PennState

Parsec: Fast, Scalable, and Secure Design with Wait-Free Parallelism

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Thread Synchronization

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- Alternatives: fine-grained locks and read-copy-update (RCU)
  - These approaches are still blocking and need mutual exclusion
- **Non-blocking** data structures are becoming increasingly popular
  - ***Obstruction-freedom***: a thread always makes progress when executing without interference from other threads
  - ***Lock-freedom****:* at least one thread always makes progress (even with interference)
  - ***Wait-freedom****:* all threads always make progress

Lock-Freedom vs. Wait-Freedom

- **Deadlock-freedom** and **starvation-freedom** are well-known properties in the blocking world
  - **Lock-free** algorithms only guarantee global progress since individual threads can still starve
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Background: Read-Copy-Update (RCU)

- Used widely in the Linux kernel
  - Avoids mutual exclusion for readers
  - But does not solve synchronization for writers unless it is trivial
- Great performance for reading-dominated workloads
- Has a built-in memory reclamation strategy
  - Can safely reclaim memory objects even though readers have stale pointers

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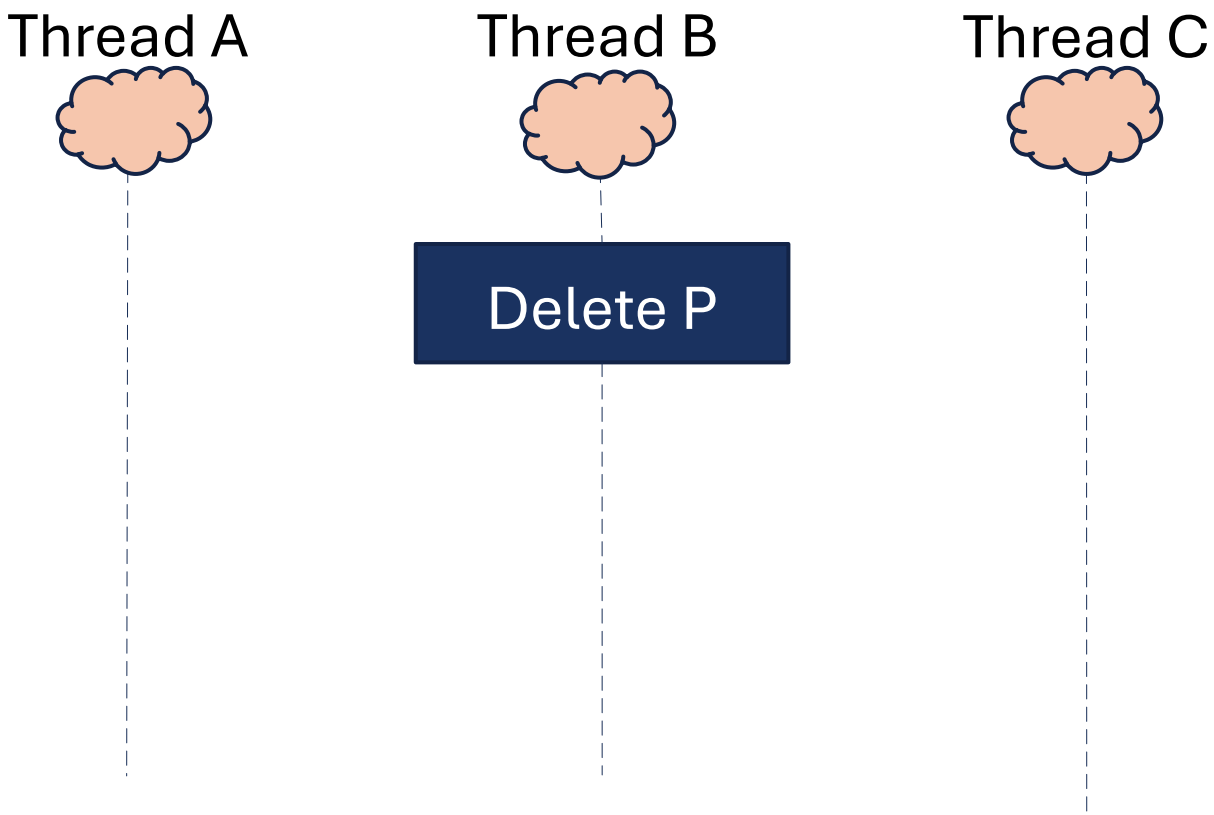

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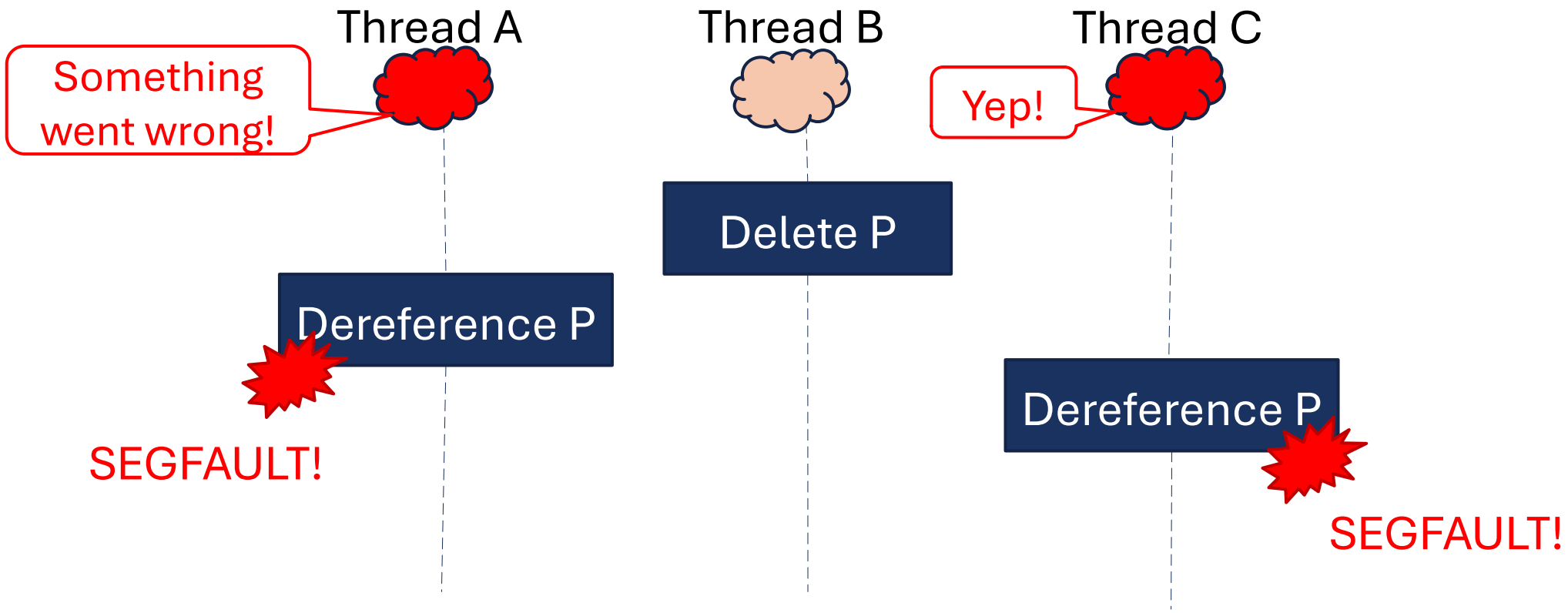

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RCU Vulnerability: Exhausting Memory

```
struct foo { struct rcu_head rh; };
struct foo *g;

void reader() {
    rcu_read_lock();
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```
void writer_block() {
    new_mem = malloc(sizeof(struct foo));
    old_mem = rcu_dereference(g);
    rcu_assign_pointer(g, new_mem);
    synchronize_rcu(); // Blocks indefinitely!
    kfree(old_mem); // Not reachable
}
```

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}
                void writer_nonblock() {
                    for (i = 0; i < count; i++) {
                        new_mem = malloc(sizeof(struct foo));
                        old_mem = rcu_dereference(g);
                        rcu_assign_pointer(g, new_mem);
                        call_rcu(&old_mem->rh, callback_kfree);
                        // Exhausts memory because it allocates
                        // new memory without releasing anything!
                    }
                }
```

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- Non-blocking **call_rcu** is problematic
  - Can easily exhaust memory, virtually no limit
  - High memory footprints: see “**The RCU-Reader Preemption Problem in VMs**” by Aravinda Prasad, K. Gopinath, and Paul E. McKenney **[ATC'17]**

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  - Has a high latency of at least 1 jiffy, slowdowns of several milliseconds
- High latency of **synchronize_rcu** can mitigate DoS attacks
  - But not fully and is **not always acceptable**…
  - **synchronize_rcu_expedited** => more aggressive and vulnerable to DoS

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  - Recall: lock-freedom means at least one thread **always** makes progress
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- **Solution:** Use **non-blocking** approaches instead?
  - Note ***obstruction-free*** approaches are vulnerable to DoS because they depend on non-interference of threads
  - ***Can lock-free algorithms help with that?***

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Short answer: No

But **wait-free** algorithms can

What is the Problem with Lock-Freedom?

- A given thread may theoretically **never** complete due to starvation
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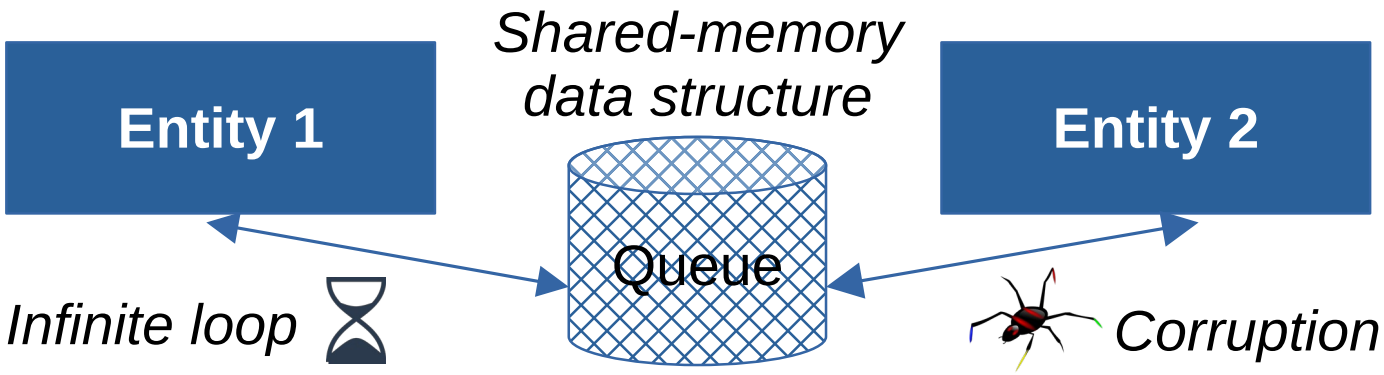

How do we know that the delay is not transient and the loop is infinite (e.g., queue is corrupted)?

Wait-Free Approaches

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- Historically harder to implement
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  - Now more feasible with Kogan-Petrank [PPoPP'12] “fast-path-slow-path” and similar methods
  - Threads collaborate to bound the number of operations for each thread
- Provide a ***theoretical upper-bound*** for the number of iterations
  - When exceeding this threshold, we can declare that the data structure is corrupted by the other side
  - Assuming rigorous memory safety checks and this bound, we can avoid DoS => an insight that was not widely discussed in the literature

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  - A **single** CPU instruction => does not have the above problem
- Specialized instructions
  - Fetch-and-Add (FAA) and SWAP (XCHG)
  - Can be implemented via LL/SC and CAS

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- CAS is considered inferior to LL/SC [Herlihy's Hierarchy]
  - ABA problem (false-positive match) is possible when objects are being recycled and pointers happen to be the same
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  - FAA, SWAP, etc. is potentially more expensive via CAS
  - LL/SC while theoretically superior, prevents nesting and restricts types of operations in practice
- But these problems can be solved
  - Double-width CAS (cmpxchg16b), where the second word is a monotonically increasing tag, solves the ABA problem
  - **Wait-free** FAA and SWAP can be implemented natively in hardware

Issues with LL/SC

- “Strong” CAS implemented via LL/SC is problematic
  - Programmers expect CAS either succeed or fail after ***finite time***
  - But when implementing via LL/SC, we have a potentially infinite loop
- “Weak” CAS is safer for lock-free algorithms
  - But programmers are not necessarily aware of this
  - No ***bound*** for wait-free algorithms => **no wait-freedom**
- No “weak” FAA, etc.
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Conclusion: LL/SC is unsafe and bad even for RISC architectures!
Fortunately, AArch64 and RISC-V already fixed this problem

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  - Up to 512 messages in any channel

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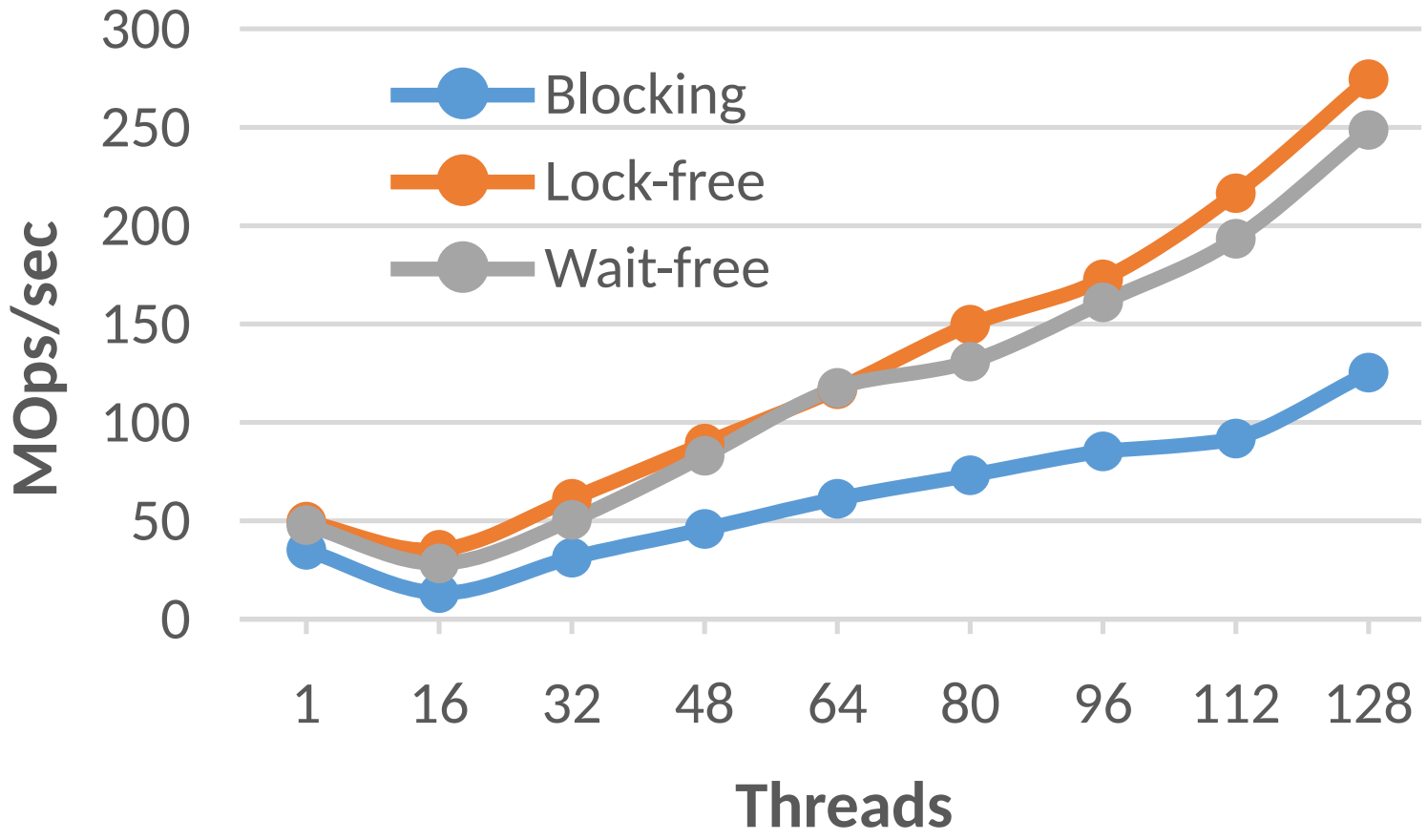
  - Every thread sends to or receives from its own channel and from another channel for the next thread => at most **two** threads access any channel
  - Up to 512 messages in any channel
- Our C implementation
  - Straight-forward implementation using semaphores and buffer **locks**
  - Semaphores and a **lock-free** ring buffer by Nikolaev **[DISC'19]**
  - Semaphores and a **wait-free** ring buffer by Nikolaev & Ravindran **[SPAA'22]**
  - The latter two approaches are **non-blocking** unless sleeping (nothing to produce or to consume)

Evaluation


300
250
200
150
100
50
0
MOps/sec
Blocking
Lock-free
Wait-free
1
16
32
48
64
80
96
112
128
Threads

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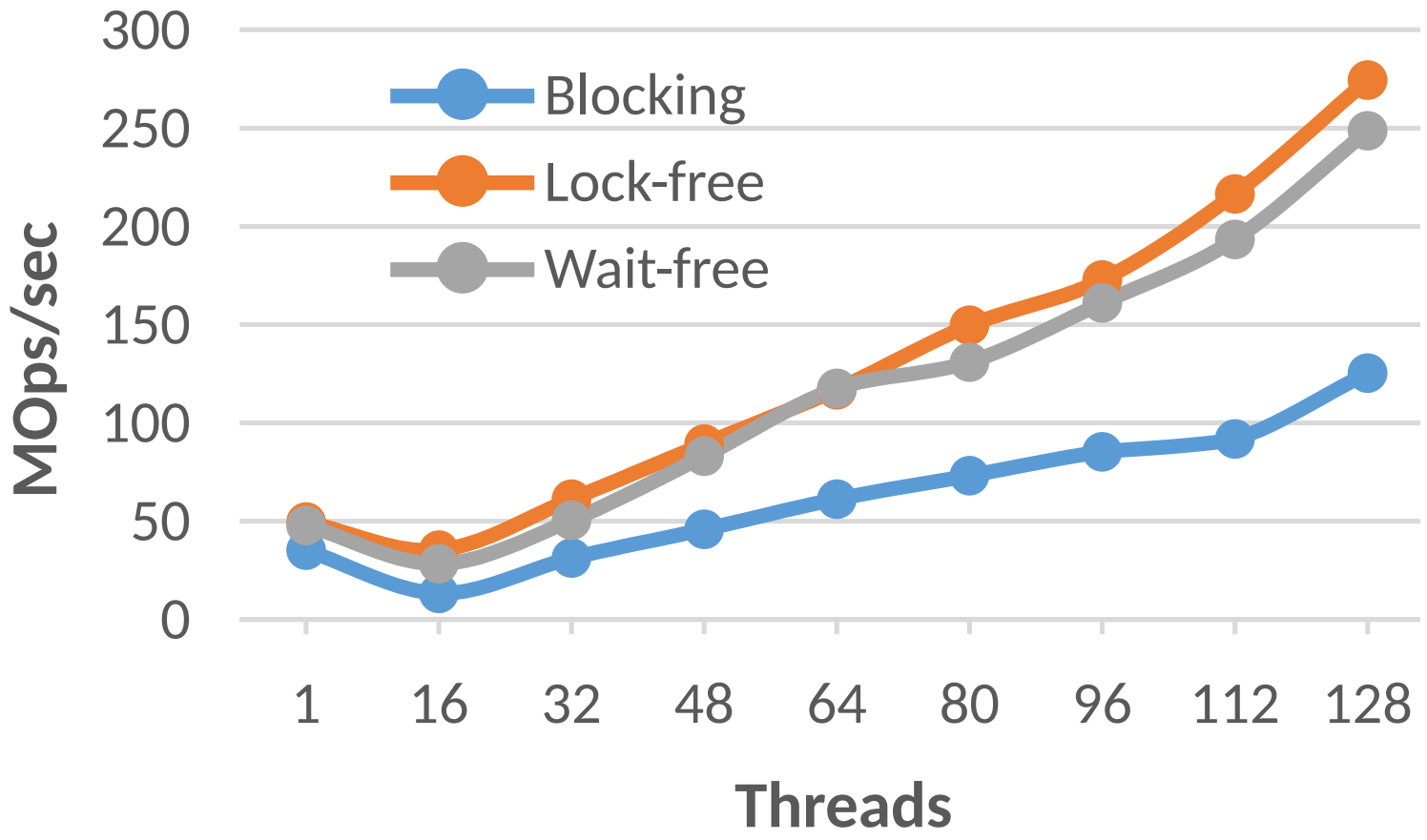

Despite low-contention, blocking version is **2x-3x** slower

*System calls are needed to synchronize even just **two** threads*

Code Availability

- More information and code to be released at:

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Thank You!

Questions?