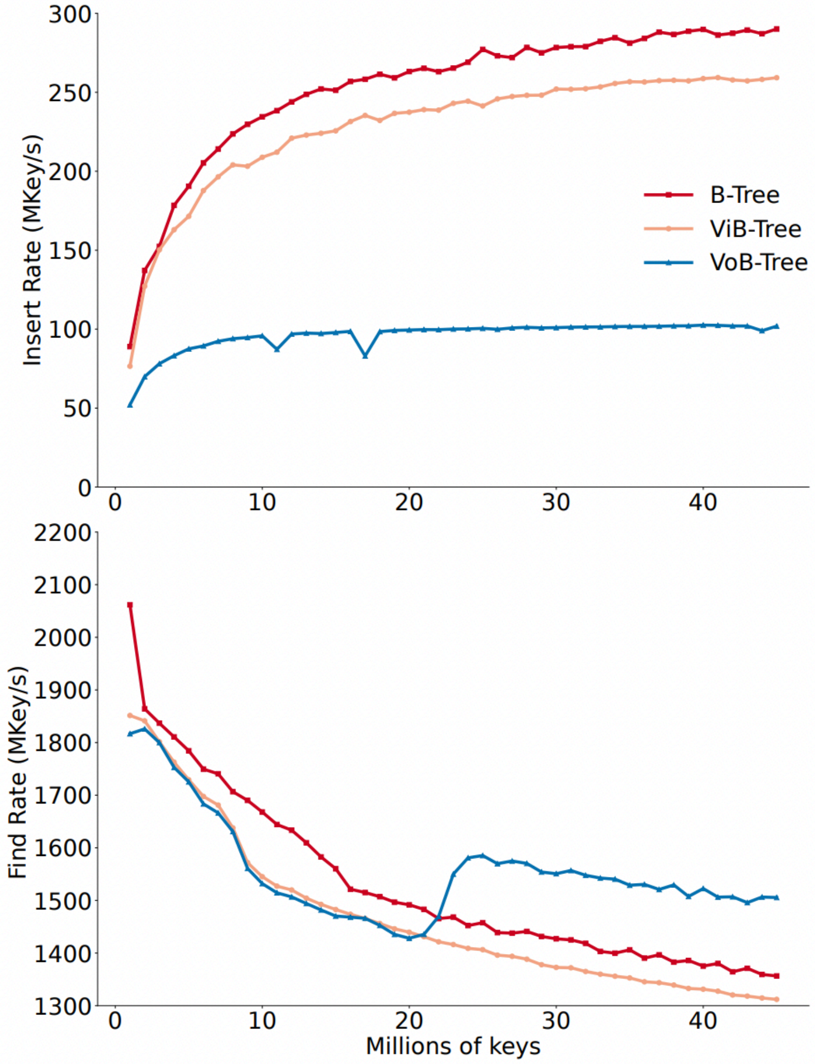
# Results

# Results: Versioning overhead

- Insertion and find rates
  - B-Tree
    - Baseline that is not linearizable
  - ViB-Tree
    - Multiversion B-Tree
      - Only perform in-place updates
  - VoB-Tree
    - Multiversion B-Tree
      - Only perform out-of-place updates




Using Tesla V100 PCIe (Volta architecture) GPU with 32 GB DRAM

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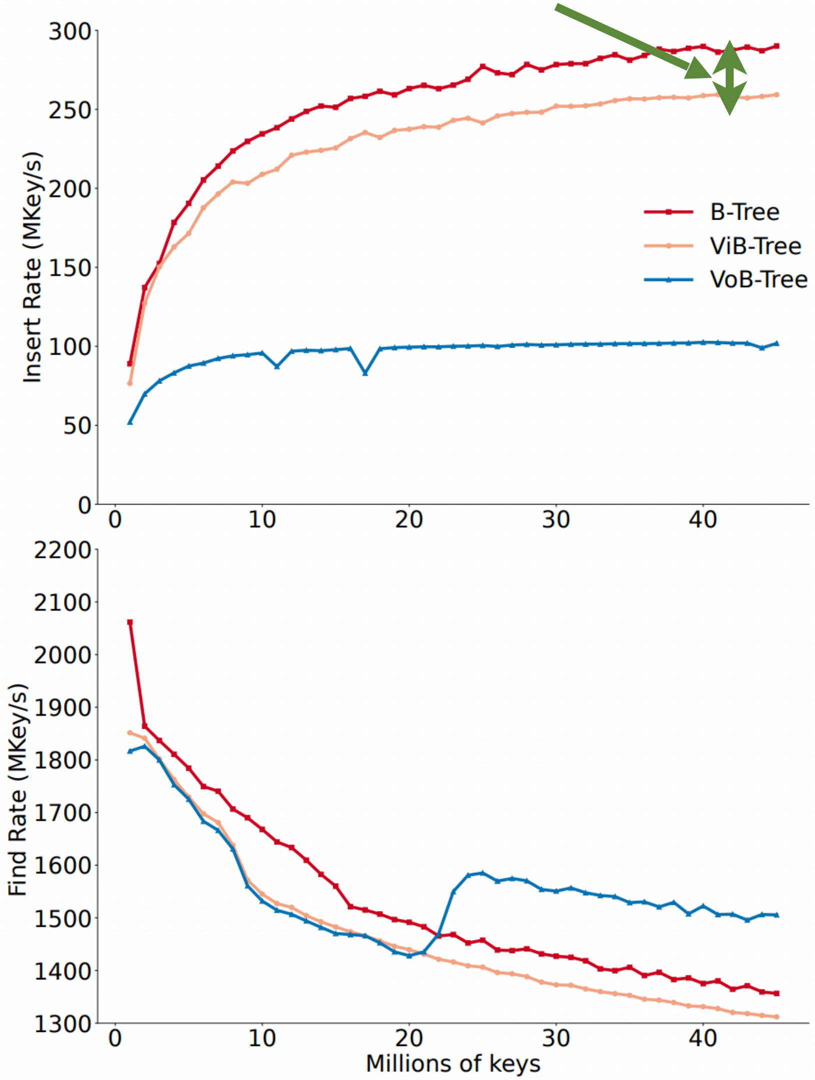
Low overhead when all updates are in-place

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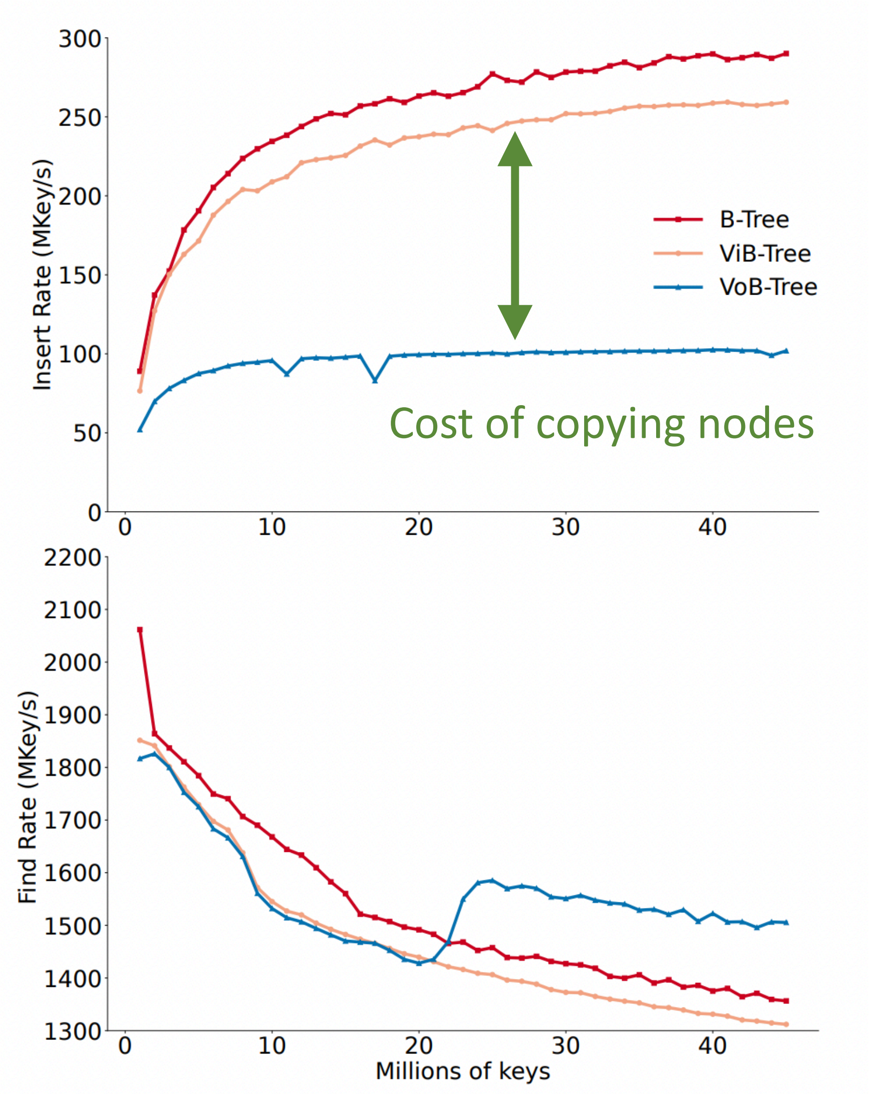


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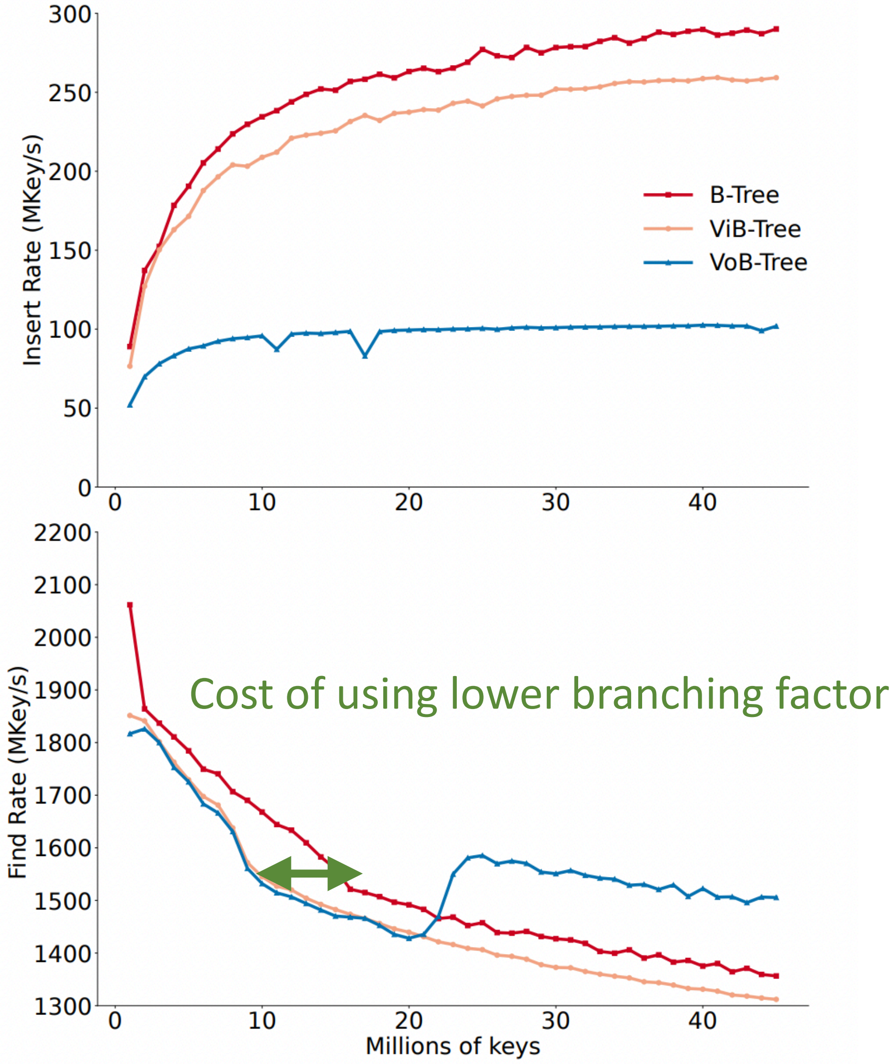


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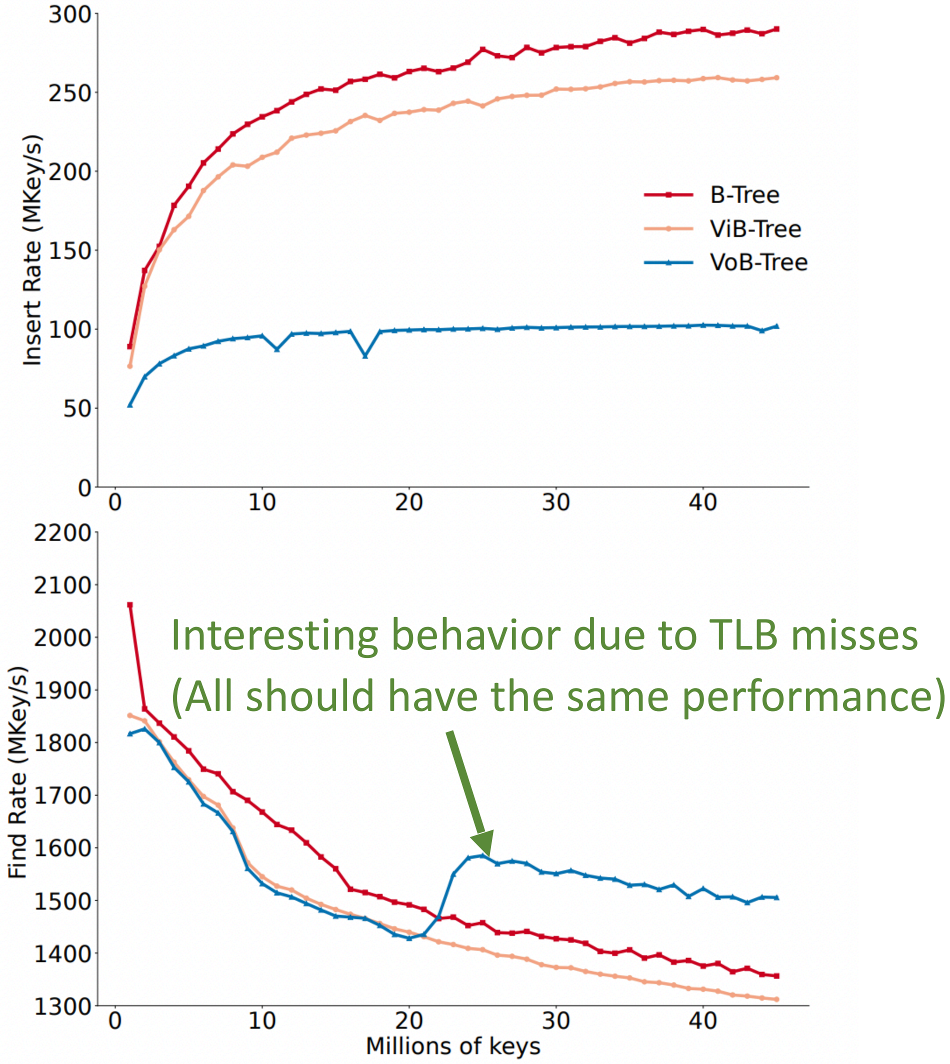


Using Tesla V100 PCIe (Volta architecture) GPU with 32 GB DRAM

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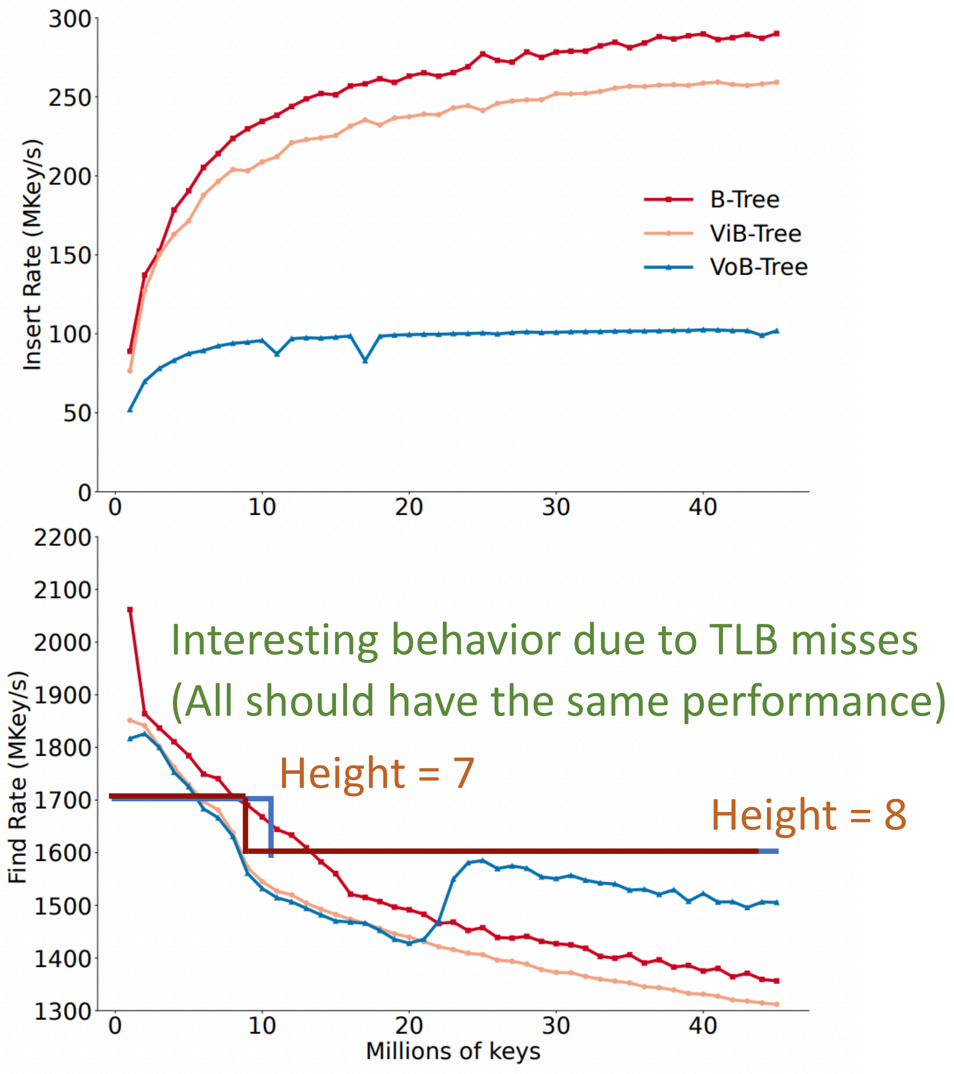


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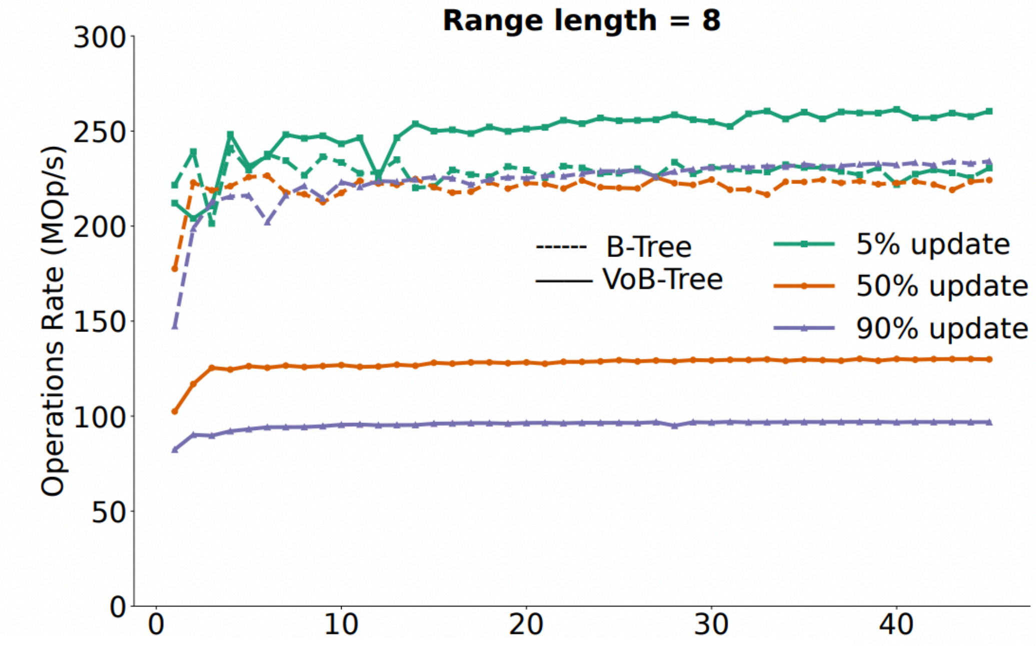
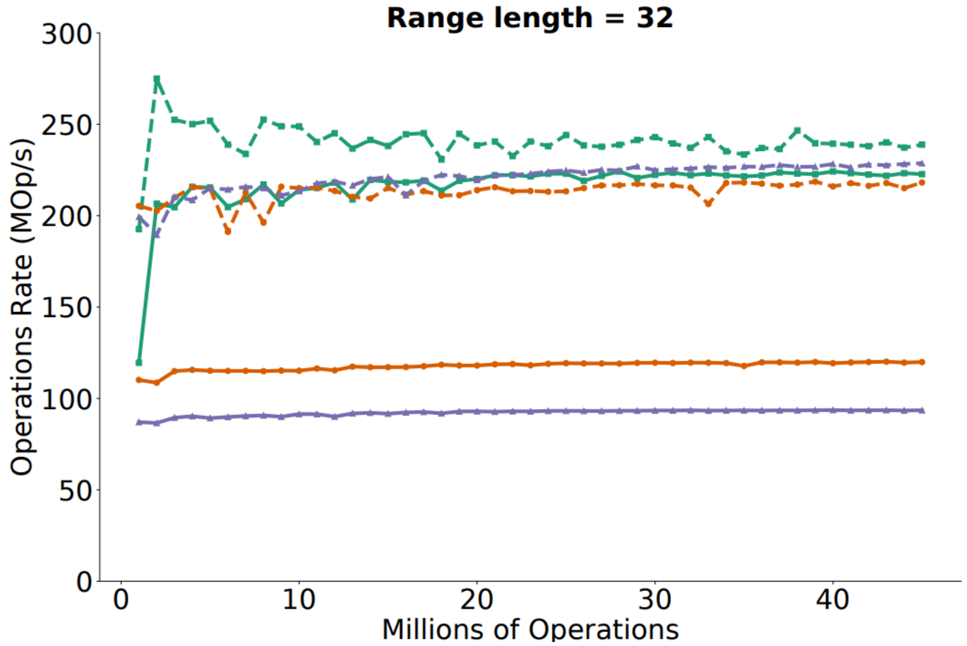
# Results: Linearizable multipoint queries

- Concurrent insertion and range query operations



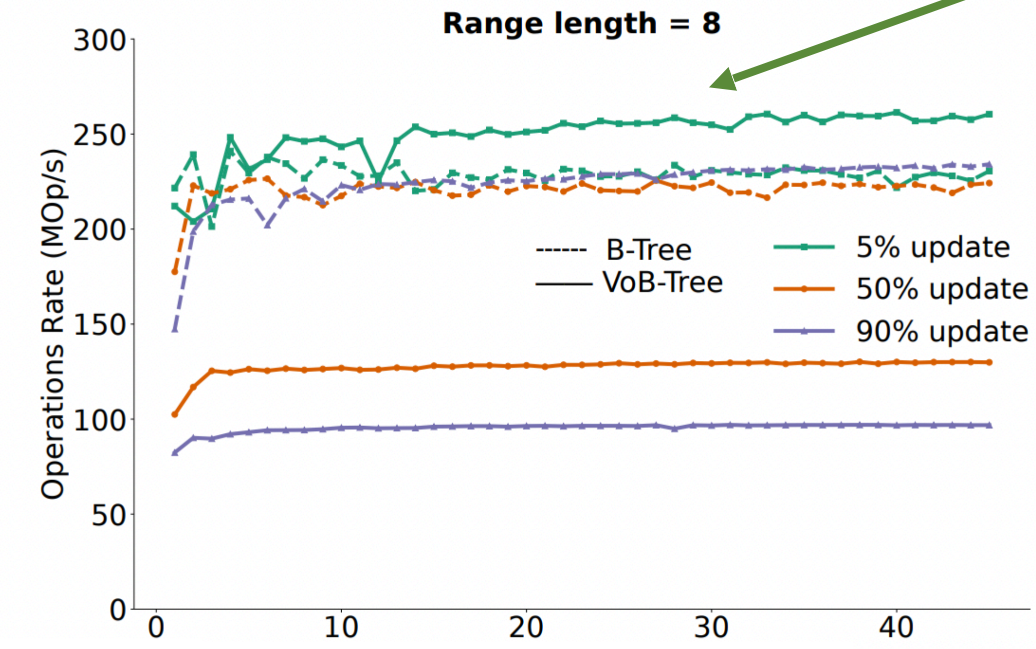

**Initial tree size of 40M.**

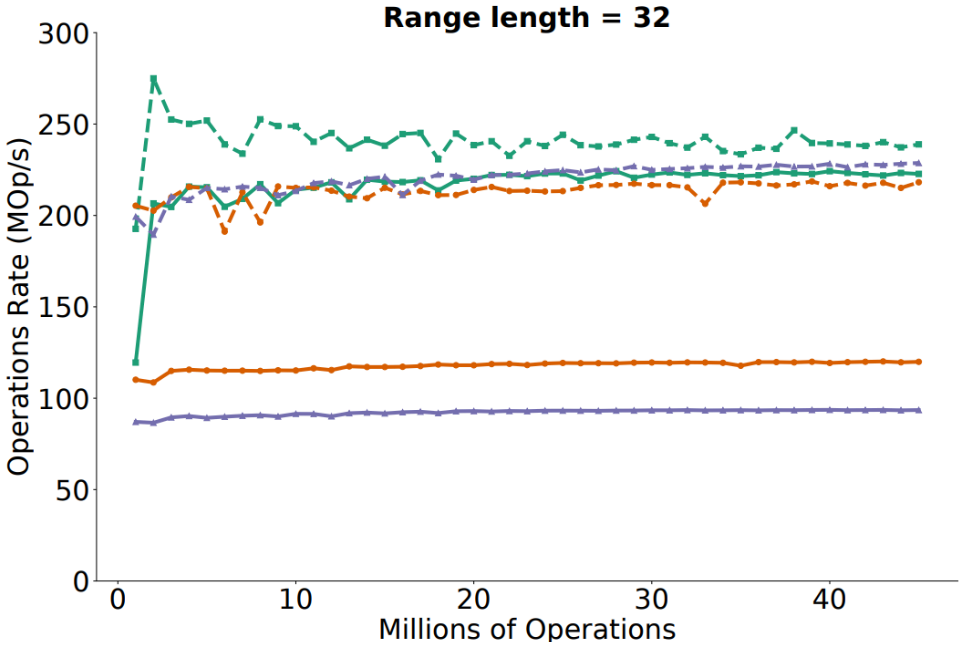
Using Tesla V100 PCIe (Volta architecture) GPU with 32 GB DRAM

# Results: Linearizable multipoint queries

- Concurrent insertion and range query operations

Interestingly, our VoB-Tree is faster than the baseline

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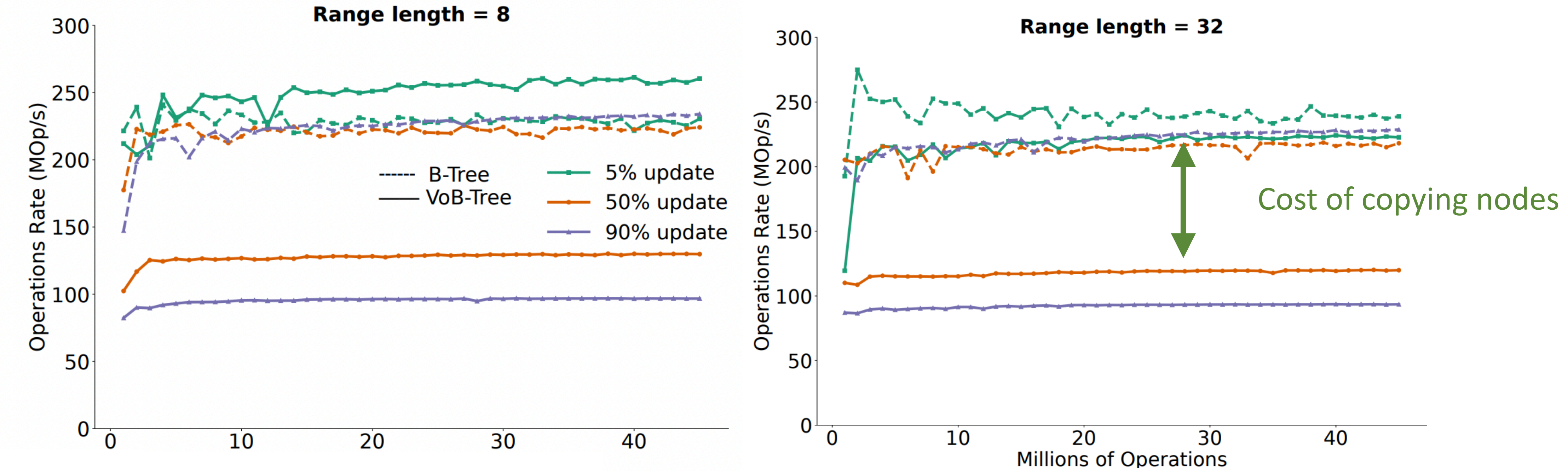


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Using Tesla V100 PCIe (Volta architecture) GPU with 32 GB DRAM

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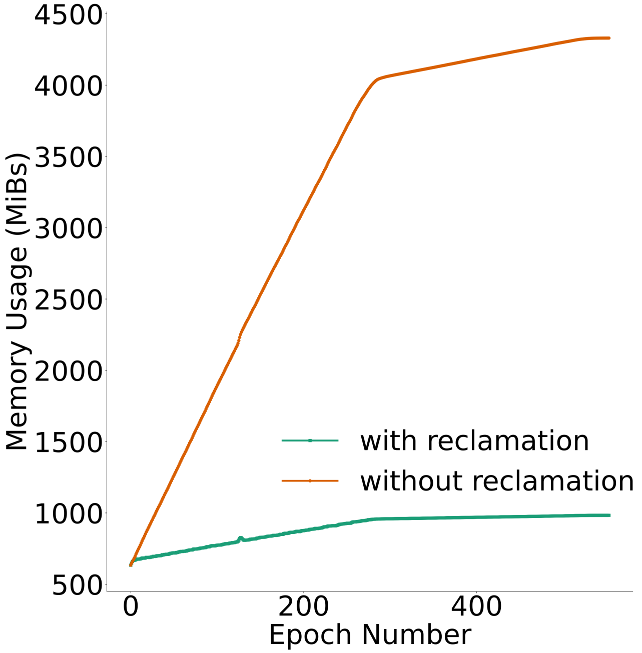
# Results

- Safe memory reclamation




Using Tesla V100 PCIe (Volta architecture) GPU with 32 GB DRAM

Block-wide EBR performance

45 million insertion and range query operations
50% update ratio, and average range length of 16

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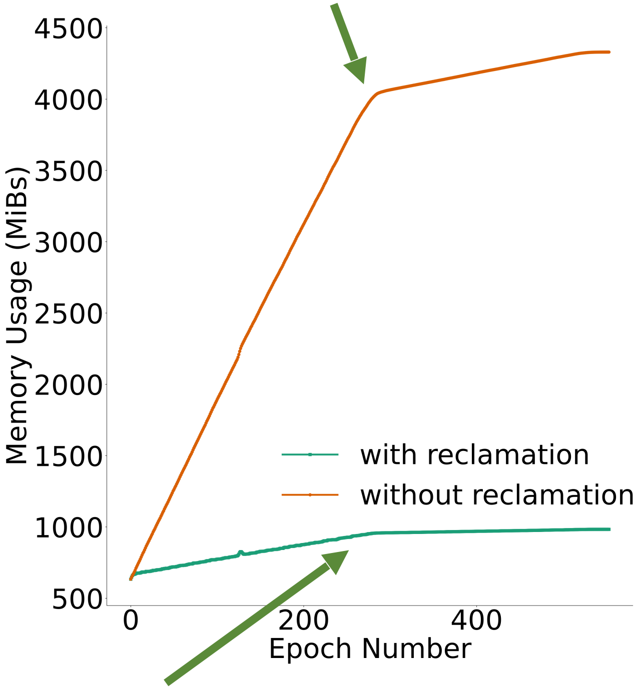
# Results

- Safe memory reclamation

Blocks performing insertion start to exit

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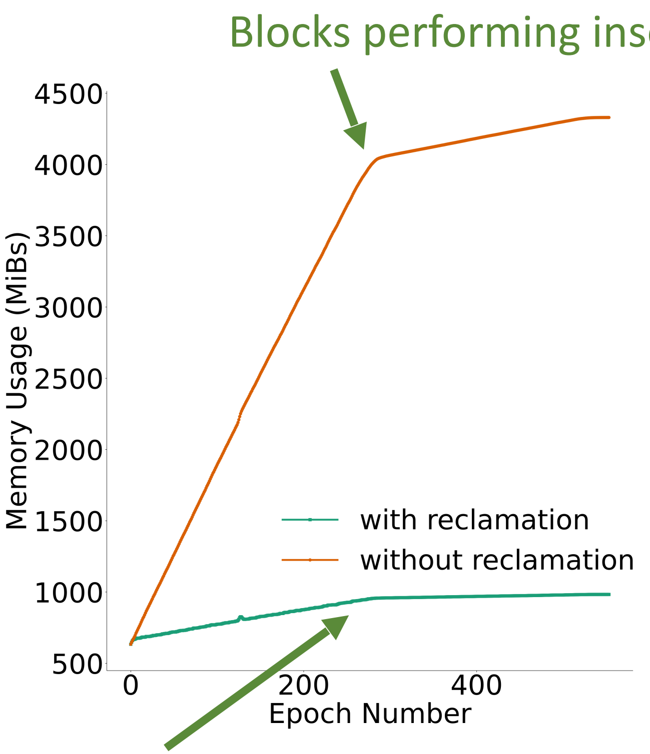
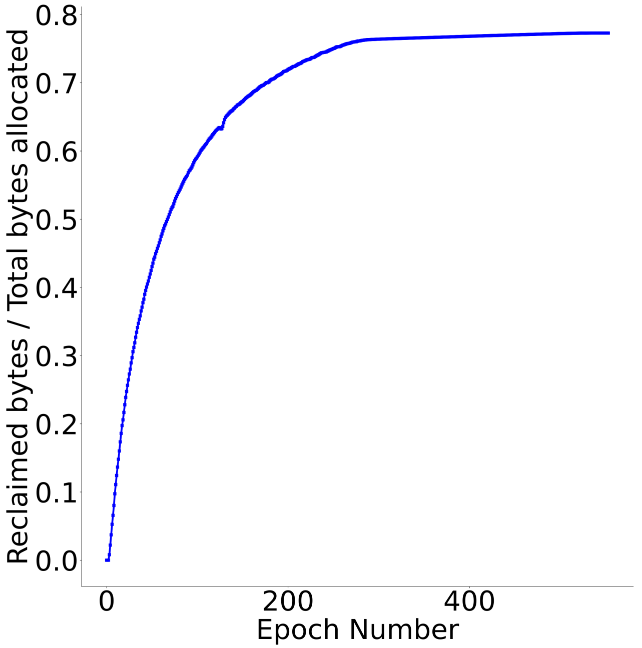
- Safe memory reclamation

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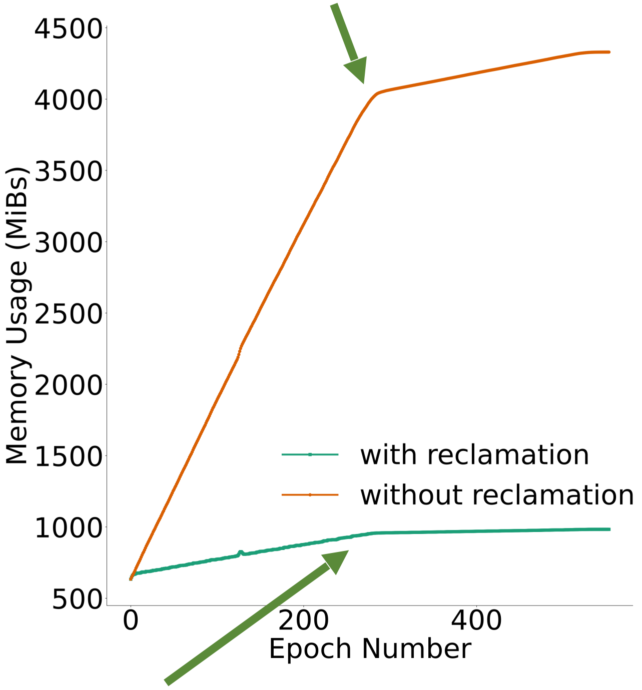
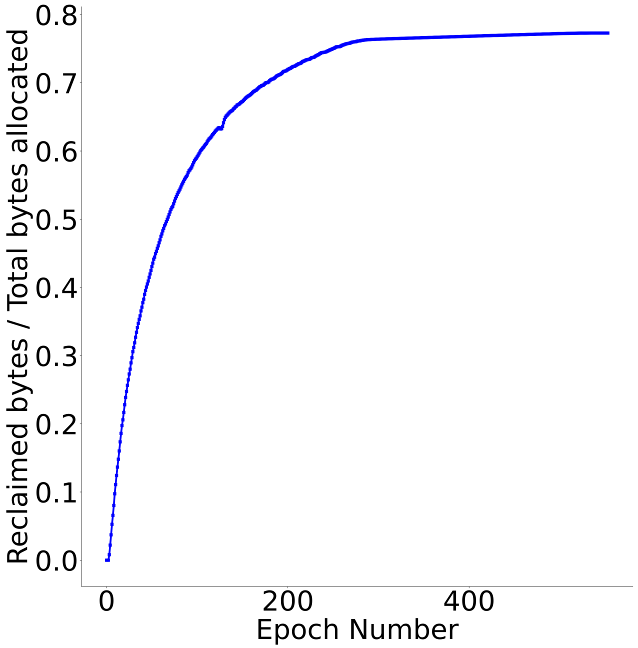
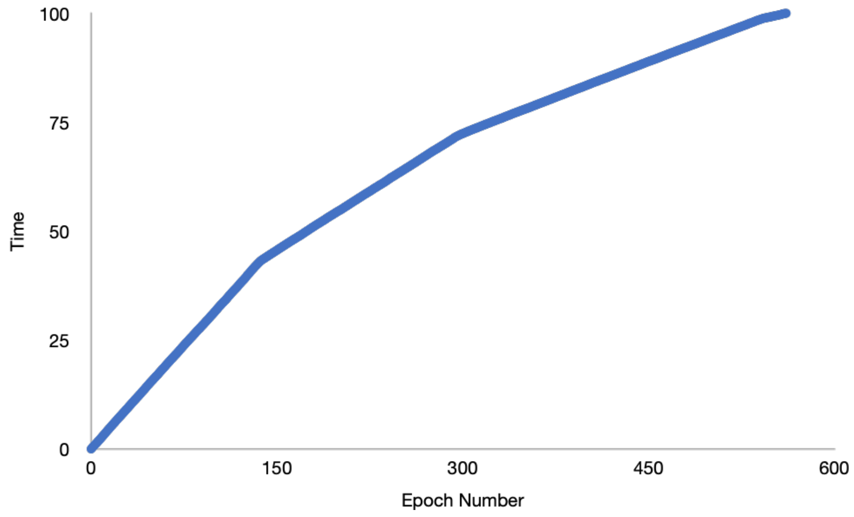



Epoch is not time

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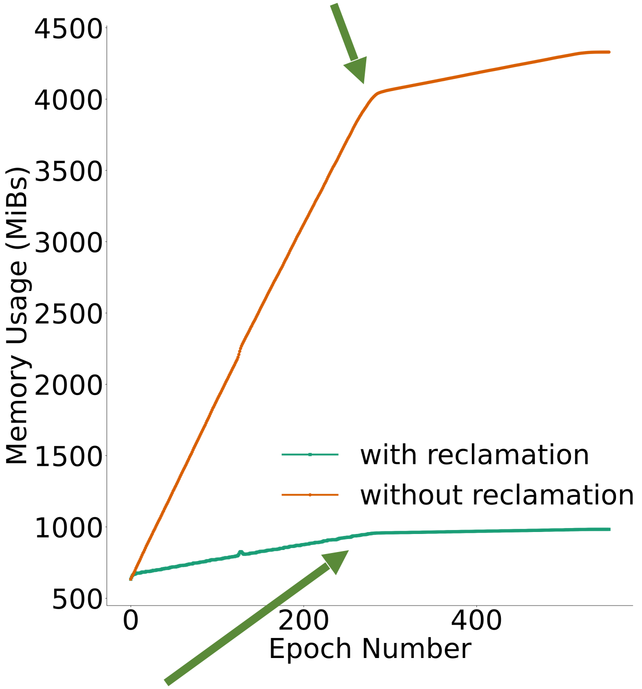


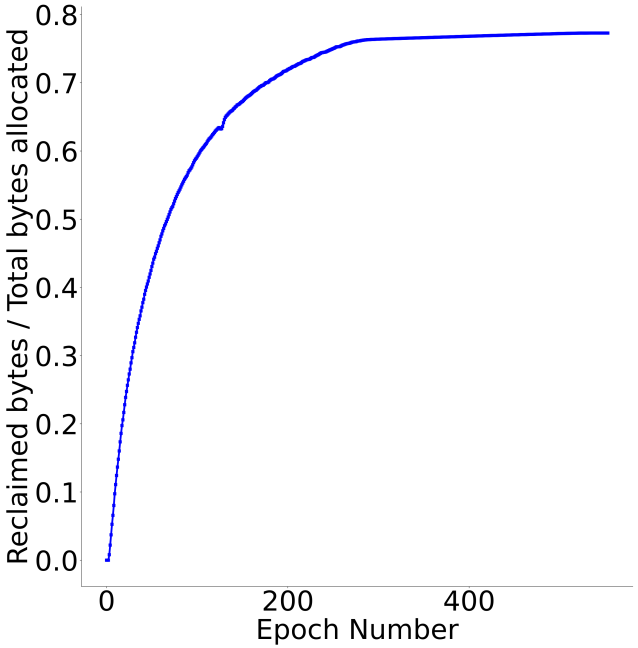


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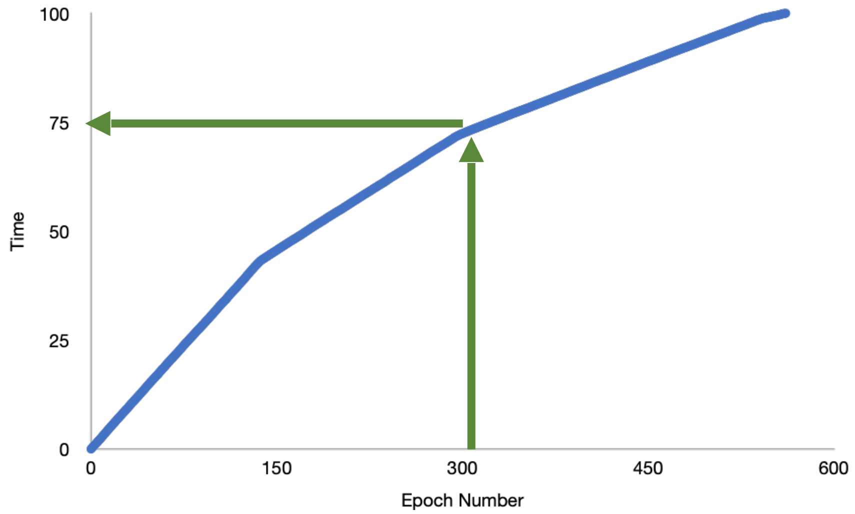


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# **Our solutions** to the Multiversion GPU B-Tree challenges

1. Memory access patterns during traversal
   - Data structure layout in memory
     - ***Use cache-line-sized nodes and cooperative processing***
2. Contention during updates
   - Atomics and locks
     - ***Relax data structure invariants, avoid spin locks, and use restarts***
3. Memory allocation and reclamation
   - When can we free a pointer?
     - ***Use block-wide epoch-based reclamation***
4. Abstractions
   - Defining APIs for GPU data structures
     - ***Define APIs at the lowest efficient level (e.g., tile)***
5. Semantics
   - Meaningful results of concurrent operations
     - ***Achieve linearizability using (scoped) snapshots***

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# Summary and future research directions

**Summary**

- Our data structure supports snapshots with **minimal overhead** in point queries (1.04× slower) and insertions (1.11× slower) compared to baseline
- **Similar** performance for read-heavy workloads and **2.39× slower** for write-heavy workloads

**Future research directions**

- Wait-free data structure
  - **Helping** algorithms
- Multiversion GPU graph data structure
  - **Composed** from per-vertex multiversion B-Tree
- Exploration of various safe memory reclamation techniques

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# Thank you!

## Other GPU data structures work:

"Better GPU Hash Tables", *APOCS 2023*.
https://github.com/owensgroup/BGHT
"Engineering a High-Performance GPU B-Tree", *PPoPP 2019.*
https://github.com/owensgroup/GpuBTree
"Dynamic Graphs on the GPU", *IPDPS 2020.*
https://github.com/gunrock/gunrock
"A GPU Multiversion B-Tree", *PACT 2022.*
https://github.com/owensgroup/MVGpuBTree
"Fully Concurrent GPU Data Structures", *Ph.D. dissertation, UC Davis, 2022.*
https://escholarship.org/uc/item/5kc834wm

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