GETTING TO THE ROOT OF CONCURRENT BINARY SEARCH TREE PERFORMANCE

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MOTIVATION

Optimistic concurrent search trees are crucial in many applications

- (e.g., in-memory databases, internet routers and operating systems)

We want to understand their performance

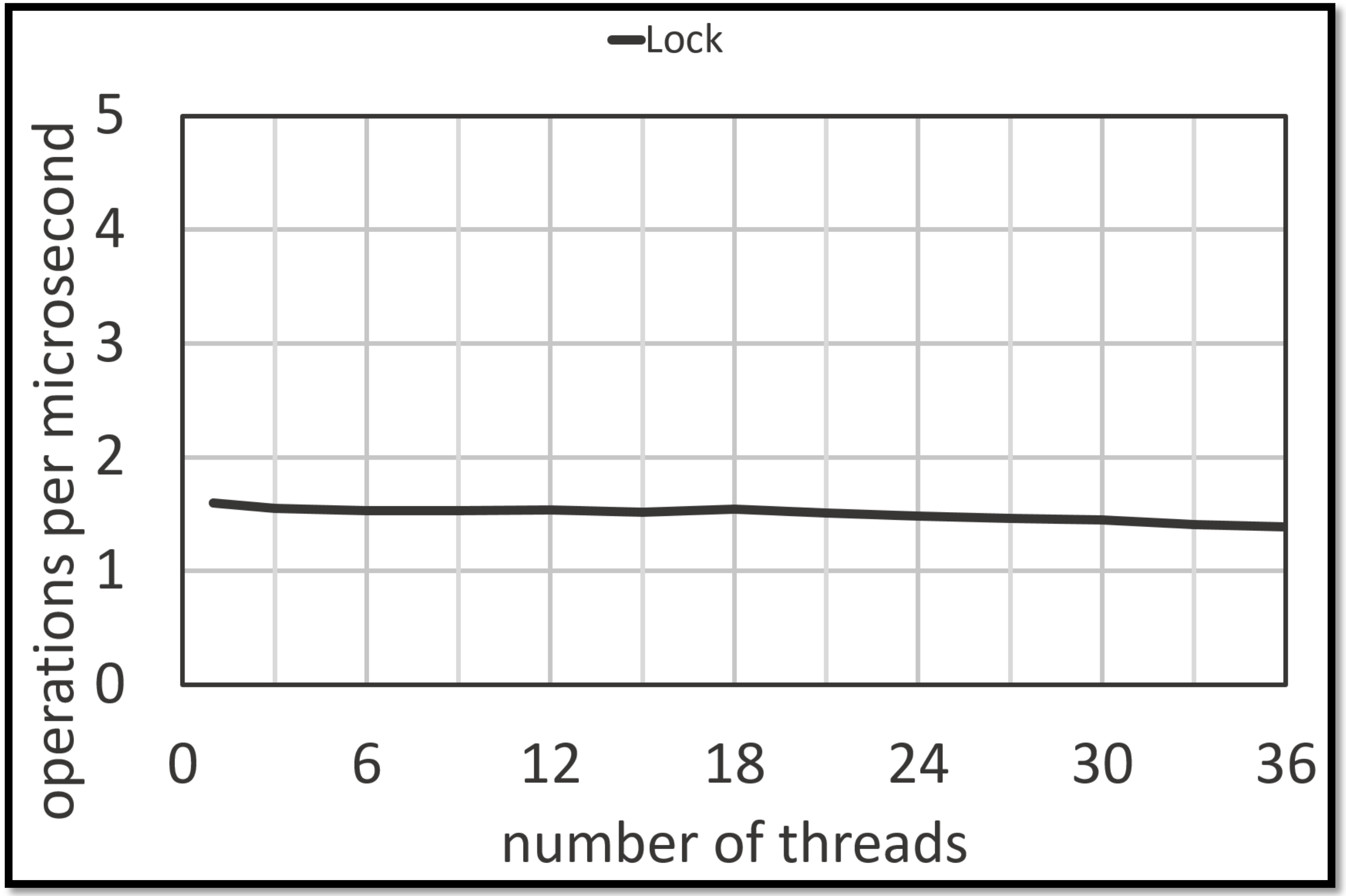
We study BSTs because there are many variants,
making comparisons easier

BST PROTECTED BY A GLOBAL LOCK

Synthetic experiment:

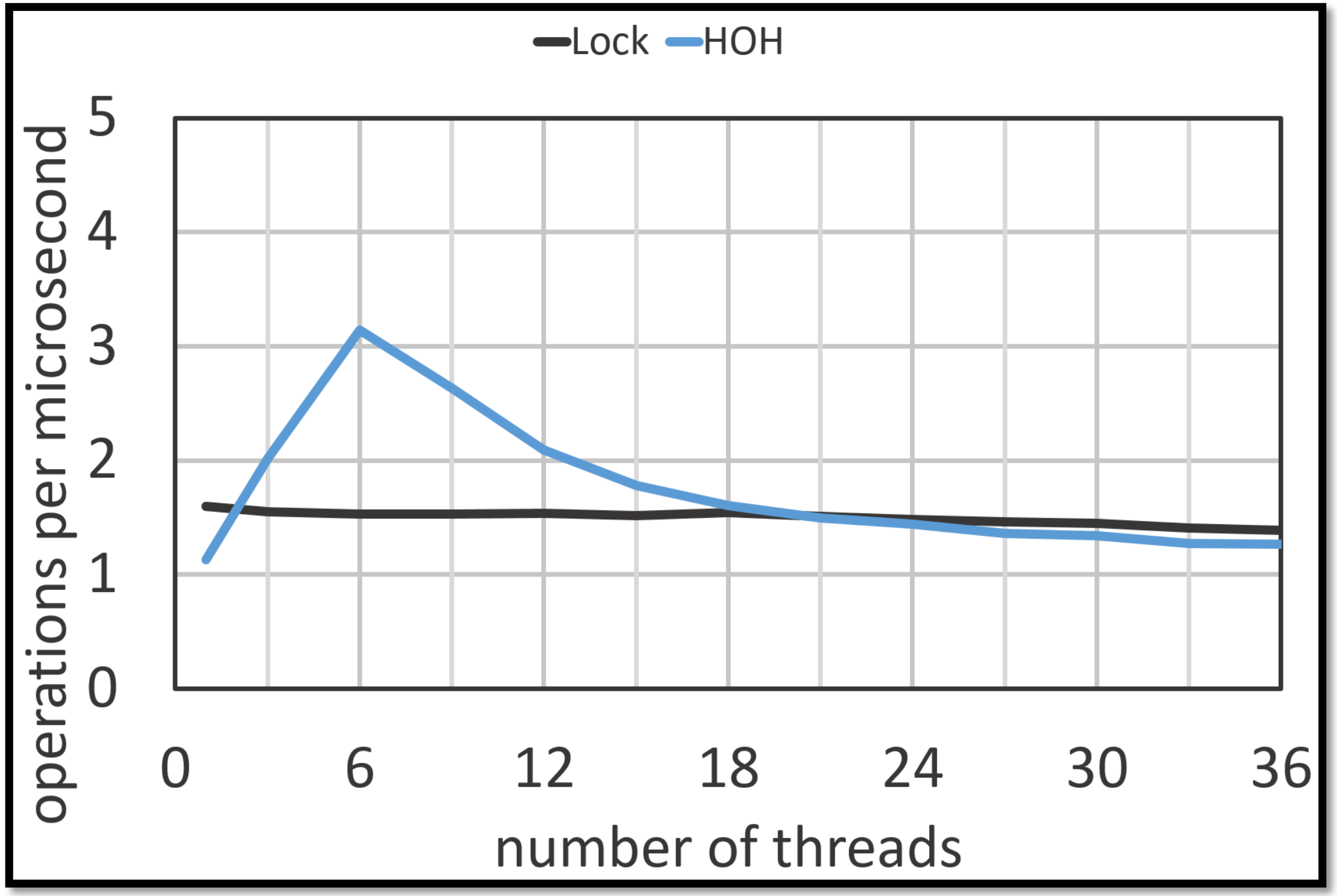
Insert 100,000 keys, then

n threads perform **searches**

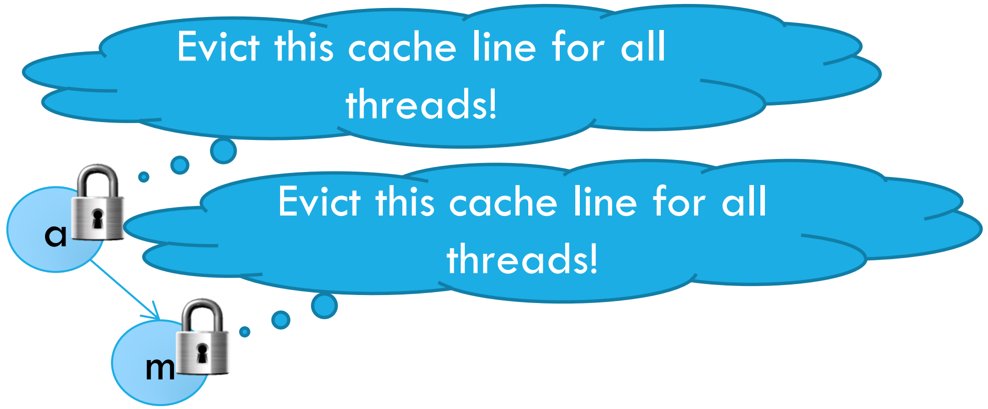


HAND-OVER-HAND LOCKING (HOH)

Same experiment



LOCKING AND CACHE COHERENCE



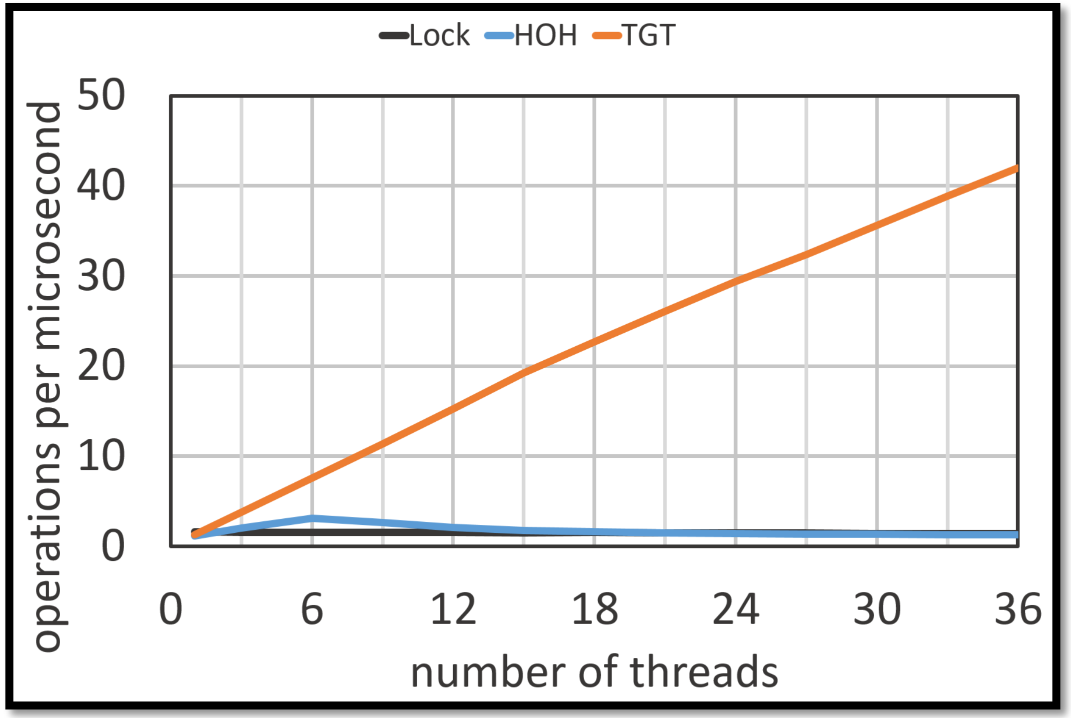
Algorithm	L2 misses / search	L3 misses / search
Global lock	15.9	3.9
HOH	**25.1**	***7.7***

ACHIEVING HIGH PERFORMANCE

NO locking while **searching**!

Example: Unbalanced DGT BST

- Standard BST search
- No synchronization!



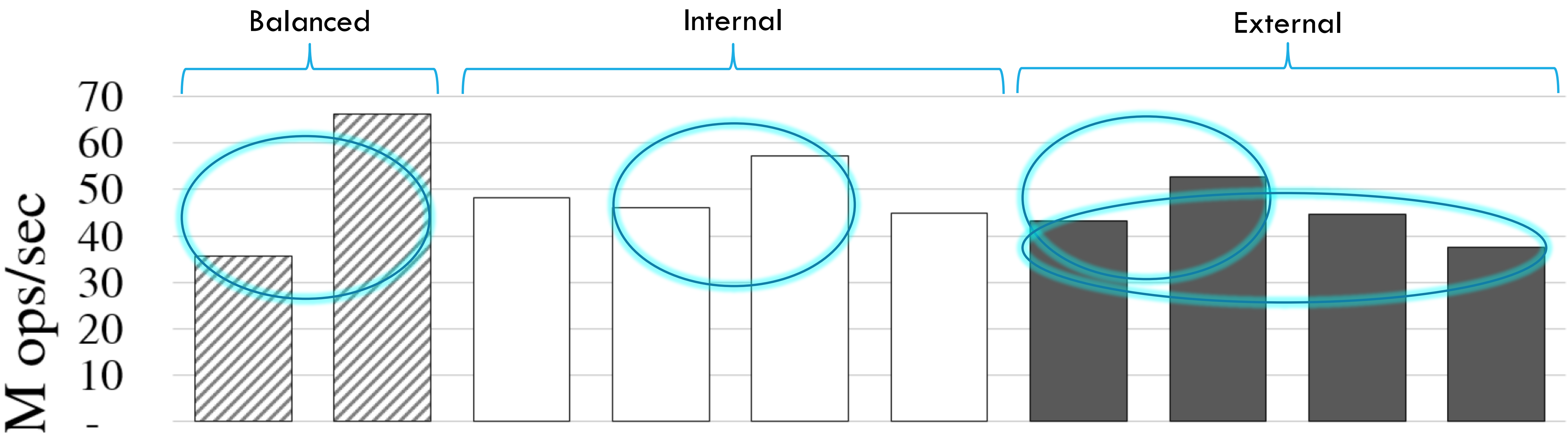
STATE OF THE ART BSTS

	BST	Balanced?	Tree type	Search overhead
Blocking	BCCO	Y	Internal*	Read **per-node**
	DVY		Internal*	
	AA		Internal	Write **per-search**
	DGT		External	
Lock-free	HJ		Internal	Read **per-node**
	RM		Internal	Read **per-search**
	NM		External	
	EFRB		External	

Not covered: lock-free balanced BSTs …

HOW DO THEY PERFORM?

EXPERIMENT: 100% SEARCHES WITH 64 THREADS



	BCCO1	BCCO2	HJ	DVY	RM	AA	NM1	NM2	DGT	EFRB
Search overhead	Read **per-node**	Read **per-node**	Read **per-node**		Read **per-search**	Write **per-search**				

BASIC IMPLEMENTATION ISSUES

Bloated nodes

- Why does node <u>size</u> matter?
- Larger nodes → fewer fit in cache → more cache misses

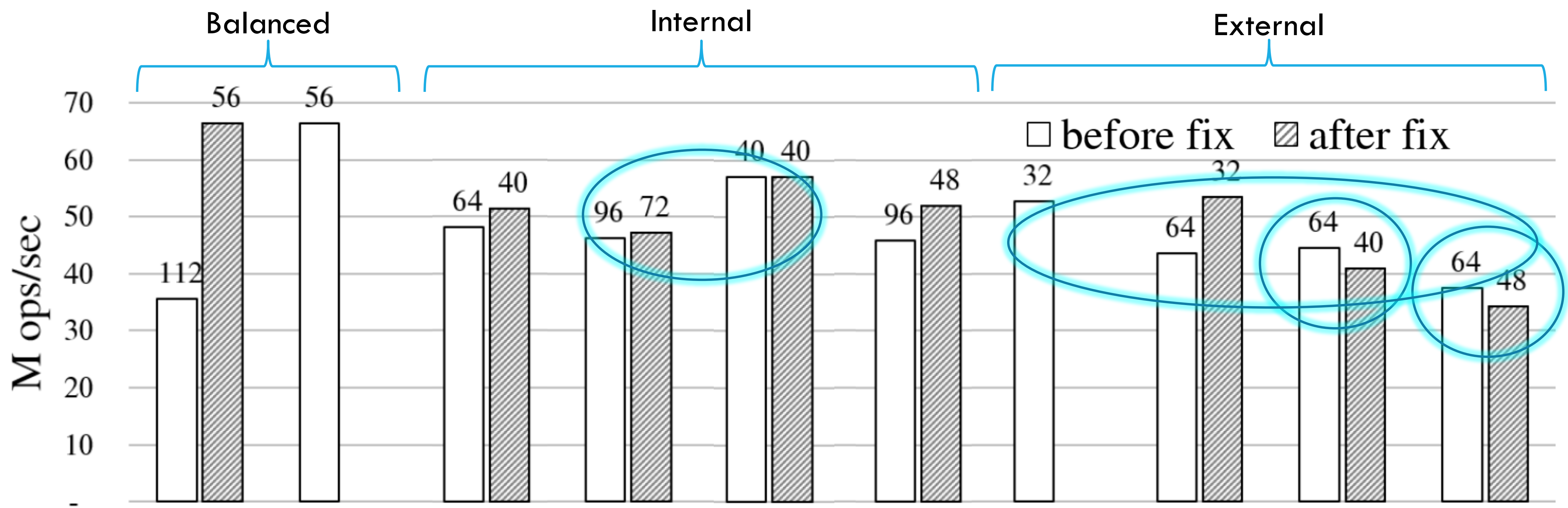
Scattered fields

- Why does node <u>layout</u> matter?
- Searches may only access a few fields
- Scattered fields → more cache lines → more cache misses

Incorrect usage of C volatile

- Missing volatiles → correctness issue
- Unnecessary volatiles → performance issue

IMPACT OF FIXING THESE ISSUES



	BCCO1	BCCO2	HJ	DVY	RM	AA	NM1	NM2	DGT	EFRB
Search overhead	Read **per-node**	Read **per-node**	Read **per-node**		Read **per-search**	Write **per-search**				
Bloated nodes	x		x	x		x		x	x	x
Scattered fields	x			x						
Incorrect C volatile			x	x		x	x	x	x	x

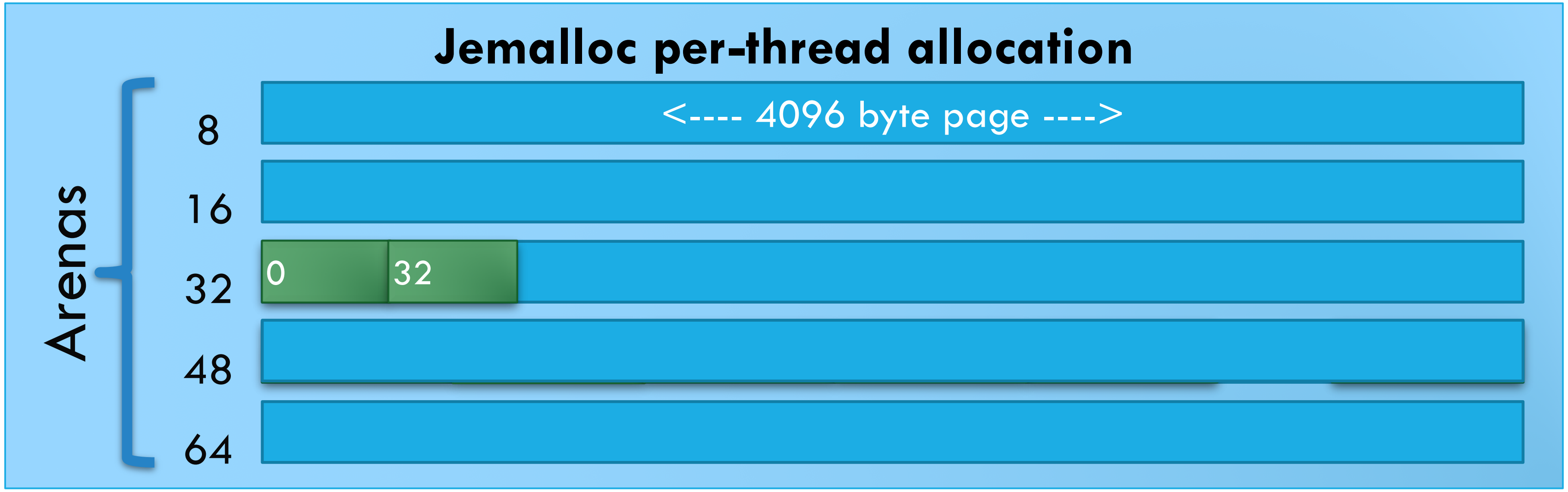
HOW A FAST ALLOCATOR WORKS

Jemalloc: threads allocate from private **arenas**

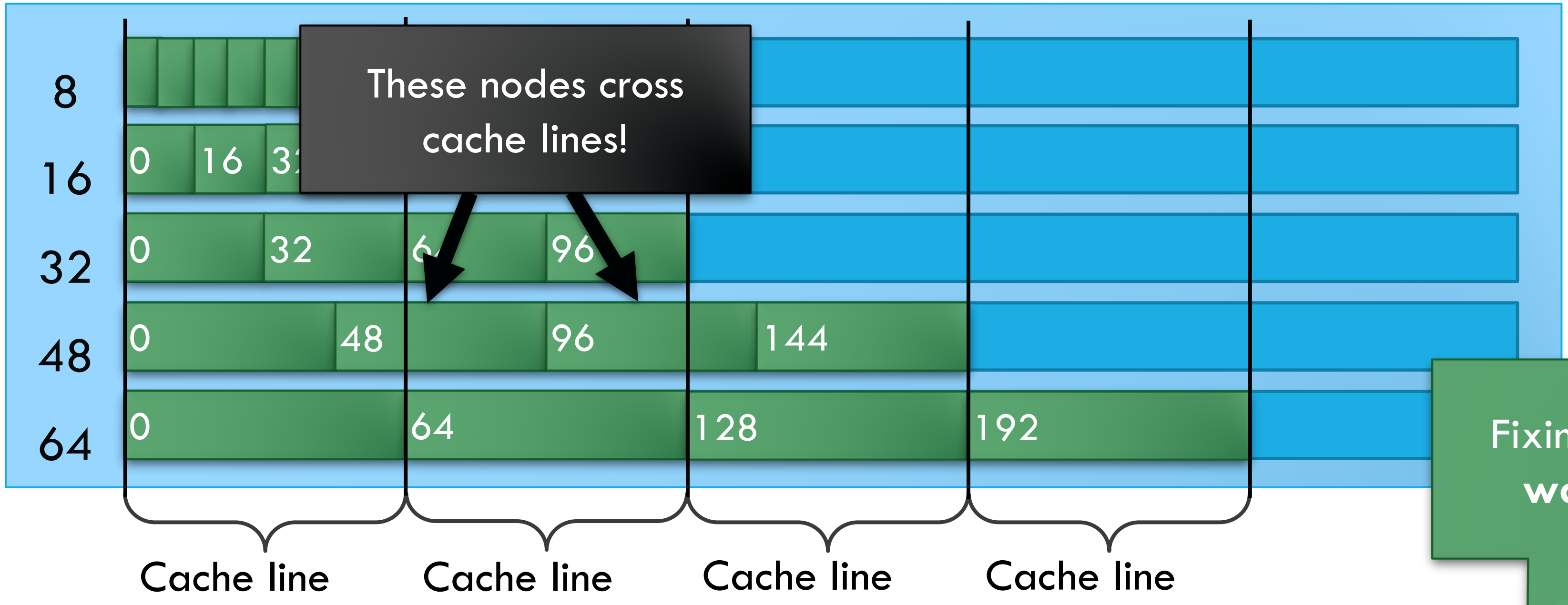
Each thread has an arena for each **size class:**

- **8, 16, 32, 48, 64, 80, 96, 112, 128, 192, 256, 320, 384, 448, 512, …**

malloc(48)
malloc(36)
malloc(40)
malloc(44)
malloc(32)
malloc(17)
malloc(40)
…
malloc(33)



CACHE LINE CROSSINGS



Fixing bloated nodes can **worsen** performance!

Not a big deal if the tree fits in the cache

If the tree does not fit in cache, **double cache misses** for half of your nodes!

CACHE SETS

Cache is sort of like a hash table

Maps addresses to buckets (4096 for us)

Buckets can only contain up to c elements (64 for us)

If you load an address, and it maps to a full bucket

- A cache line is evicted from that bucket

"Mod 4096" is not a good hash function

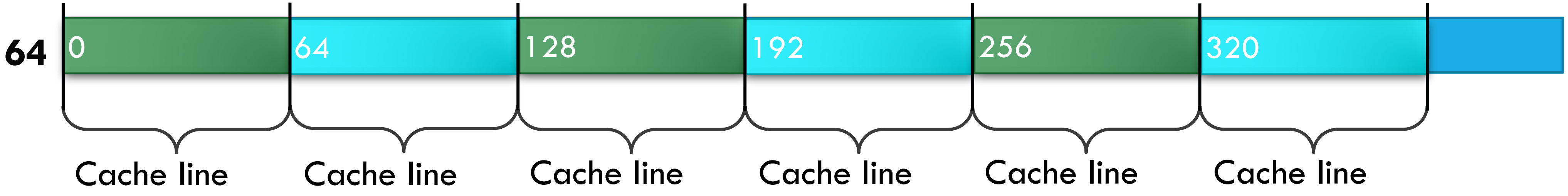
- Patterns in allocation can lead to patterns in bucket occupancy

Hashing a cache line to a bucket:
physical address mod 4096

CACHE SET USAGE IN HJ BST

Insert creates a **node** and a **descriptor** (to facilitate *lock-free helping*)

Node size class: 64 Descriptor size class: 64



Which cache sets will these nodes map to?

- Cache indexes used: 0, 2, 4, … (only **even numbered** indexes)
- Taken modulo 4096, these can only map to **even numbered** cache sets!
- Only **half of the cache** can be used to store nodes!

SIMPLE FIX: RANDOM ALLOCATIONS

Hypothesis: problem is the rigid even/odd allocation behaviour

Idea: break the pattern with an occasional dummy 64 byte allocation

Fixes the problem!

- Reduces unused cache sets to 1.6%
- Improved search performance by 41%
- … on our first experimental system, which was an AMD machine.
- However, on an Intel system, this did **not** improve search performance!

THE DIFFERENCE BETWEEN SYSTEMS

Intel processors prefetch more aggressively

- Adjacent line prefetcher: load one extra adjacent cache line
  - Not always the next cache line (can be the previous one)
- Smallest unit of memory loaded is 128 bytes (two cache lines)
  - This is also the unit of memory contention

EFFECT OF PREFETCHING ON HJ BST

The occasional dummy allocations break up the even/odd pattern

But…

Whenever search loads a **node,** it also loads the **adjacent cache line**

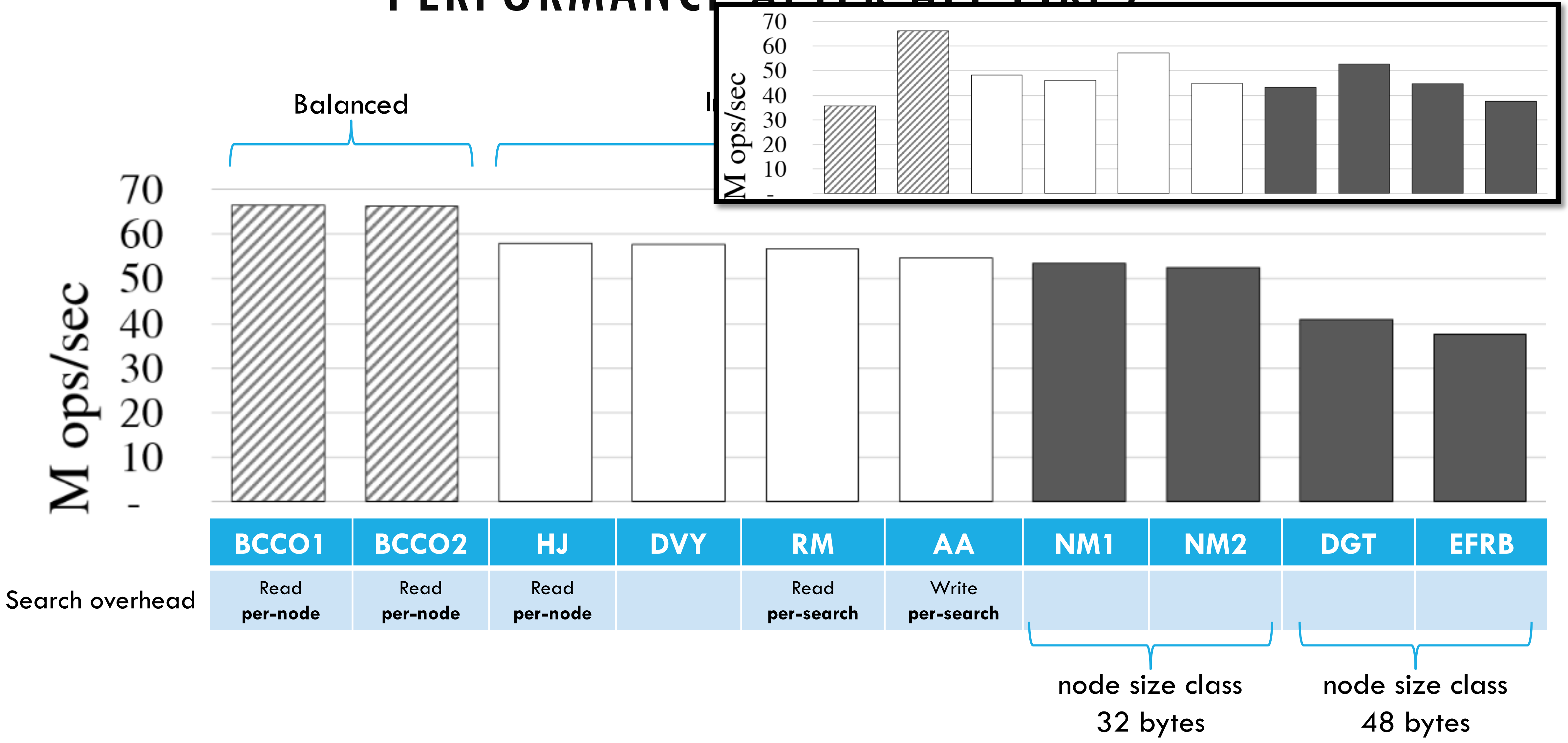
- This is a **descriptor** or a **dummy allocation**!
- This is useless for the search
- Only half of the cache is used for nodes

Fix: **add padding**
to nodes or descriptors
so they are in
different size classes

SEGREGATING MEMORY FOR DIFFERENT OBJECT TYPES

1. Previously described solution
   - Add padding so objects have different size classes
2. A more principled solution
   - Use multiple instances of jemalloc
   - Each instance has its own arenas
   - Allocate different object types from different jemalloc instances
3. An even better solution
   - Use an allocator with support for segregating object types

PERFORMANCE AFTER ALL FIXES



APPLICATION BENCHMARKS

In-memory database DBx1000 [Yu et al., VLDB 2014]

- Yahoo! Cloud Serving Benchmarks
- TPC-C Database Benchmarks

Used each BST as a database index

- Merges the memory spaces of DBx1000 and the BST!
- Creates similar memory layout issues (e.g., underutilized cache sets)
- And new ones (e.g., scattering of nodes across many pages)
- Even accidentally fixes memory layout issues in DBx1000

See paper for details

RECOMMENDATIONS

When designing and testing a data structure

- Understand your memory layout!
- How are nodes laid out in cache lines? Pages?
- What types of objects are near one another?

When adding a data structure to a program

- You are merging two memory spaces
- Understand your **new** memory layout!

New tools needed?

http://tbrown.pro
Tutorials, code, benchmarks

Companion talk:
Good data structure experiments are R.A.R.E