Scalable and Practical Locking with Shuffling

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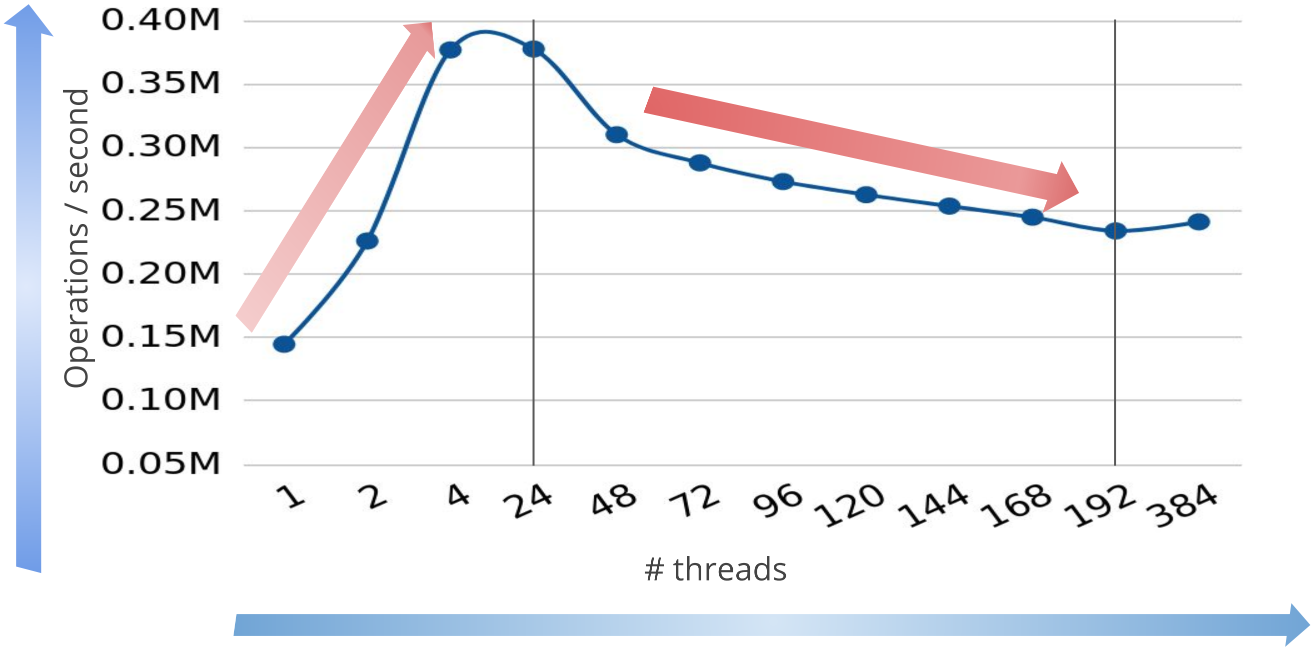
*On the job market

Locks are critical for application performance

A ***typical*** performance graph on manycore machines (e.g., 192-core/8-socket)



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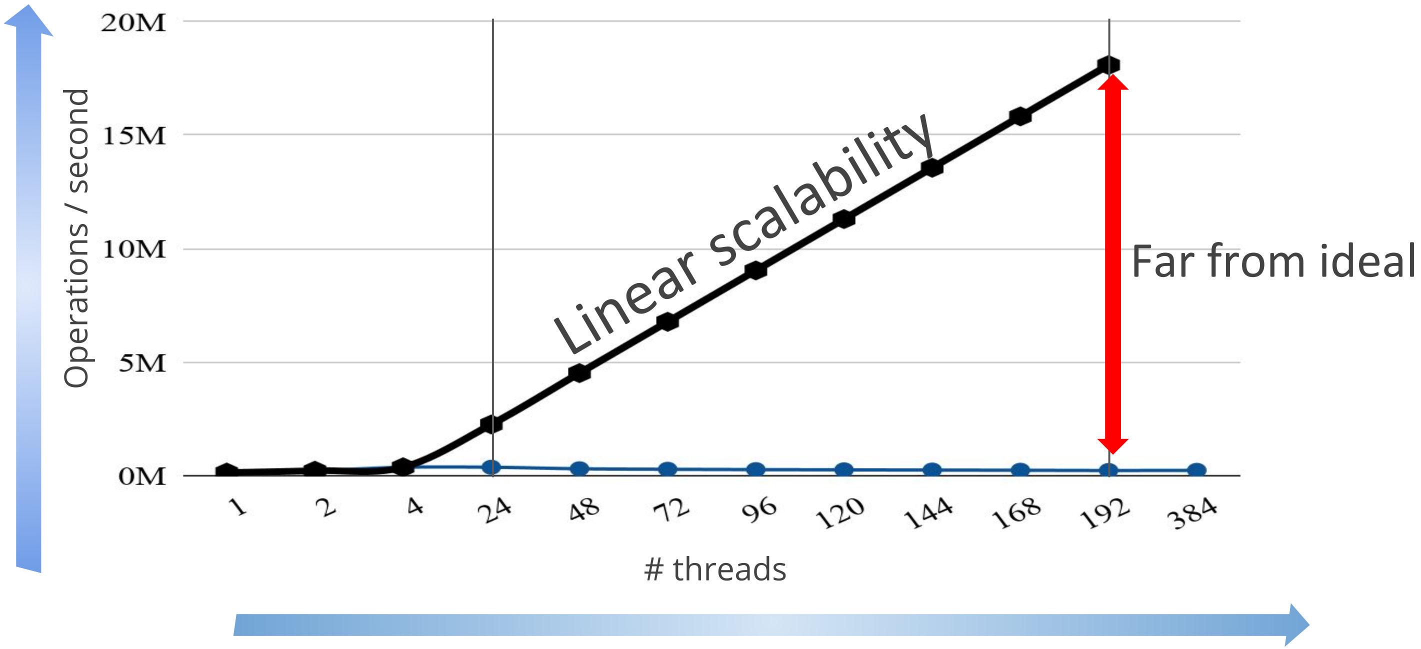


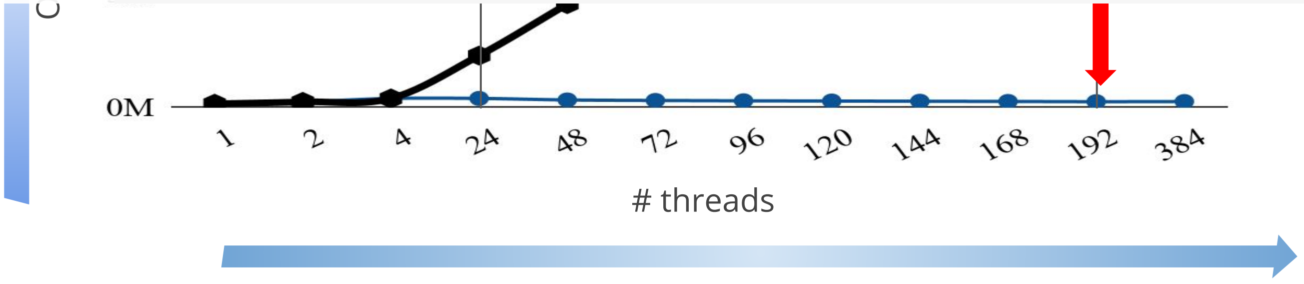
Future hardware further exacerbates the problem

Intel to Offer Socketed 56-core Cooper Lake Xeon Scalable in new Socket Compatible with Ice Lake

by Dr. Ian Cutress on August 6, 2019 8:01 AM EST

AMD's New 280W 64-Core Rome CPU: The EPYC 7H12

by Dr. Ian Cutress on September 18, 2019 9:15 AM EST



Two dimensions of lock design/goals

1) High throughput

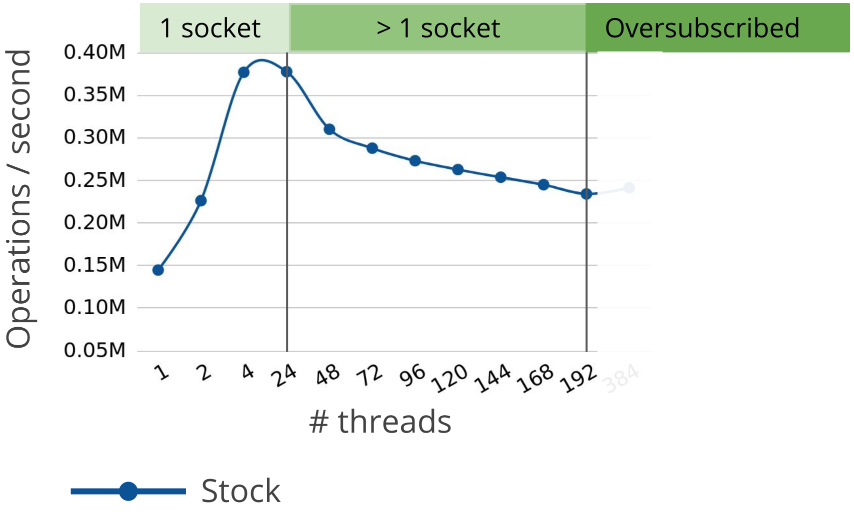
- In high thread count ⇒ Minimize lock contentions
- In single thread ⇒ No penalty when not contended
- In oversubscription ⇒ Avoid bookkeeping overhead

2) Minimal lock size

- Memory footprint ⇒ Scales to millions of locks (e.g., file inode)

Locks performance: Throughput

(e.g., each thread creates a file, a serial operation, in a shared directory)



- **Performance crashes after 1 socket**

Due to non-uniform memory access (NUMA)

Accessing local socket memory is faster than the remote socket memory.

Setup: 192-core/8-socket machine

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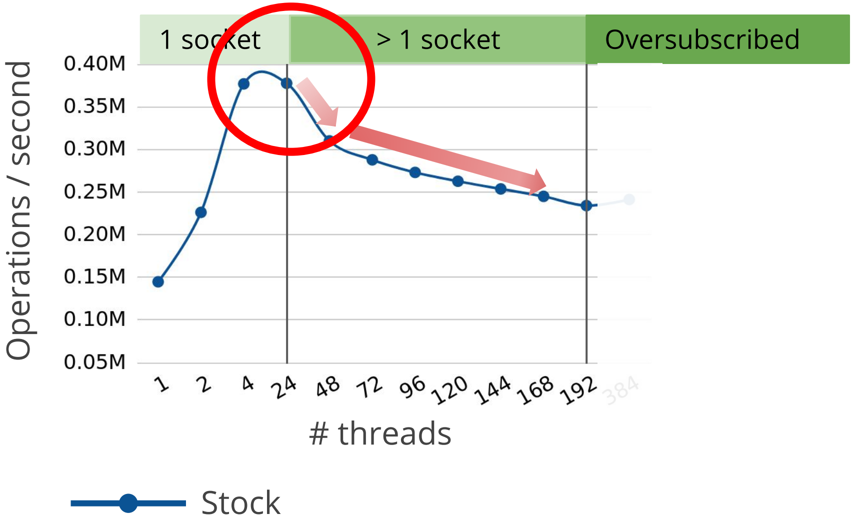

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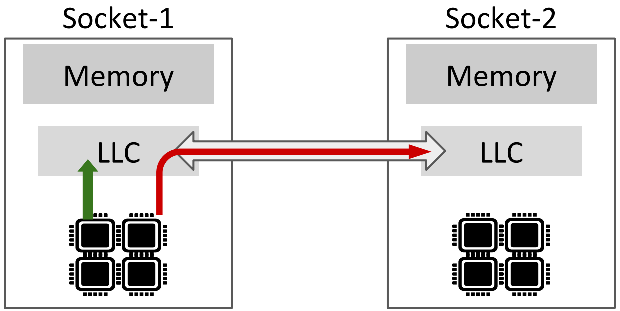

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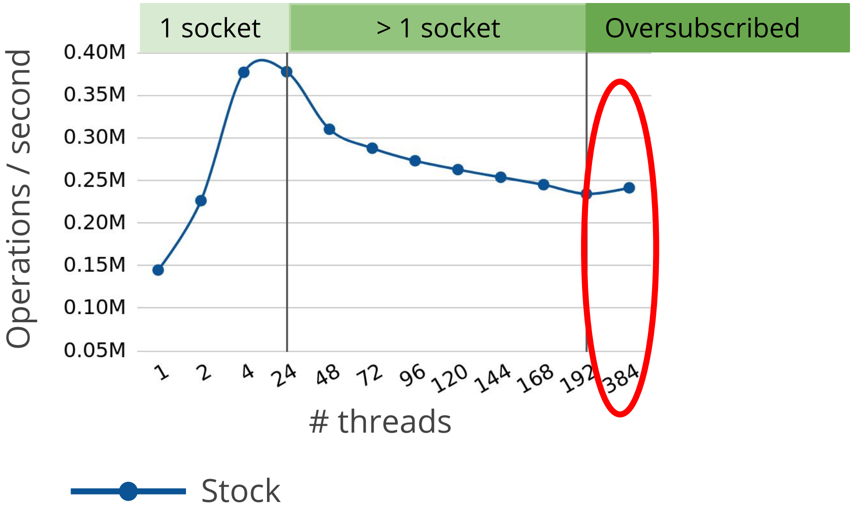

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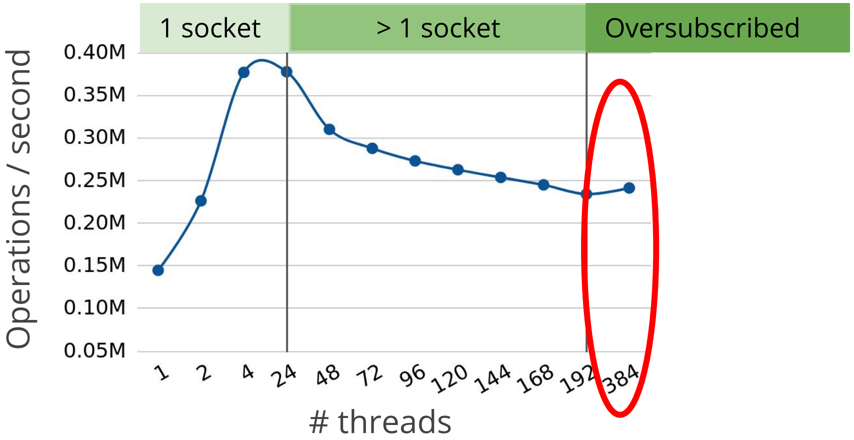

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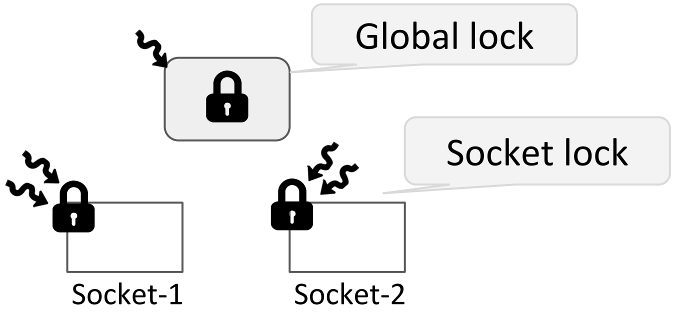
Prevent throughput crash after **one socket**

Existing research efforts

- Making locks NUMA-aware:
  - Two level locks: per-socket and global
  - Generally **hierarchical**
- Problems:
  - **Require extra memory allocation**
  - **Do not care about single thread throughput**
- Example: CST[1]



1. Scalable NUMA-aware Blocking Synchronization Primitives. ATC 2017.

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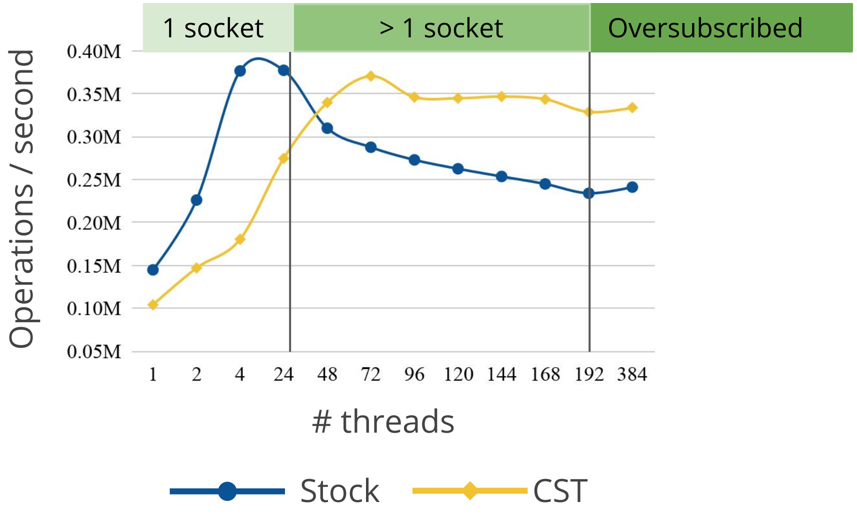

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  Beyond one socket (high thread count)
  In oversubscribed case (384 threads)
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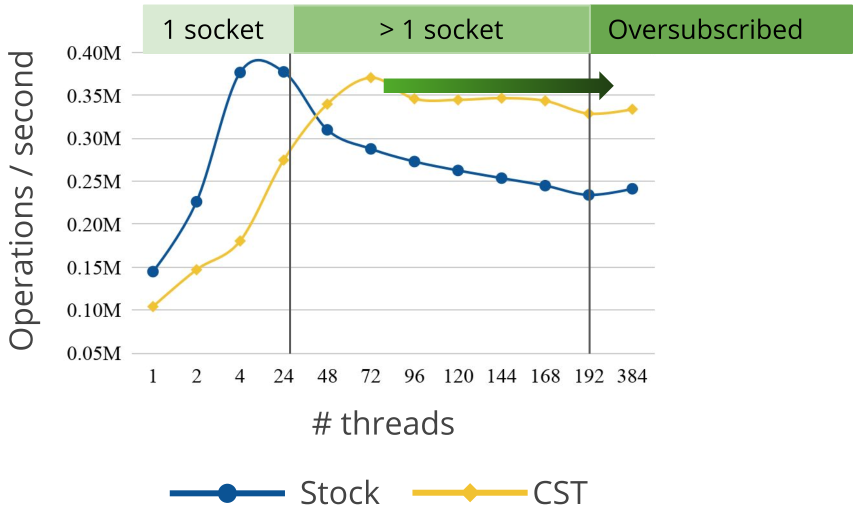

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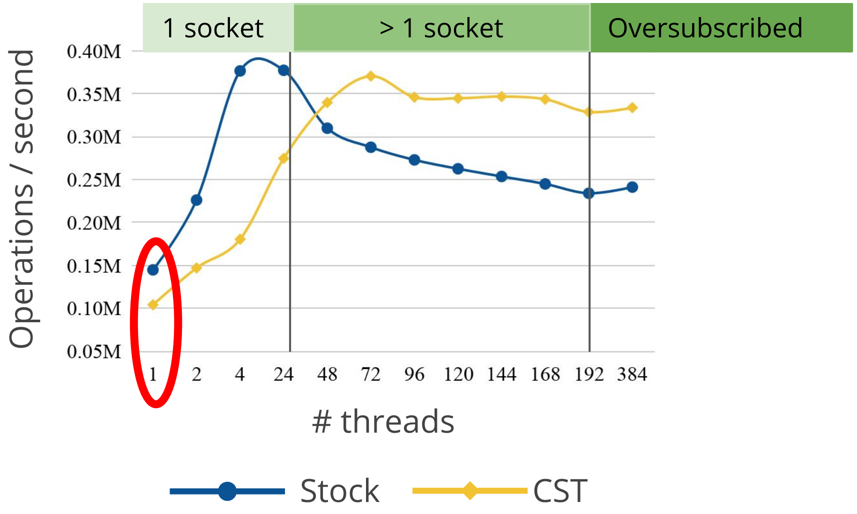

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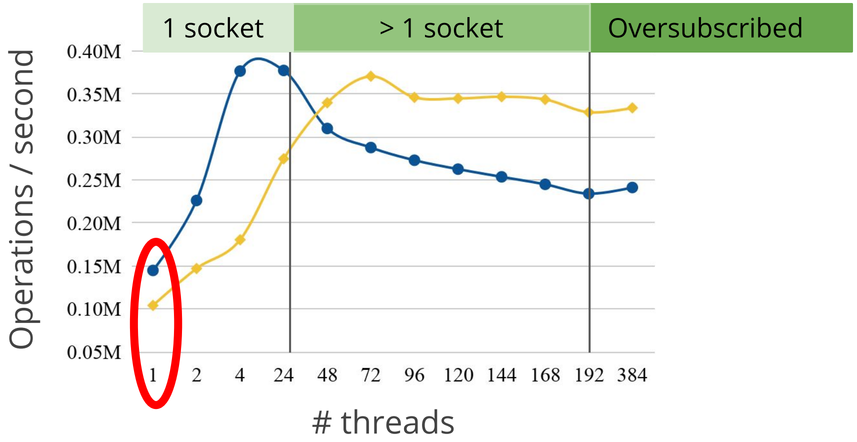

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Single thread matters in non-contended cases

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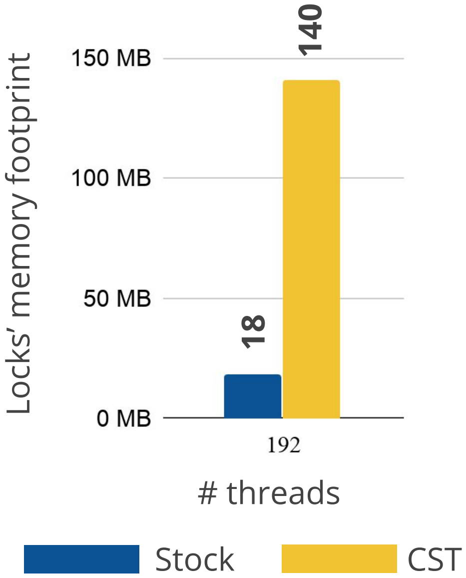

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Allocate socket structure and global lock

Worst case: ~1 GB footprint out of 32 GB application's memory

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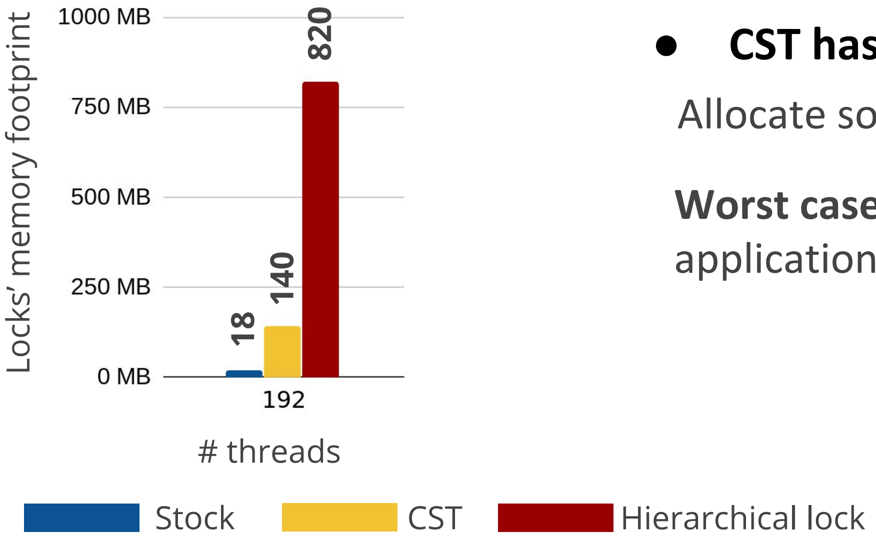

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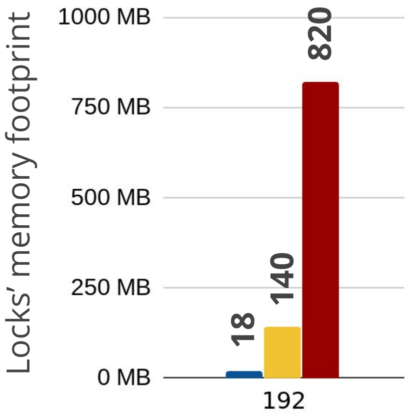

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Lock's memory footprint affect its adoption

Two goals in our new lock

1) **NUMA-aware** lock with **no memory** overhead

2) **High throughput** in **both** low/high thread count

Key idea: Sort waiters on the fly

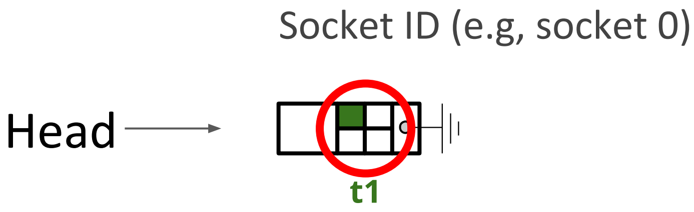
Observations:

Hierarchical locks avoid NUMA by passing the lock within a socket

Queue-based locks already maintain a list of waiters

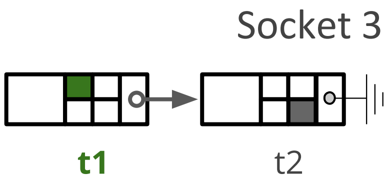
Sort waiters on the fly using socket ID

A waiting queue



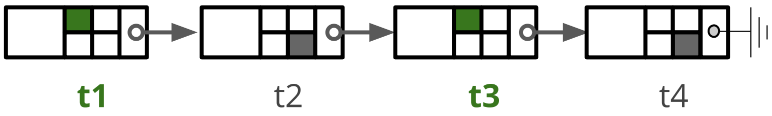
Sort waiters on the fly using socket ID

Another waiter is in a different socket



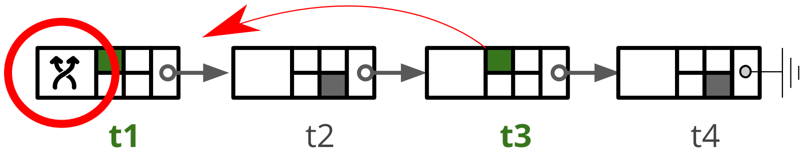
Sort waiters on the fly using socket ID

More waiters join



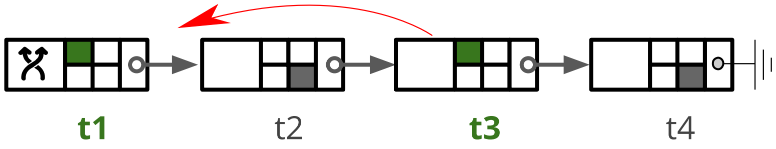
Sort waiters on the fly using socket ID

Shuffler (t1) sorts based on socket ID



Shuffling: Design methodology

A waiter (**shuffler** ⤲) reorders the queue of waiters



- A ***waiter***, otherwise spinning (i.e,. wasting), amortises the cost of lock ops
  1) By reordering (e.g., lock orders)
  2) By modifying waiters' states (e.g., waking-up/sleeping)

⟶ Shuffler **computes** NUMA-ness **on the fly without using memory**

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Blocking lock: wake up a nearby sleeping waiter

RWlock: Group writers together

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Incorporate **shuffling** in lock design

SHFLLOCKS

Minimal footprint locks
that handle any thread contention

ShflLocks

TAS (4B)
(test-and-set lock)

Queue tail (8B)
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`lock()`: Try acquiring the TAS lock first; join the queue on failure

`unlock()`: Unlock the TAS lock (reset the TAS word to 0)

SHFLLOCKS

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TAS maintains single thread performance

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- Waiters use **shuffling** to improve application throughput
  - NUMA-awareness, efficient wake up strategy
  - Utilizing Idle/CPU wasting waiters

★ **Shuffling is off the critical path most of the time**

- Maintain long-term fairness:
  - Bound the number of shuffling rounds

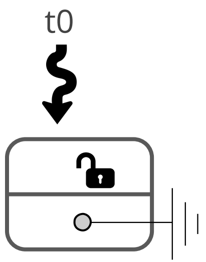
NUMA-aware SHFLLOCK in action

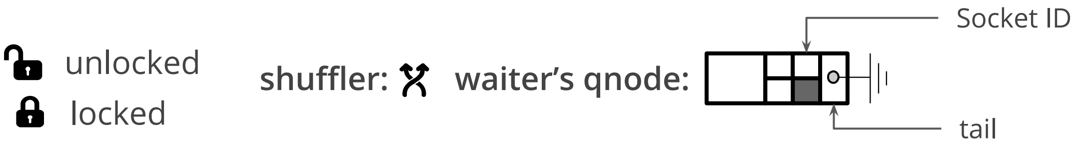
t0 (socket 0): lock()

Multiple threads join the queue

Shuffling in progress

t0: unlock()





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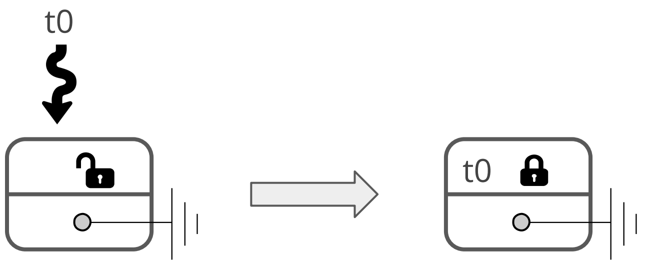
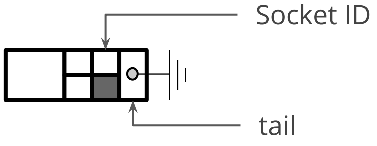


unlocked
locked

shuffler: **waiter's qnode:**



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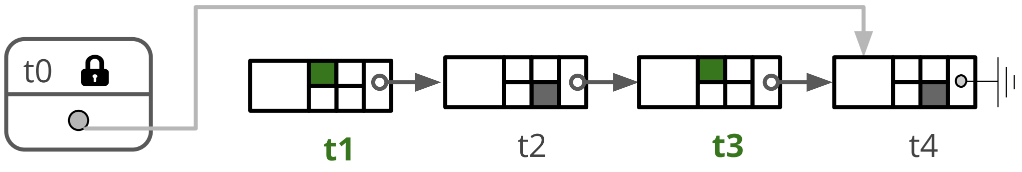

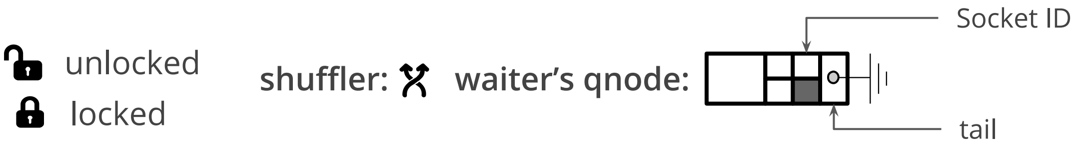

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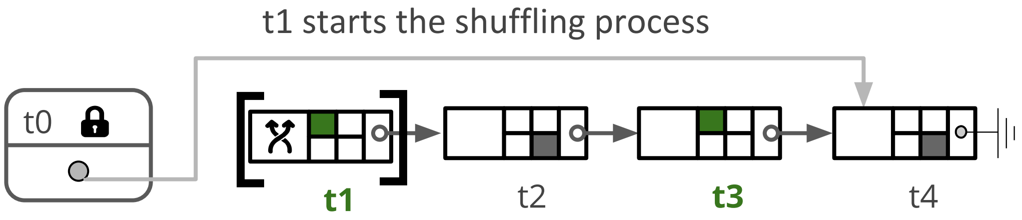

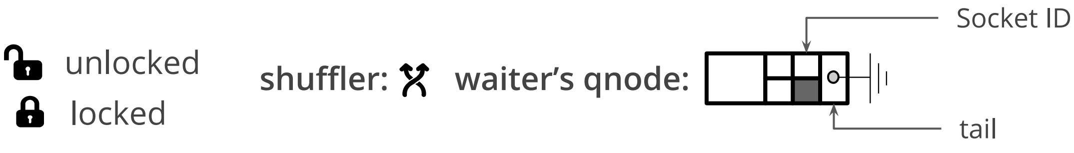

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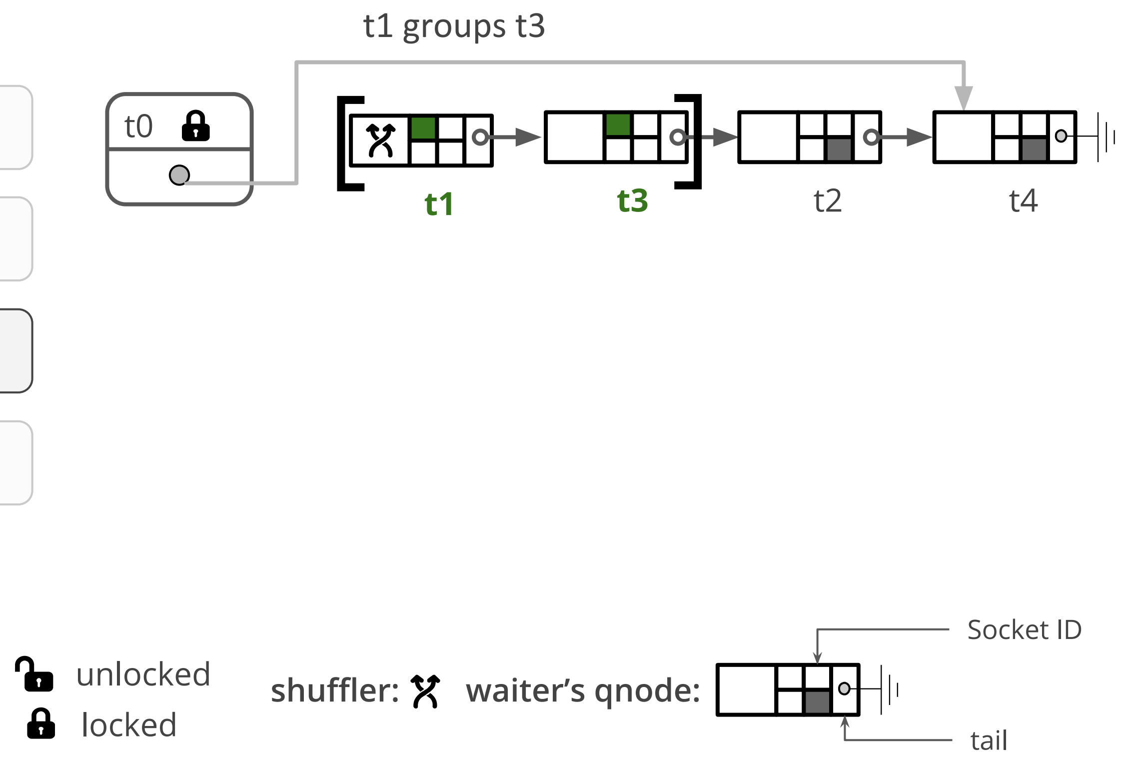

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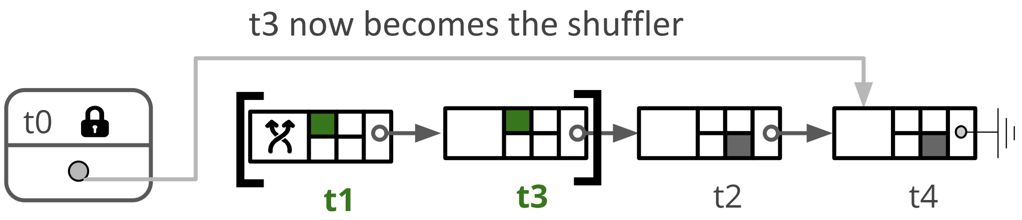

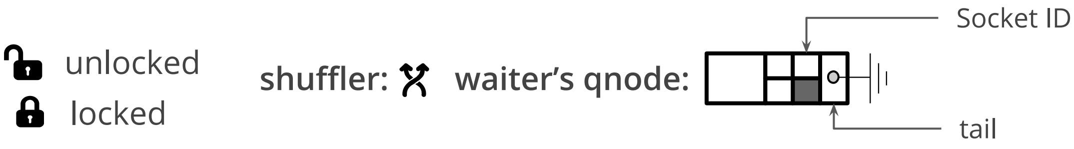

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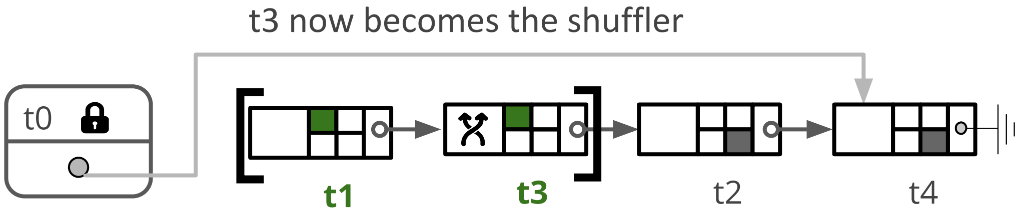

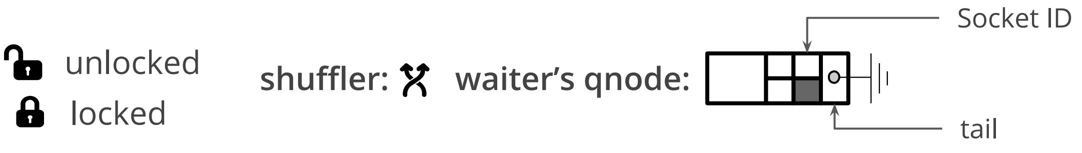

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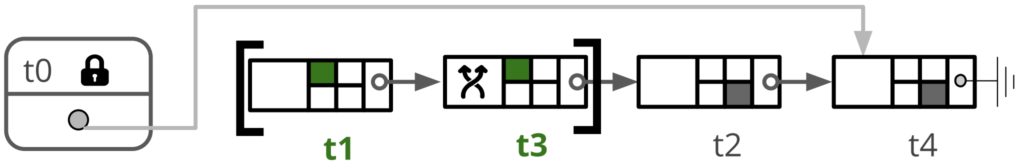

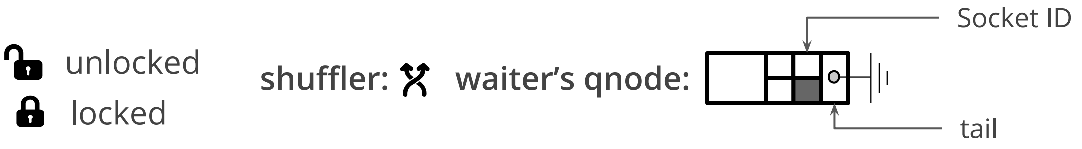

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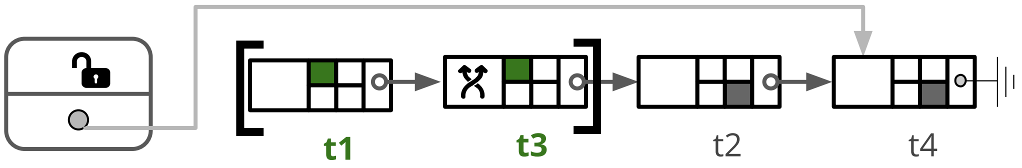

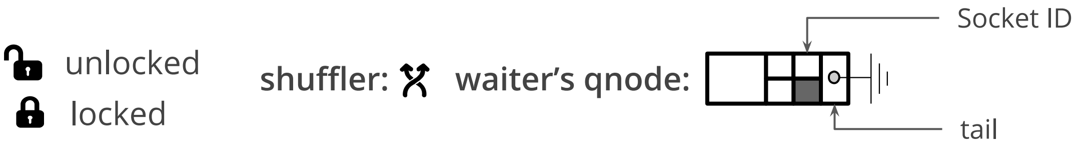

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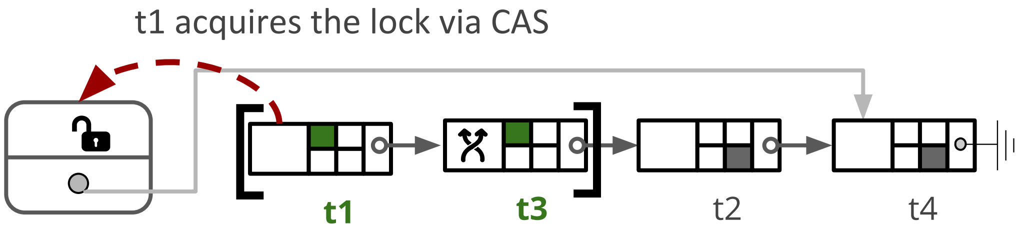

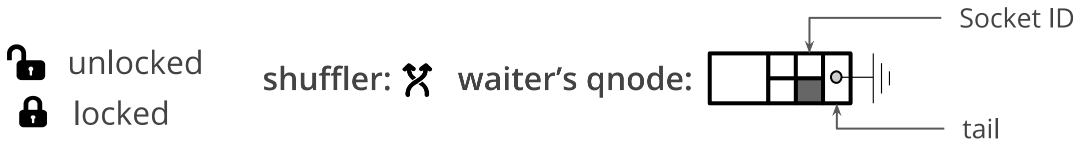

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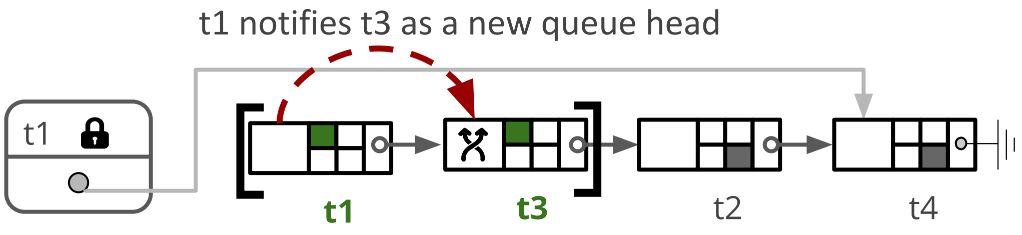

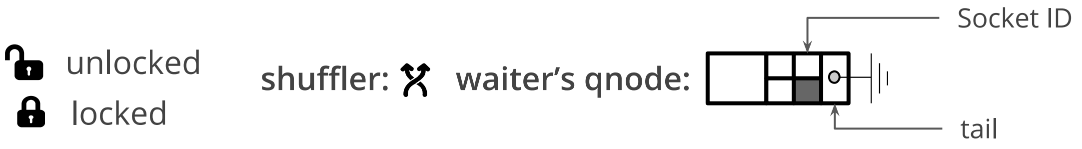

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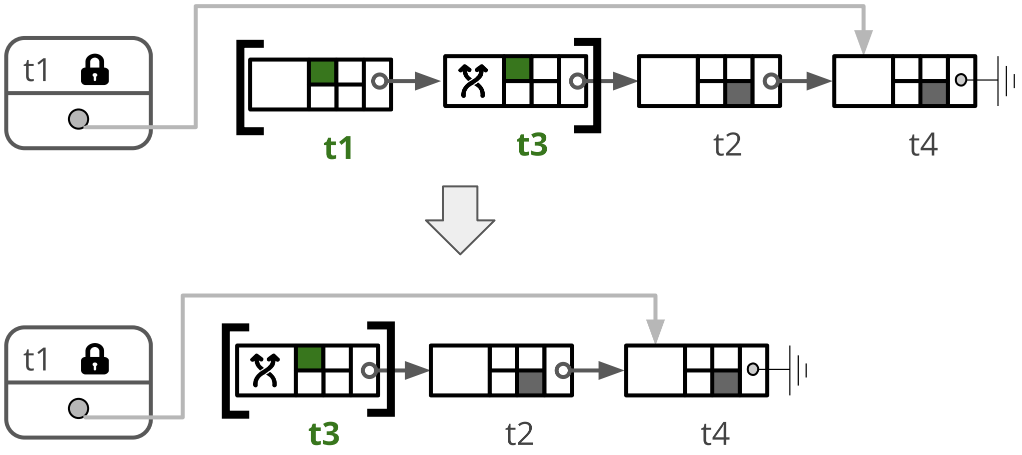

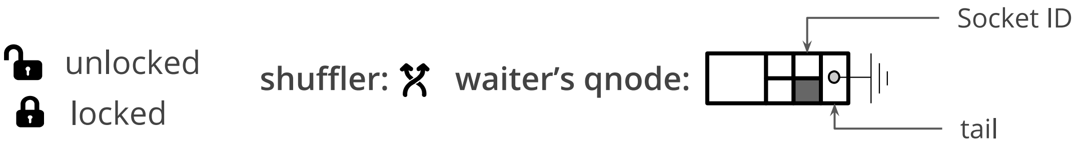

Implementation

- Kernel space:
  - Replaced ***all*** mutex and rwsem
  - Modified slowpath of the qspinlock
- User space:
  - Added to the LiTL library
- Please see our paper:
  - **Blocking lock**: Wake up nearby shuffled waiters
  - **Readers-writer lock**: Centralized rw-indicator + SHFLLOCK

https://github.com/sslab-gatech/shfllock

Evaluation

- SHFLLOCK performance:
  - Does shuffling maintains application's throughput?
  - What is the overall memory footprint?

Setup: 192-core/8-socket machine

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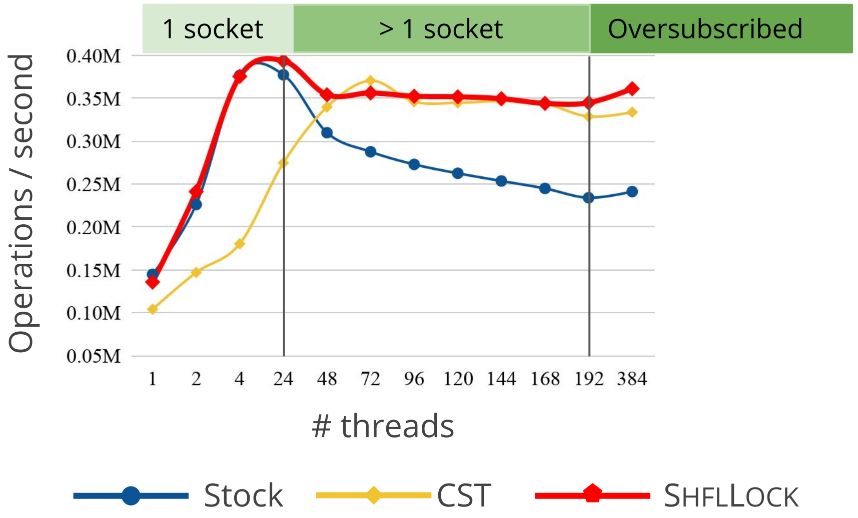

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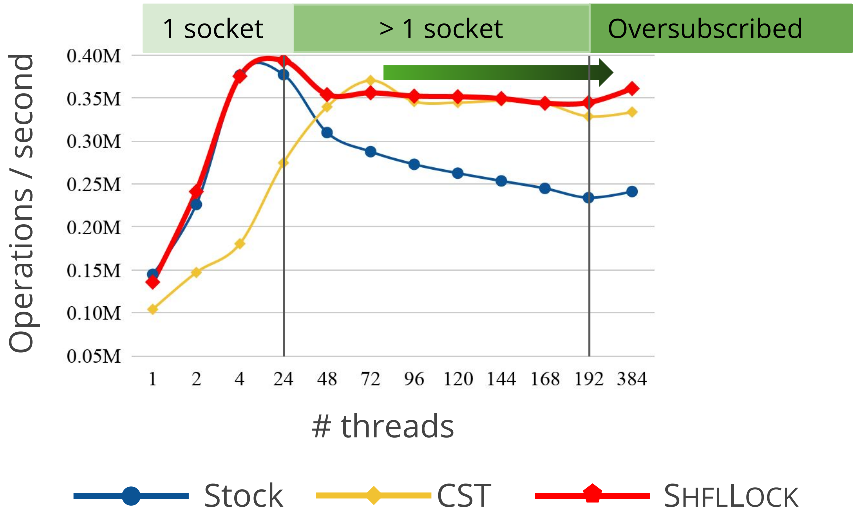

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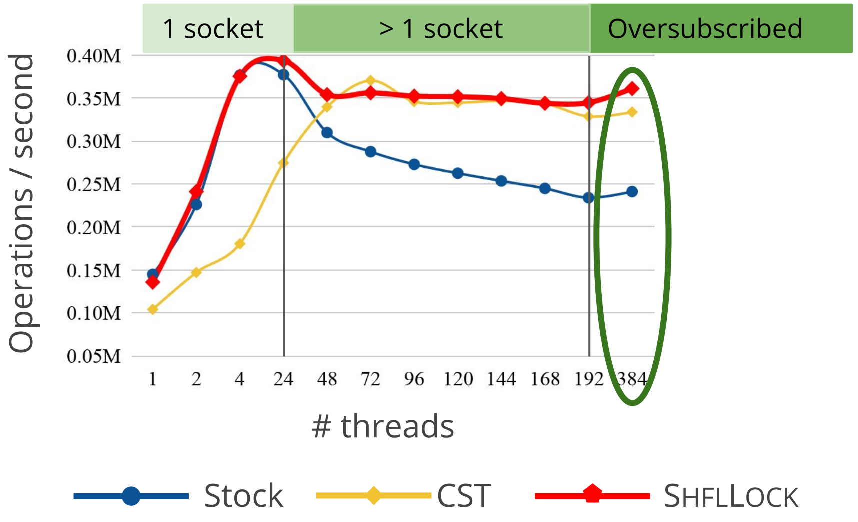

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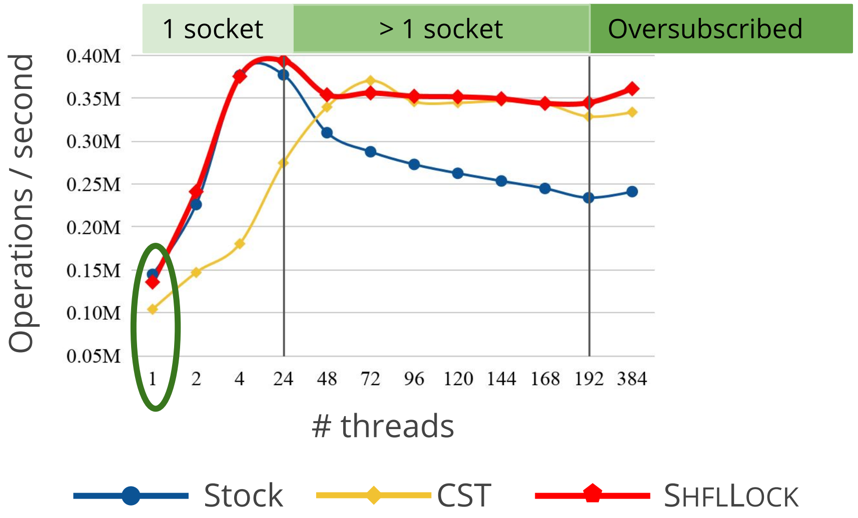

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  - Single thread
    - **TAS acquire and release**

Locks performance: Memory footprint

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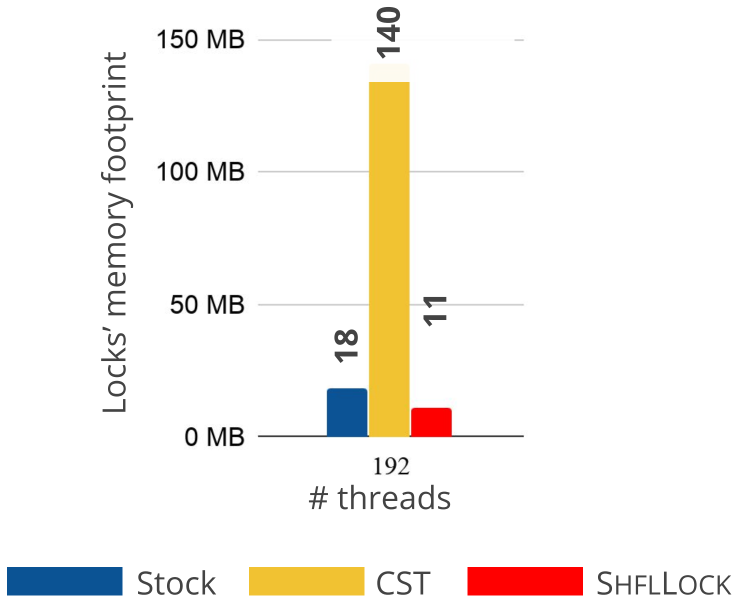

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  Reason: No extra auxiliary data structure

  ➢ Stock: parking list structure + extra lock

  ➢ CST: per-socket structure

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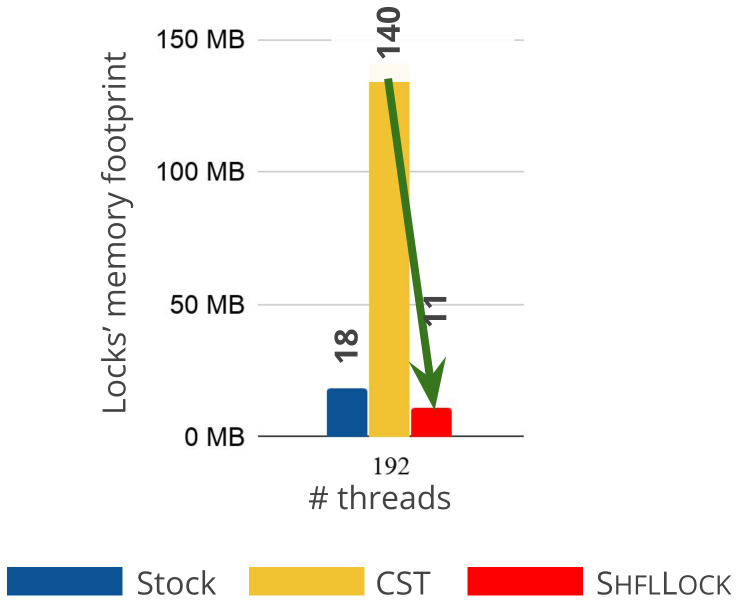

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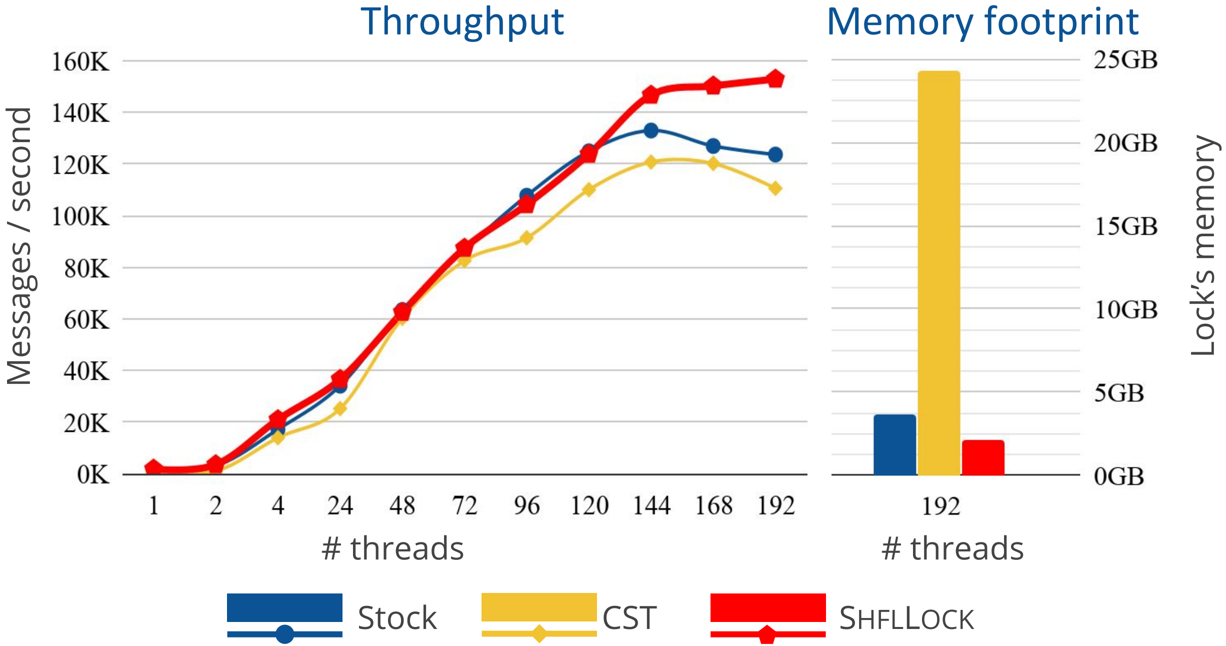
It is fork intensive and stresses memory subsystem, file system and scheduler



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Decreases memory footprint up to 93%

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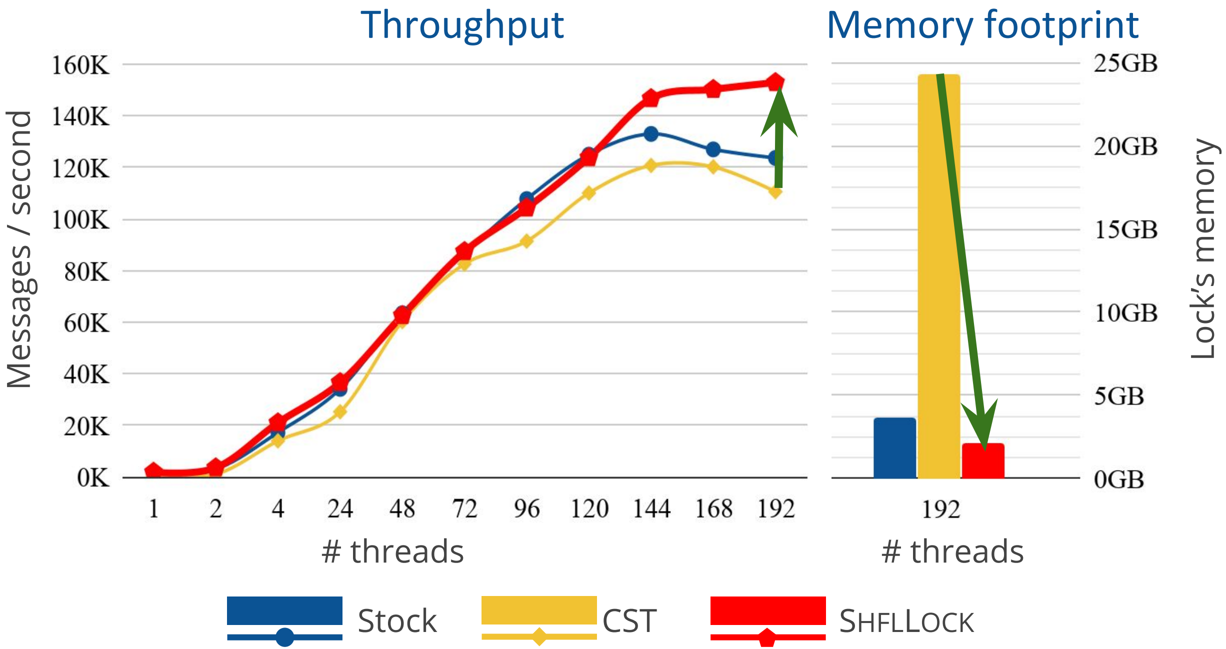

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Conclusion

- Current lock designs:
  - Do not maintain best throughput with varying threads
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- **Shuffling**: Reorder the list or modify a waiter's state on the fly
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- **SHFLLOCKS**: Shuffling-based family of lock algorithms
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Thank you!