Practical Hardware Transactional vEB Trees

PPoPP'24

Mohammad Khalaji [1] Trevor Brown[1] Khuzaima Daudjee[1] Vitaly Aksenov[2]

1

2

Introduction

Sets and Maps

DS	Look-up	Insert	Delete	Predecessor	Successor
Hash Table	$O(1)$	$O(1)$	$O(1)$	$\boldsymbol{O(N)}$	$\boldsymbol{O(N)}$
BST	$O(\lg N)$	$O(\lg N)$	$O(\lg N)$	$\boldsymbol{O(\lg N)}$	$\boldsymbol{O(\lg N)}$
B-Tree	$O(\log_B N)$	$O(\log_B N)$	$O(\log_B N)$	$\boldsymbol{O(\log_B N)}$	$\boldsymbol{O(\log_B N)}$

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B-Tree	$O(\log_B N)$	$O(\log_B N)$	$O(\log_B N)$	$\boldsymbol{O(\log_B N)}$	$\boldsymbol{O(\log_B N)}$
vEB Tree	$O(\lg \lg u)$	$O(\lg \lg u)$	$O(\lg \lg u)$	$\boldsymbol{O(\lg \lg u)}$	$\boldsymbol{O(\lg \lg u)}$

Sets and Maps

DS	Look-up	Insert	Delete	Predecessor	Successor
Hash Table	$O(1)$	$O(1)$	$O(1)$	$\boldsymbol{O(N)}$	$\boldsymbol{O(N)}$
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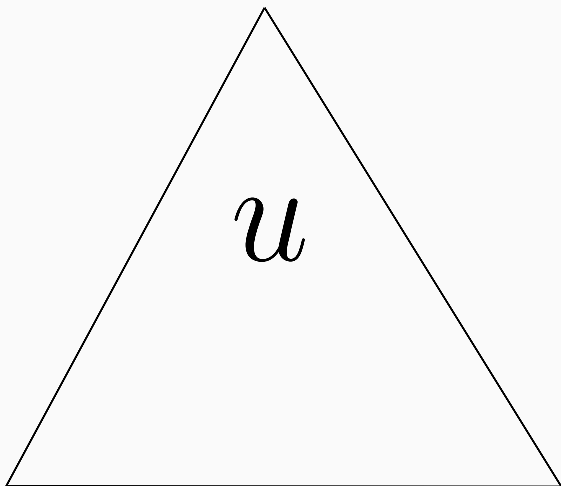
B-Tree	$O(\log_B N)$	$O(\log_B N)$	$O(\log_B N)$	$\boldsymbol{O(\log_B N)}$	$\boldsymbol{O(\log_B N)}$
vEB Tree	$O(\lg \lg u)$	$O(\lg \lg u)$	$O(\lg \lg u)$	$\boldsymbol{O(\lg \lg u)}$	$\boldsymbol{O(\lg \lg u)}$

u	$\lg \lg u$
65K	4
1M	4.3
1B	4.9
1T	5.3

vEB Trees

- Introduced in 1977 by Peter van Emde Boas [4]
- Fixed universe size $u = 2^{\lg u}$: $\{0, \ldots, u-1\}$ $\rightarrow \lg u$ bit keys
- $O(\lg \lg u)$ complexity for all operations

vEB Tree Structure



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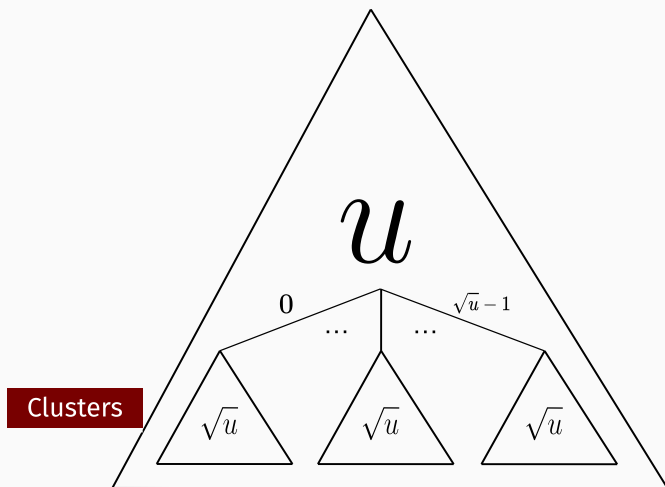

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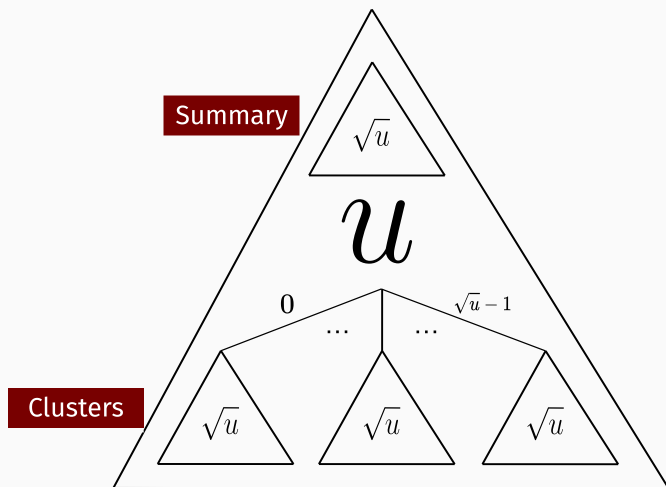
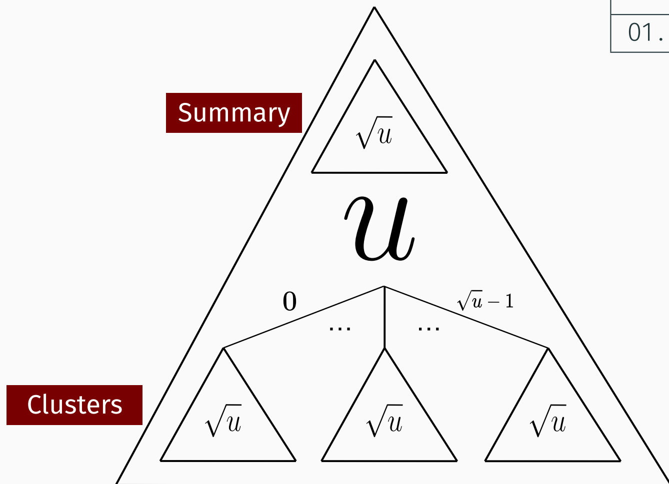


vEB Insert Example

$\lg u$ bits
01 10



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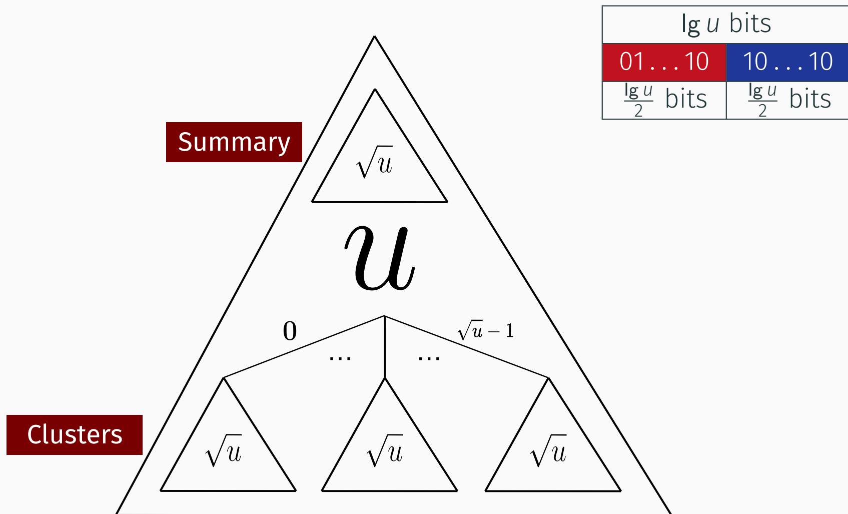

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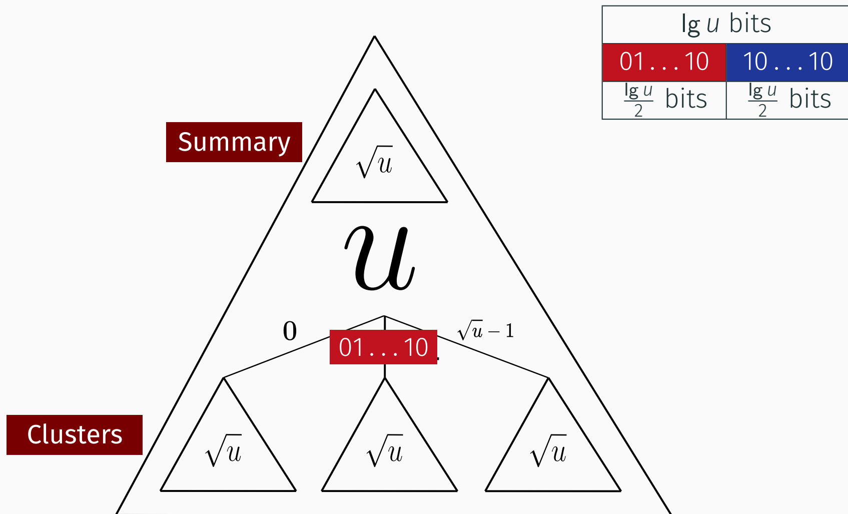

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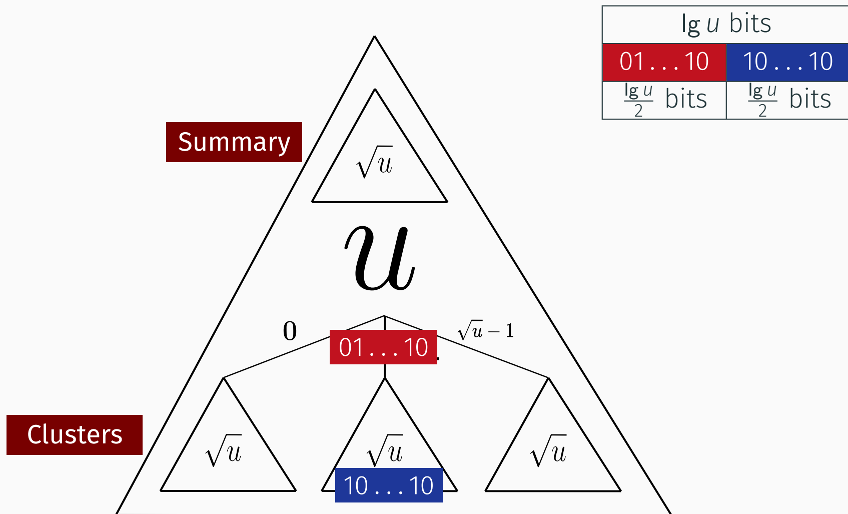

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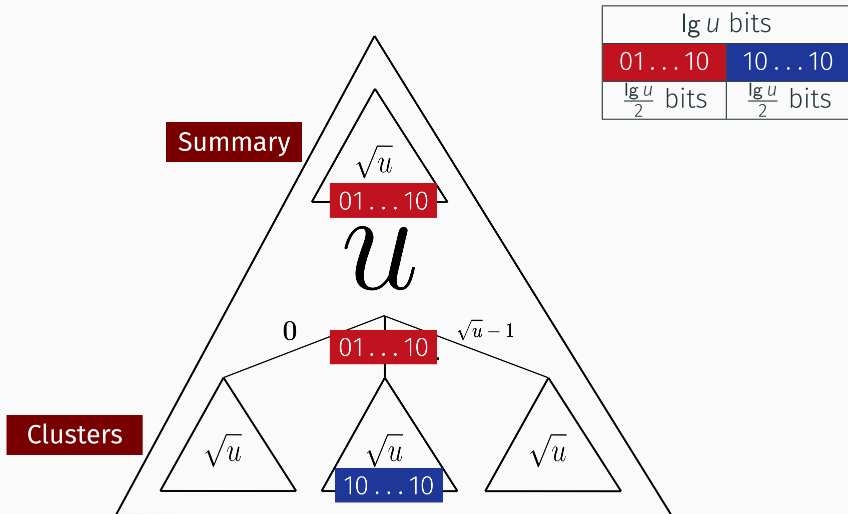

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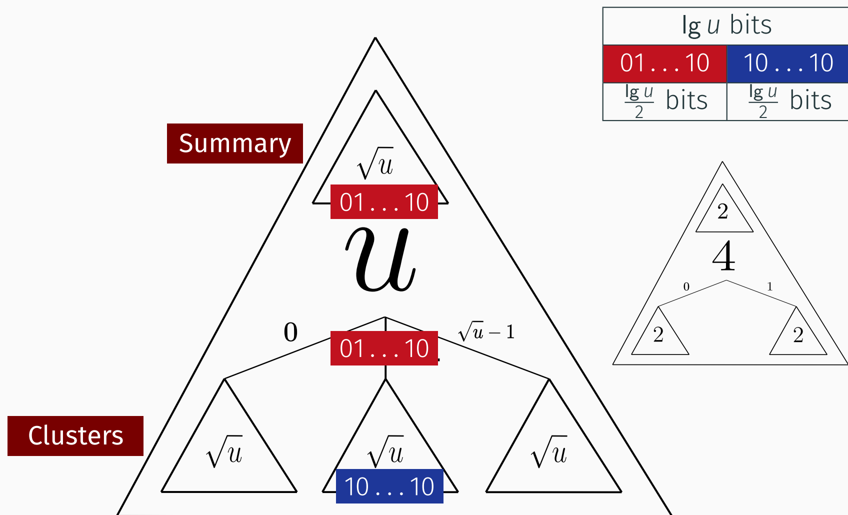

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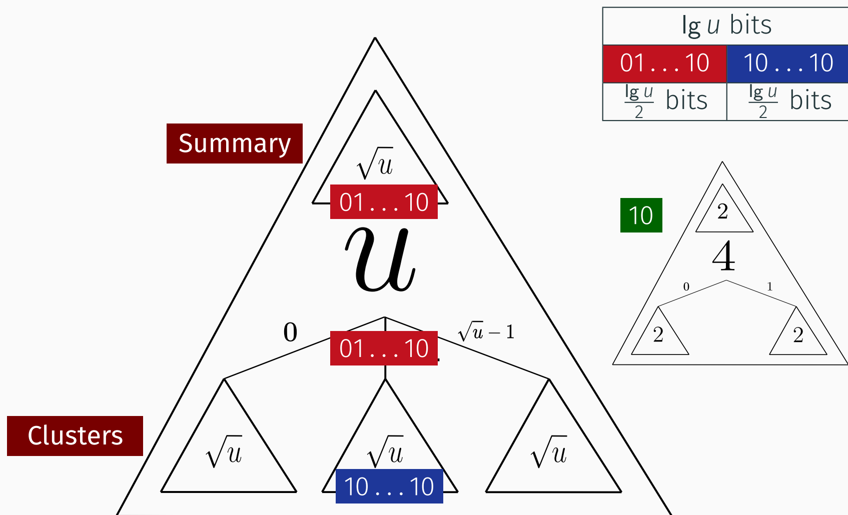

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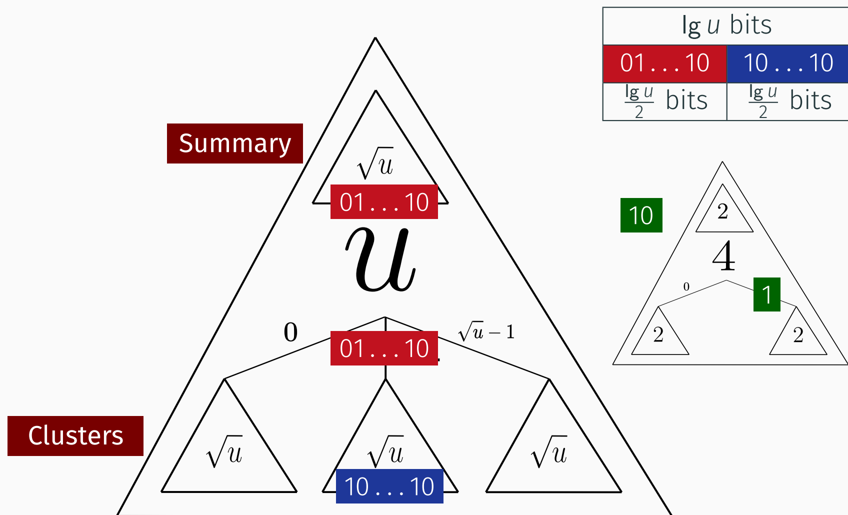

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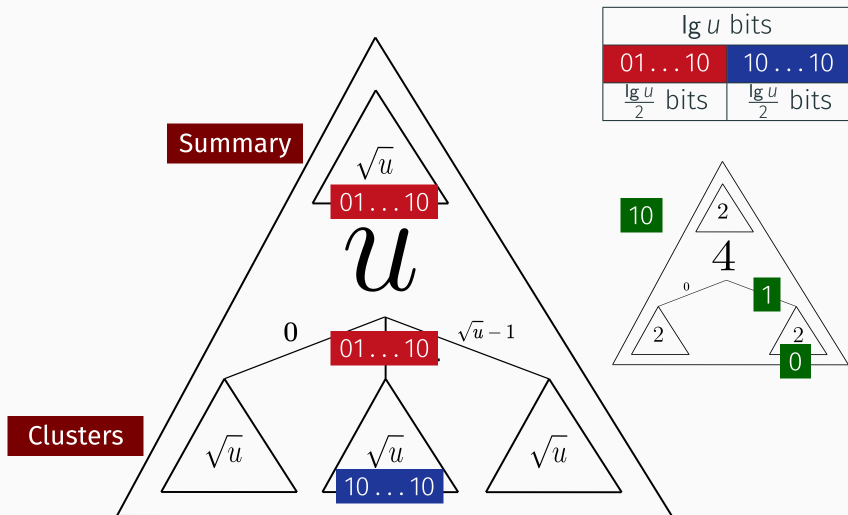

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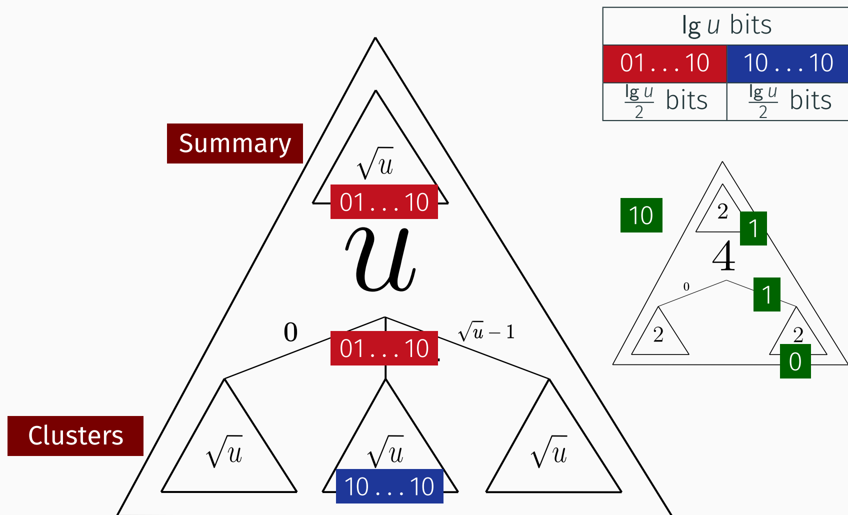

Hardware Transactional Memory (HTM)

- Atomic blocks of code
    - Take effect as a single indivisible unit (Commit)
    - Or rolled back with no effect on shared memory (Abort)
- Hardware level →Efficient

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}
else {
    Fallback code...
}
```

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Transactional Lock Elision (TLE)

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```
if (_xbegin() == _XBEGIN_STARTED) {

    Transaction body...

    _xend();
}
```

Fast Path

Transactional Lock Elision (TLE)

Fast Path

Fallback Path

```
if (_xbegin() == _XBEGIN_STARTED) {

    Transaction body...

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else {
    lock();
    Transaction body...
    unlock();
}
```

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Transactional Lock Elision (TLE)

Fast Path

Fallback Path

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if (_xbegin() == _XBEGIN_STARTED) {
    if lock is already held
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Transactional Lock Elision (TLE)

Fast Path

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if (_xbegin() == _XBEGIN_STARTED) {
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    Transaction body... ← T2

    _xend();
}
else {
    lock(); ← T1
    Transaction body...
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    lock();
    Transaction body... ← T1
    unlock();
}
```

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Methodology

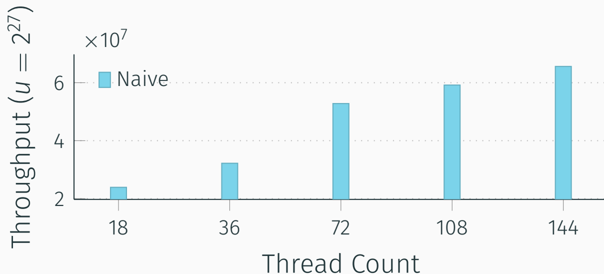
Overview

- Concurrent vEB trees with recursive summaries
- Full support for successor and predecessor queries
- Starting with a naive vEB set implementation
- Use simple building blocks to end up with a performant vEB map

First Step: Naive

Idea

Wrap sequential vEB operations in TLE blocks



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First Step: Naive

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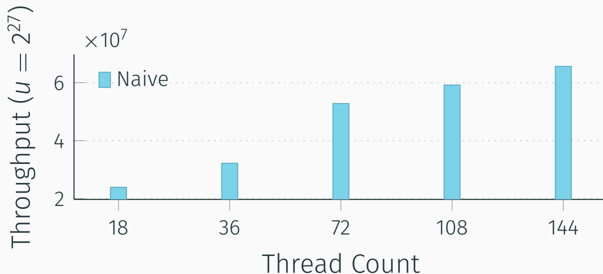

Problem

Memory usage does not depend on the number of keys!

Improve Memory Footprint: Dynamic

Can we save memory?

In the Naive variation, the entire tree is pre-allocated

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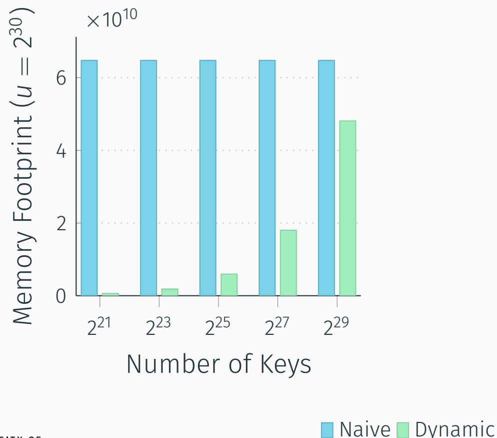

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Improve Memory Footprint: Dynamic

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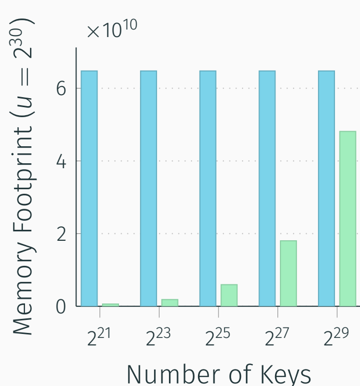

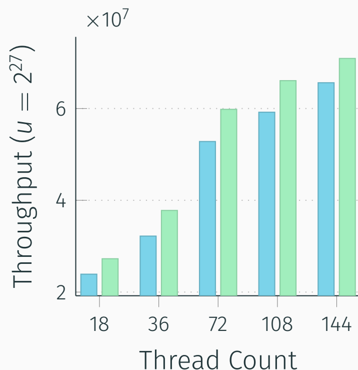

Naive Dynamic

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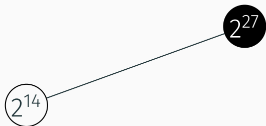
Room For Improvement: Cut-Off

u Data

2^{27}

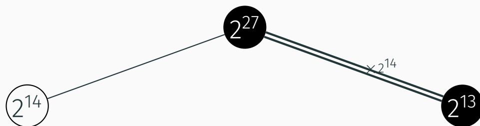
Room For Improvement: Cut-Off



Room For Improvement: Cut-Off

u Data

u Metadata



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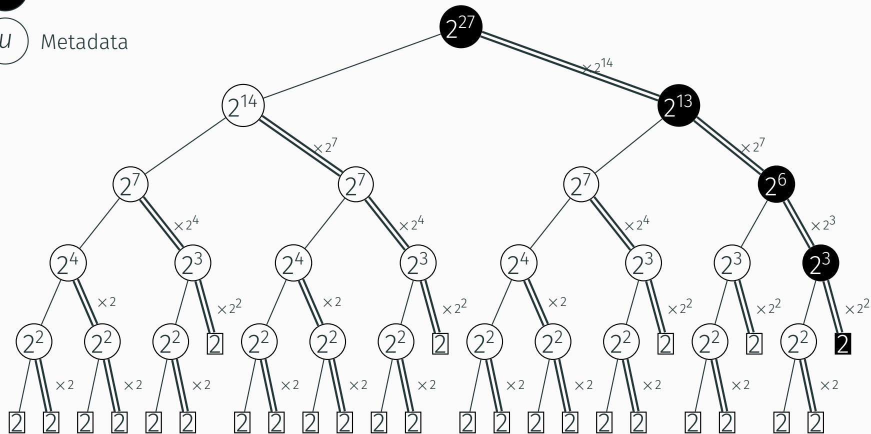

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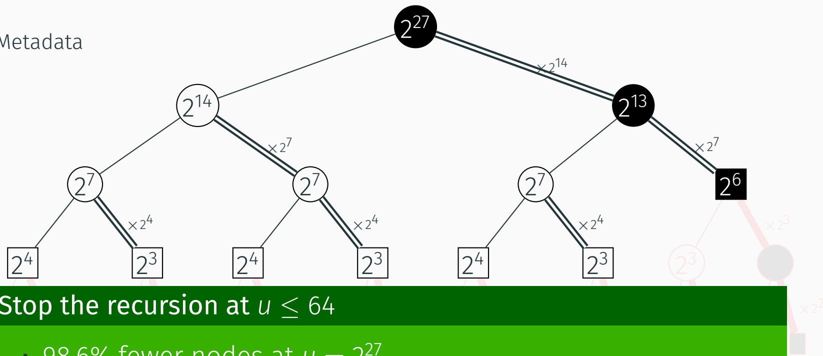
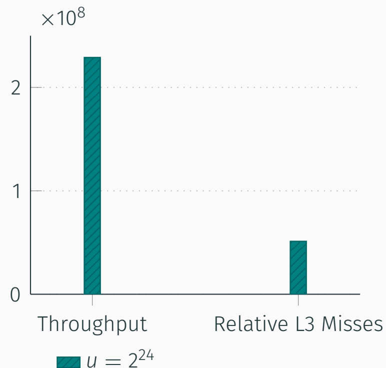
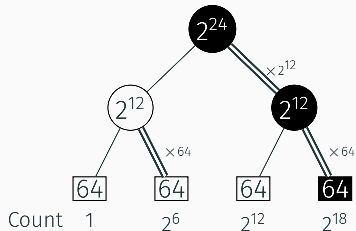


Stop the recursion at $u \leq 64$

- 98.6% fewer nodes at $u = 2^{27}$
- One L3 cache miss vs. 7
- $3\times$ faster
- 75% less memory

Problem with Cut-Off





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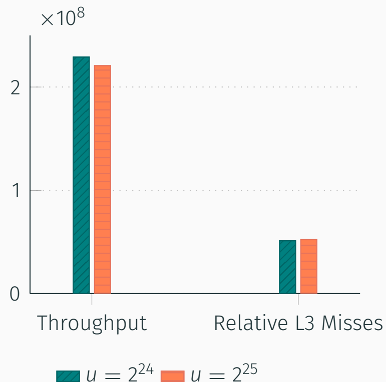

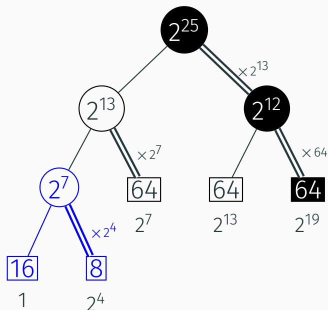

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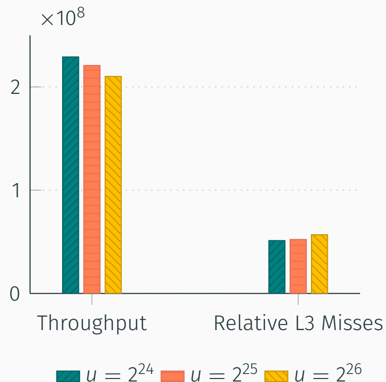
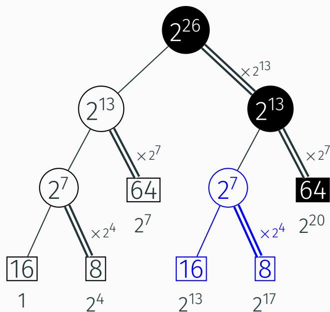
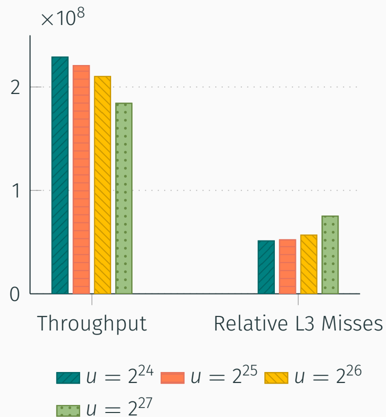
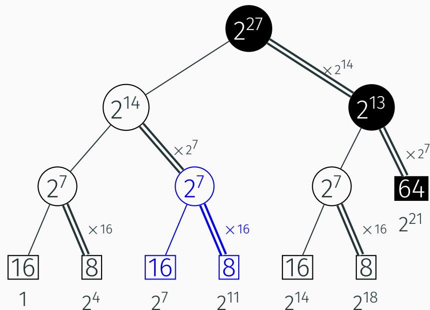
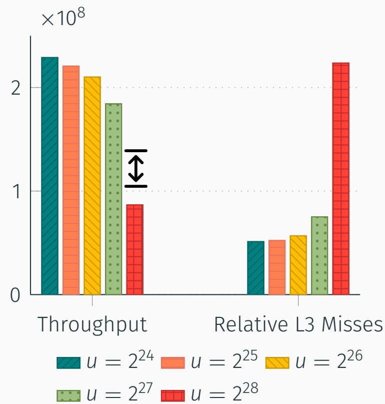





×10^8
2
1
0
Throughput
Relative L3 Misses
u = 2^24
u = 2^25
u = 2^26
u = 2^27


2^27
×2^14
2^14
2^13
×2^7
×2^7
2^7
2^7
2^7
64
2^21
×16
×16
×16
16
8
16
8
16
8
1
2^4
2^7
2^11
2^14
2^18

Problem with Cut-Off



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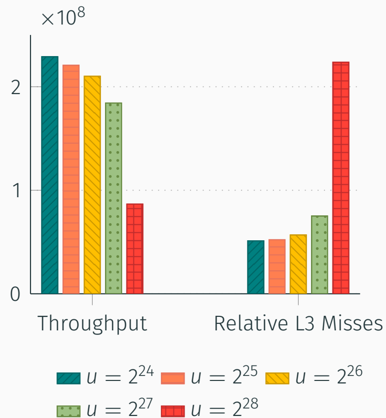
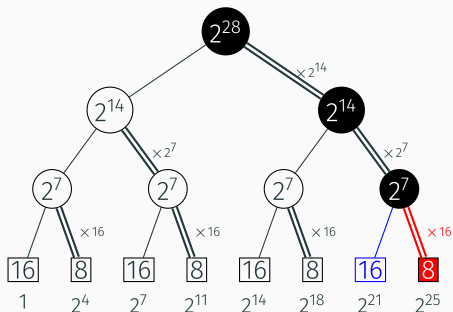
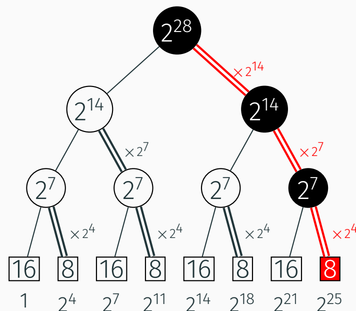




Solution: New-Root

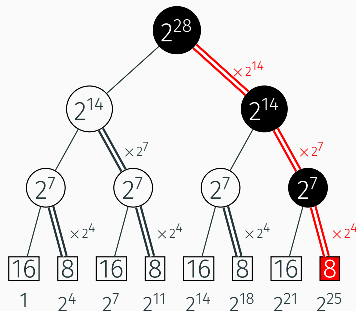
Before

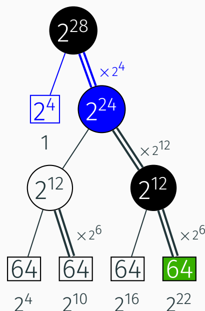


Universe Size	2^{24}	2^{25}	2^{26}	2^{27}	2^{28}	2^{29}
Data Leaf Count	2^{18}	2^{19}	2^{20}	2^{21}	2^{25}	2^{26}
Data Leaf Size	64	64	64	64	8	8

Solution: New-Root

Before	After





Universe Size	2^{24}	2^{25}	2^{26}	2^{27}	2^{28}	2^{29}
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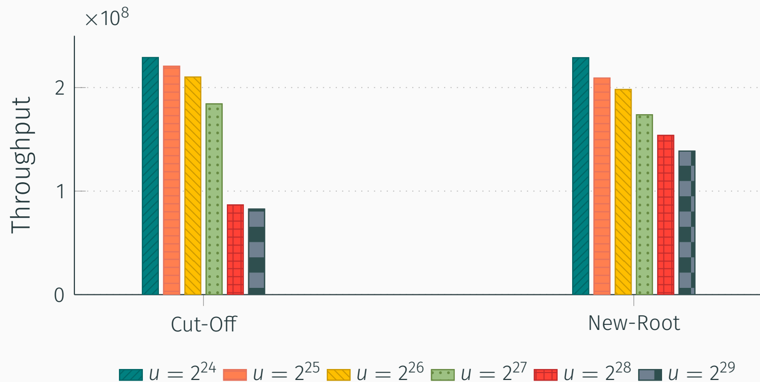
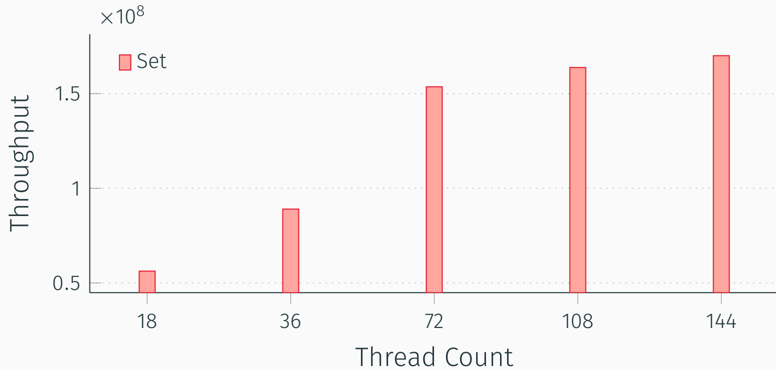


Moving On to Maps



Moving On to Maps

$\times 10^8$

Set
Map

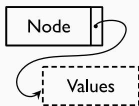
Throughput

1.5
1
0.5

18 36 72 108 144

Thread Count

Map



Moving On to Maps

$\times 10^8$

Set
Map
Embedded Map

Throughput

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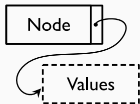
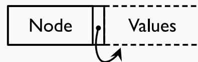
18
36
72
108
144

Thread Count

Map	Embedded Map





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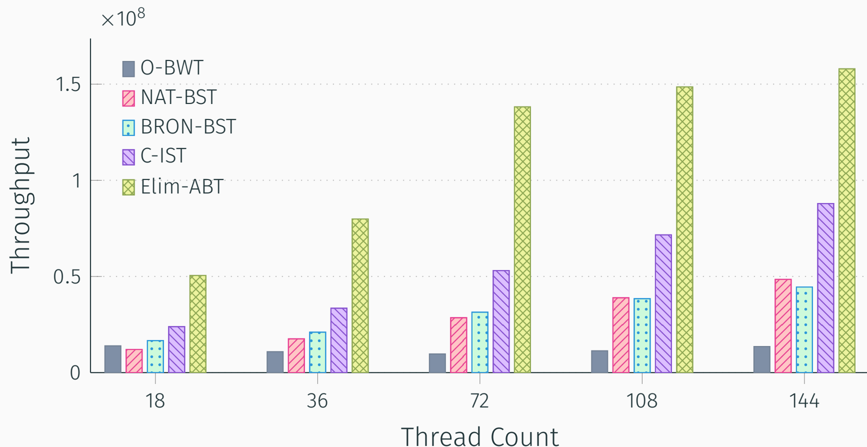
Experimental Evaluation

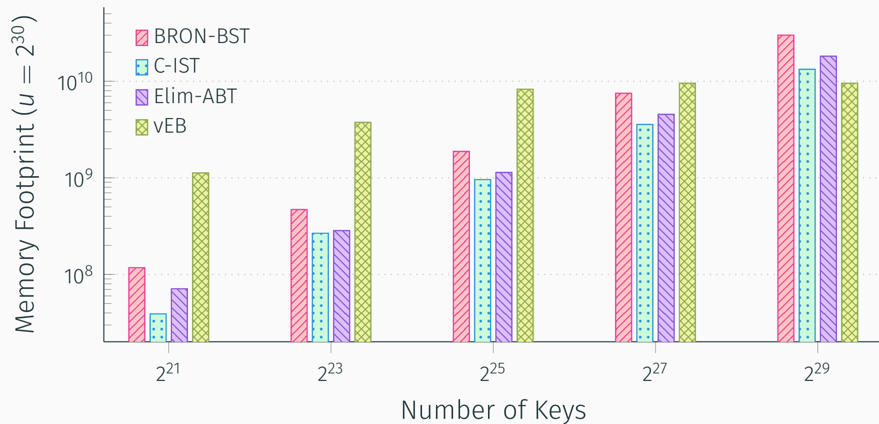
Experimental Setup

- Test harness: SetBench [2]
- 4 sockets × 18 cores per socket = 72 cores, 144 hardware threads
- Comparison points:
  - **Elim-ABT:** A concurrent (a,b)-tree [3]
  - **C-IST:** A doubly logarithmic interpolation search tree [2]
  - **BRON-BST:** An OCC BST [1]
  - **O-BWT:** The open-source implementation of BW-Tree [5]

Performance

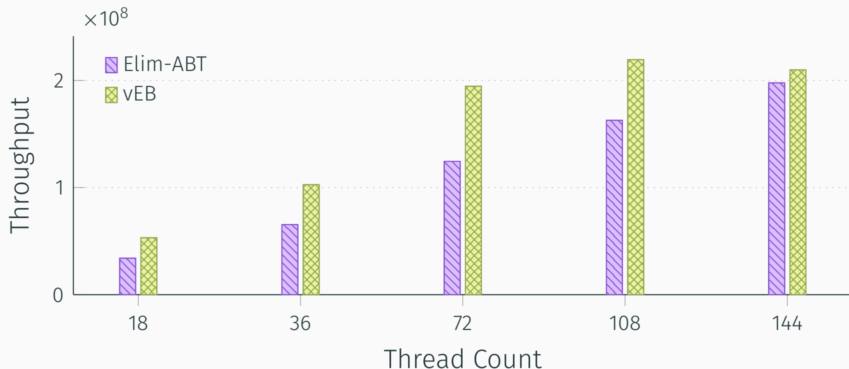


Memory Footprint



Successor Queries

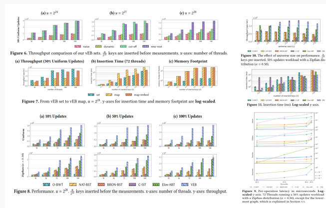
- The successor operation for Elim-ABT is non-linearizable
- Workload: 98% successor queries (Zipfian with $\alpha = 0.50$)



Summary

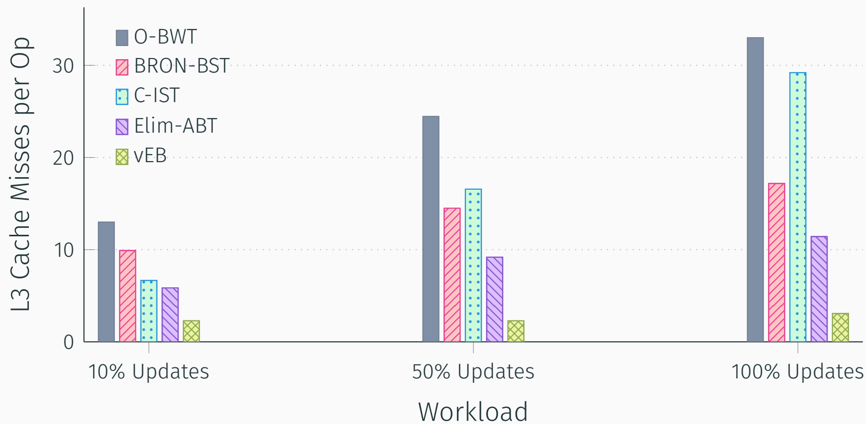
Summary

- Concurrent vEB trees utilizing HTM
- Low-overhead thread synchronization
- On average 5× faster
- More in the paper: https://bit.ly/htmveb
    - Zipfian workloads
    - Cache performance
    - Insertion time



Questions?

L3 Cache Misses



References i

[1] N. G. Bronson, J. Casper, H. Chafi, and K. Olukotun.
A practical concurrent binary search tree.
In *Proceedings of the 15th ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming, PPOPP 2010, Bangalore, India, January 9-14, 2010*, pages 257–268. ACM, 2010.

[2] T. Brown, A. Prokopec, and D. Alistarh.
Non-blocking interpolation search trees with doubly-logarithmic running time.
In *PPoPP '20: 25th ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming, San Diego, California, USA, February 22-26, 2020*, pages 276–291. ACM, 2020.

References ii

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