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BWoS: Formally Verified Block-based Work Stealing for Parallel Processing

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[4] SHANGHAI JIAO TONG UNIVERSITY

Parallel Processing Scenarios

Parallel Processing Scenarios

Java

GO

julia

Kotlin

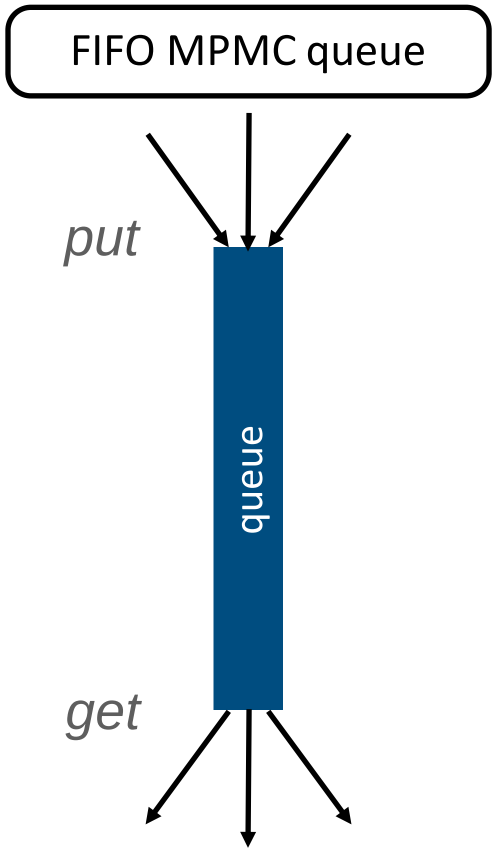
JS

Parallel Processing Scenarios

Intel® TBB runtime

Queues for Parallel Processing

Existing Approaches



Queues for Parallel Processing

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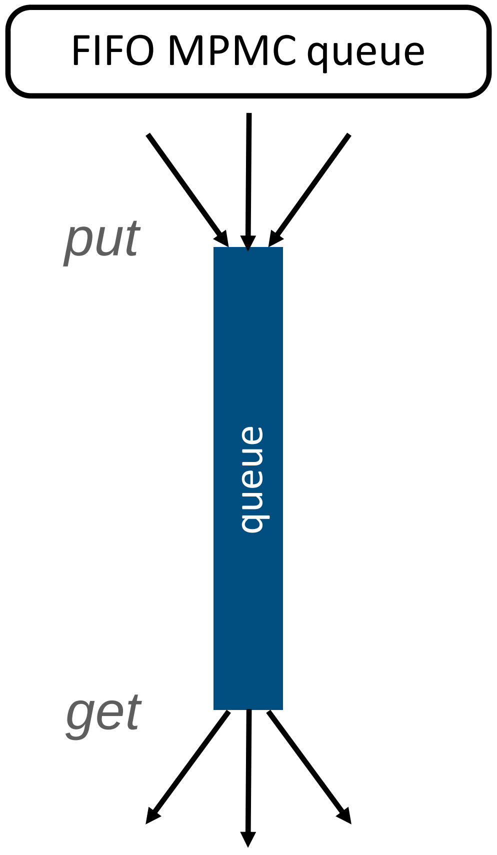
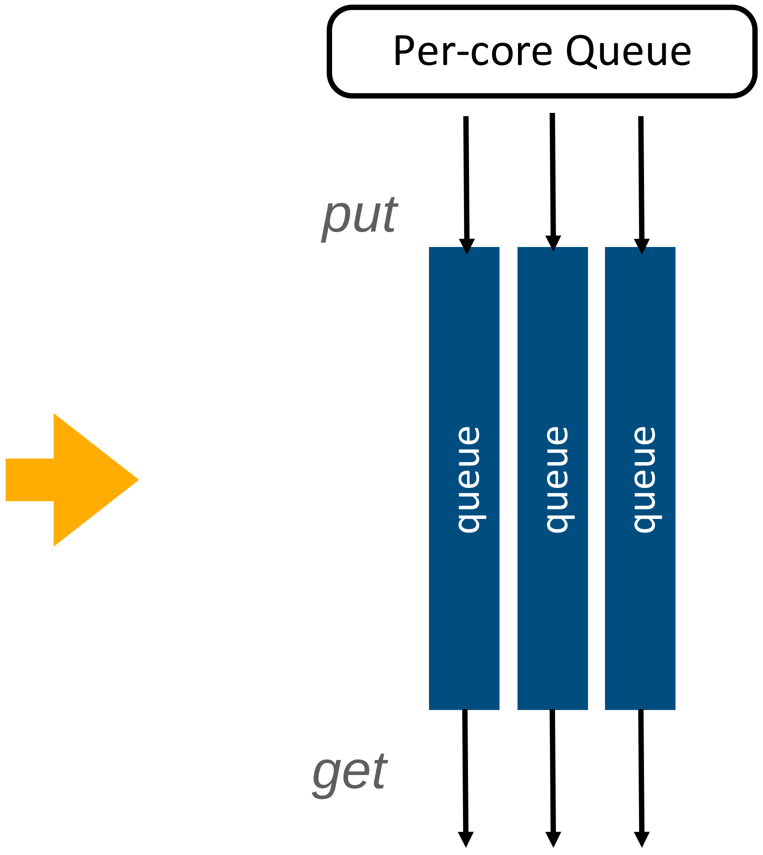


Does not scale



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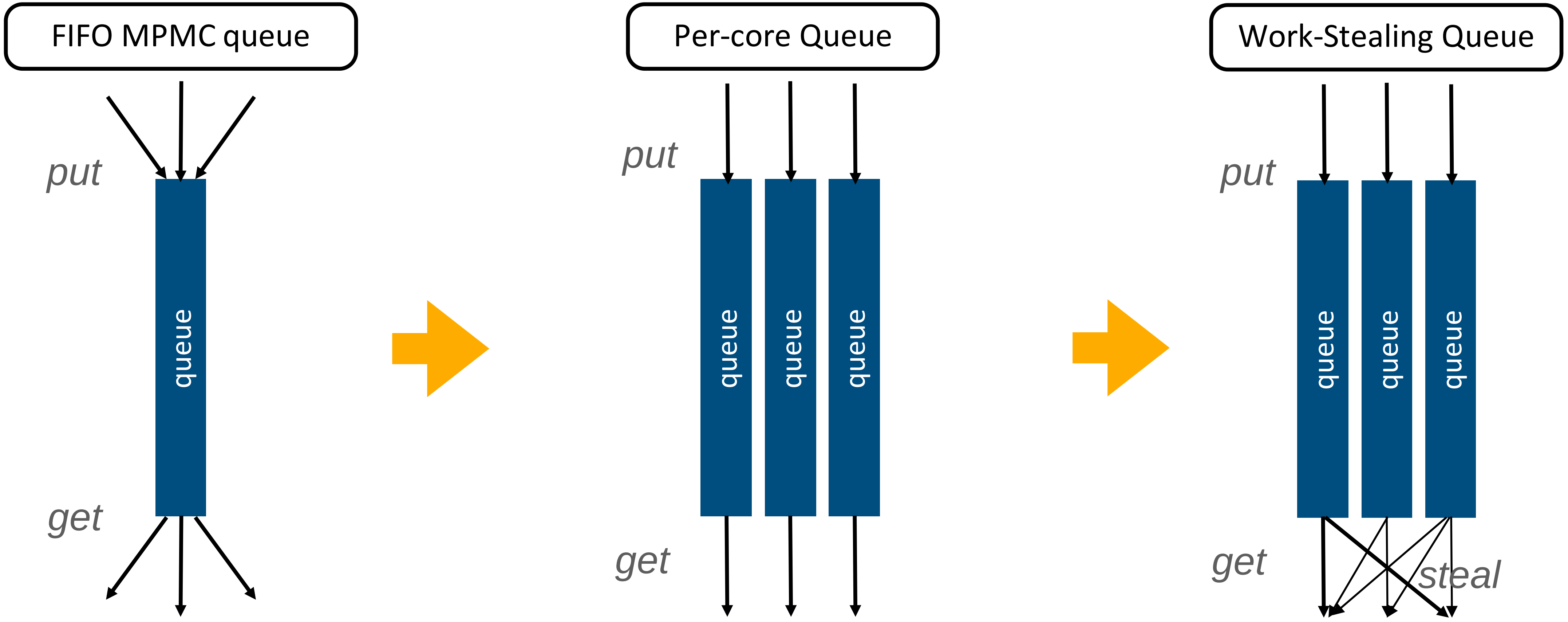
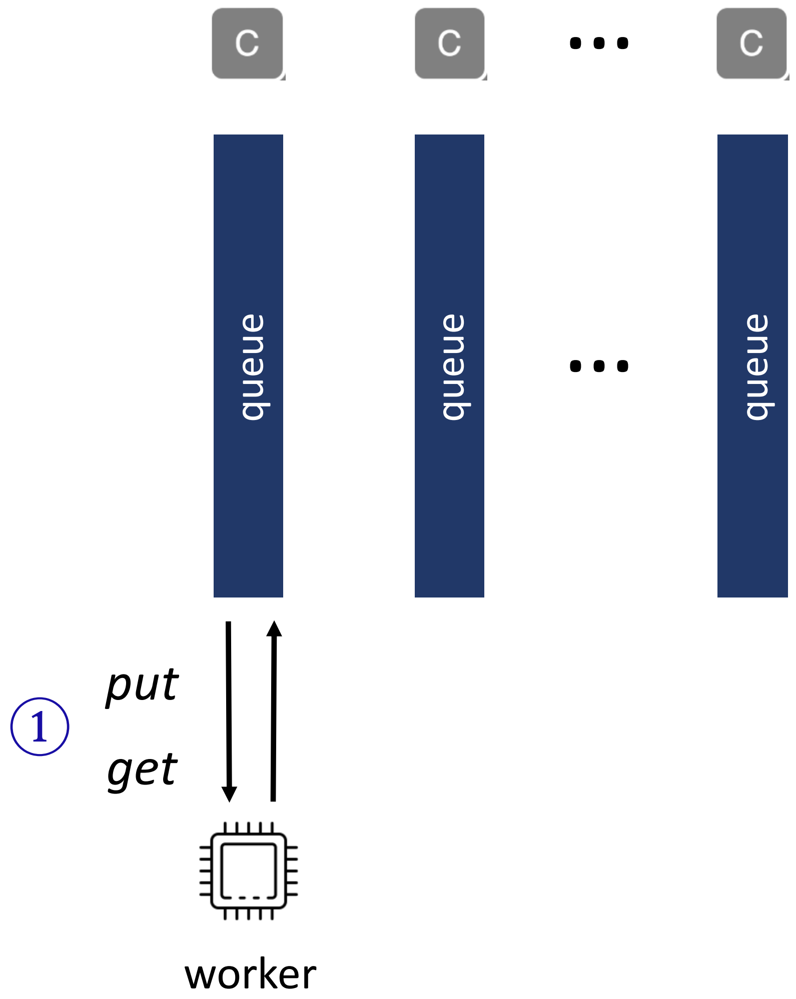


Does not scale

Fast but imbalanced

Work Stealing



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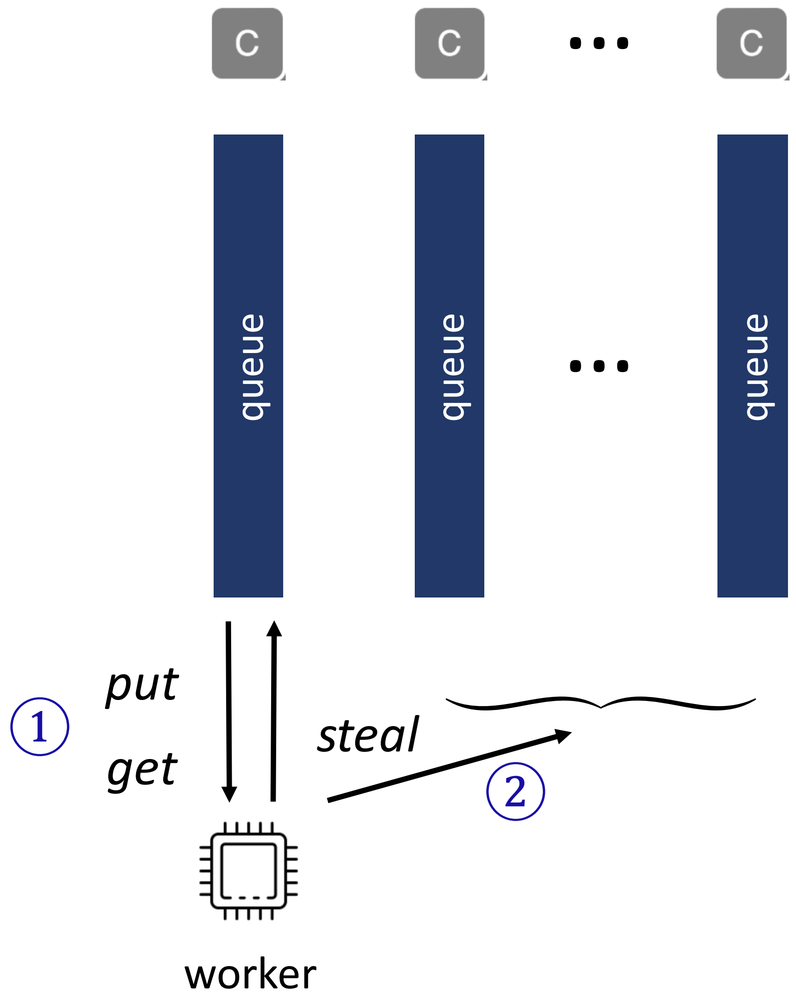

1 A worker (thread) puts on / gets from its own queue.

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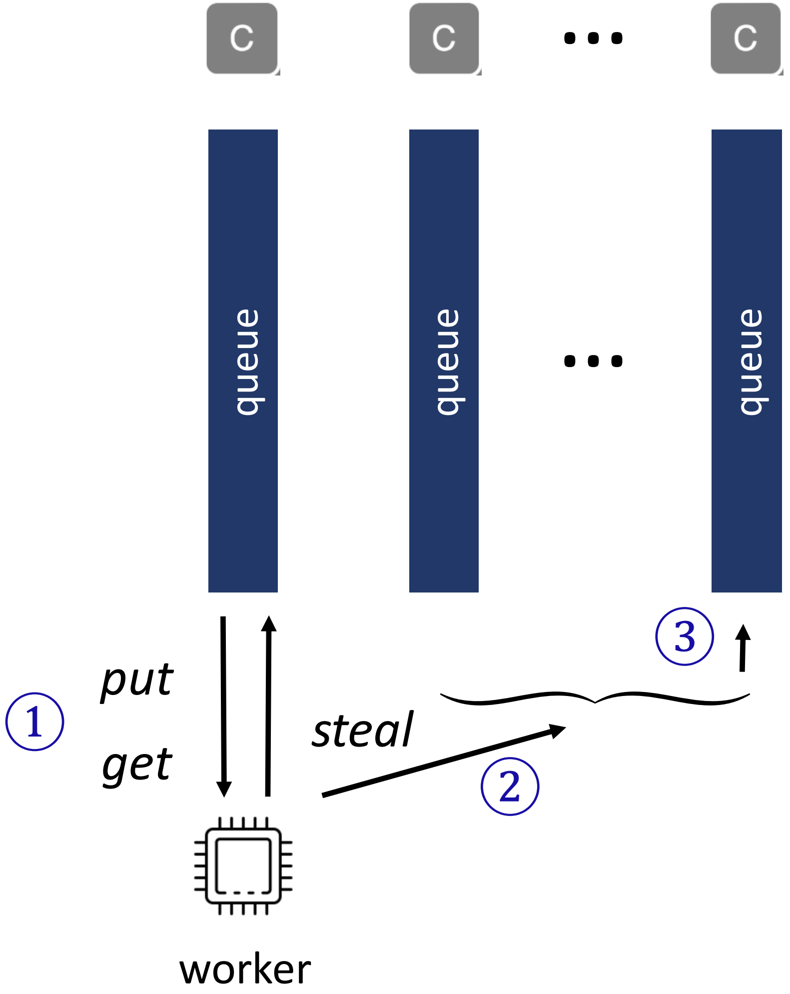
Work Stealing



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③ and try to steal from it.

Work Stealing Becomes the Bottleneck

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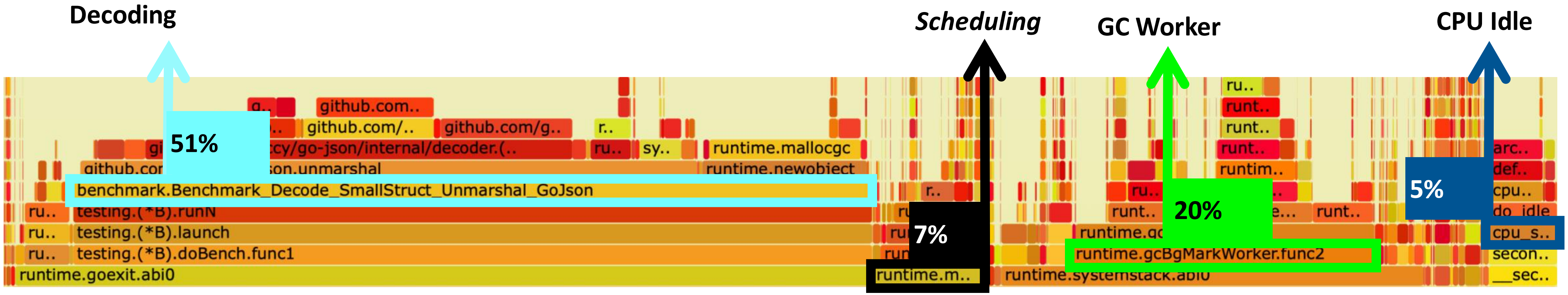
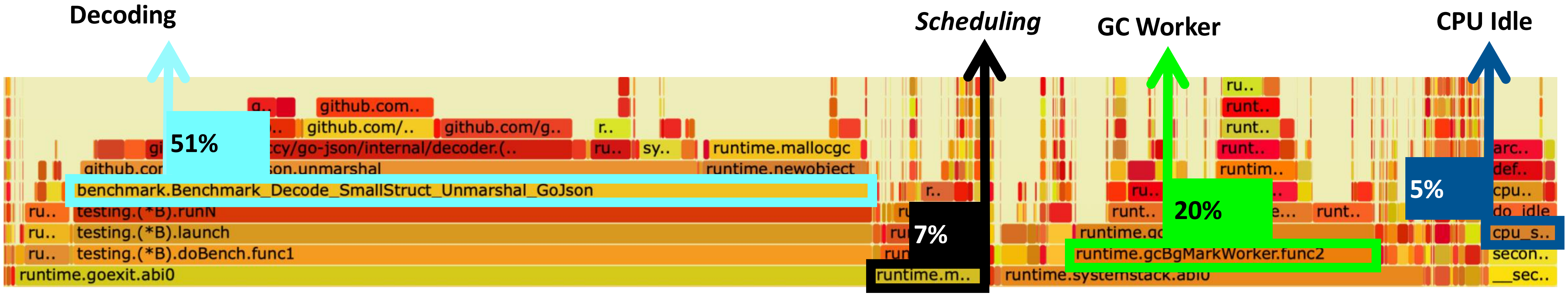
Example 1: GoJson Object Decoding Benchmark



Work Stealing Becomes the Bottleneck

Example 1: GoJson Object Decoding Benchmark



Example 2: Experience of Rust Tokio's author

[1]

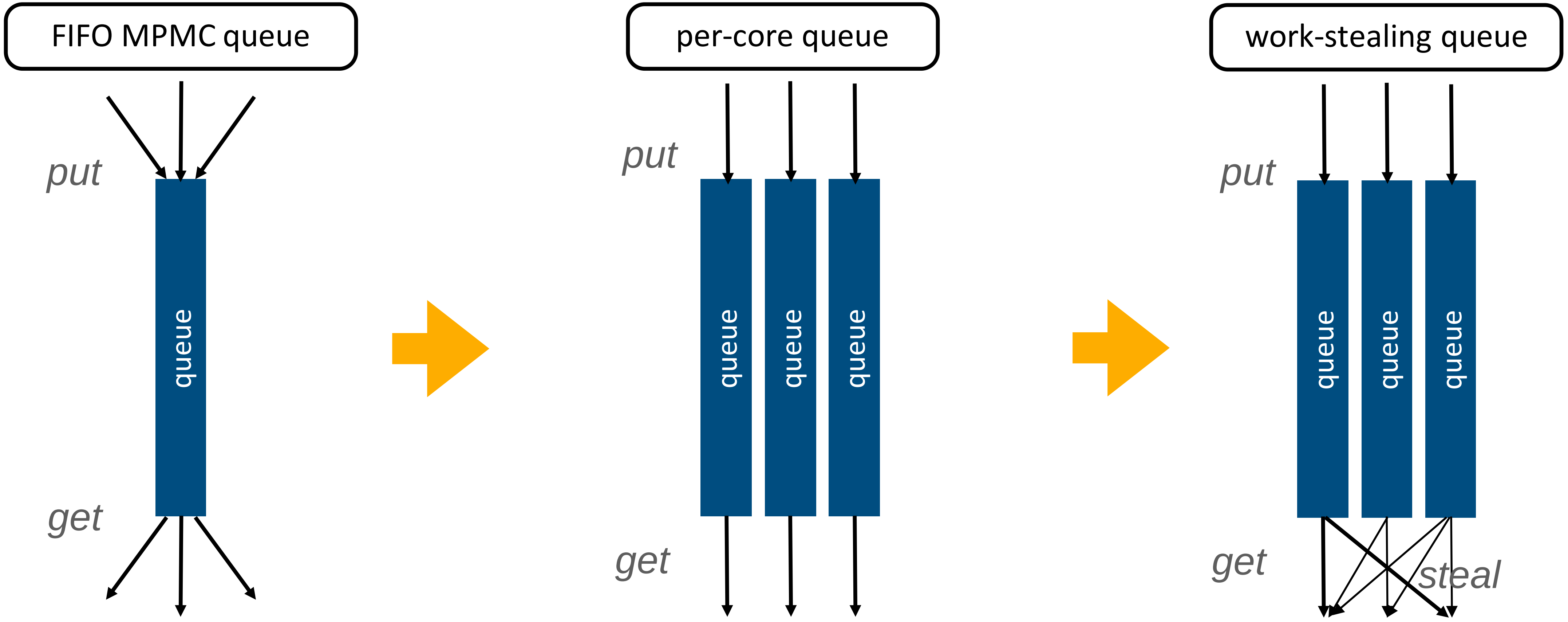
The run queue is at the heart of the scheduler. As such, it is probably the most critical component to get right. The original Tokio scheduler used crossbeam's deque implementation, which is single-producer, multi-consumer deque

contention is reduced. However, Rust's asynchronous tasks are expected to take very little time executing when popped from the run queue. In this scenario, the overhead from contending on the queue becomes significant.

[1] Making the Tokio scheduler 10x faster (https://tokio.rs/blog/2019-10-scheduler)

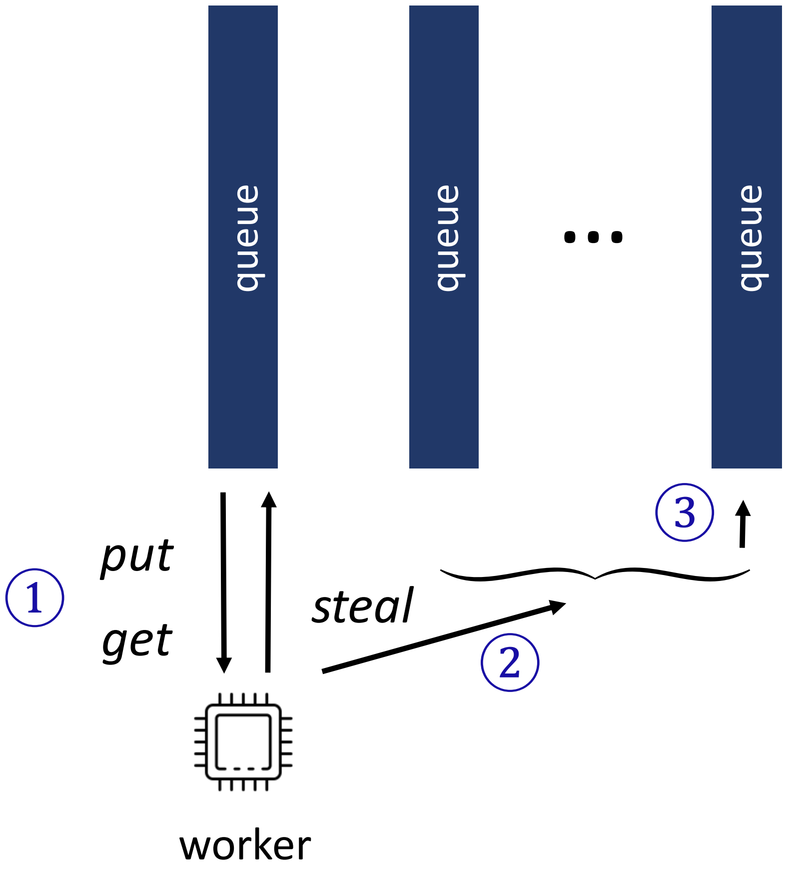
Queues for Parallel Processing

existing works



Does not scale — Fast but imbalanced — Not fast enough

Sources of the Overhead



1. A worker (thread) puts on / gets from its own queue.
   FIFO / LIFO
   A) Cost of Synchronization Operations

2. When its queue is empty, it selects another queue…
   Random, best of two, NUMA-aware, Batching …
   B) Overhead due to Victim Selection *(see paper)*

3. and try to steal from it.
   C) Interference Cost with Thieves

Sources of the Overhead

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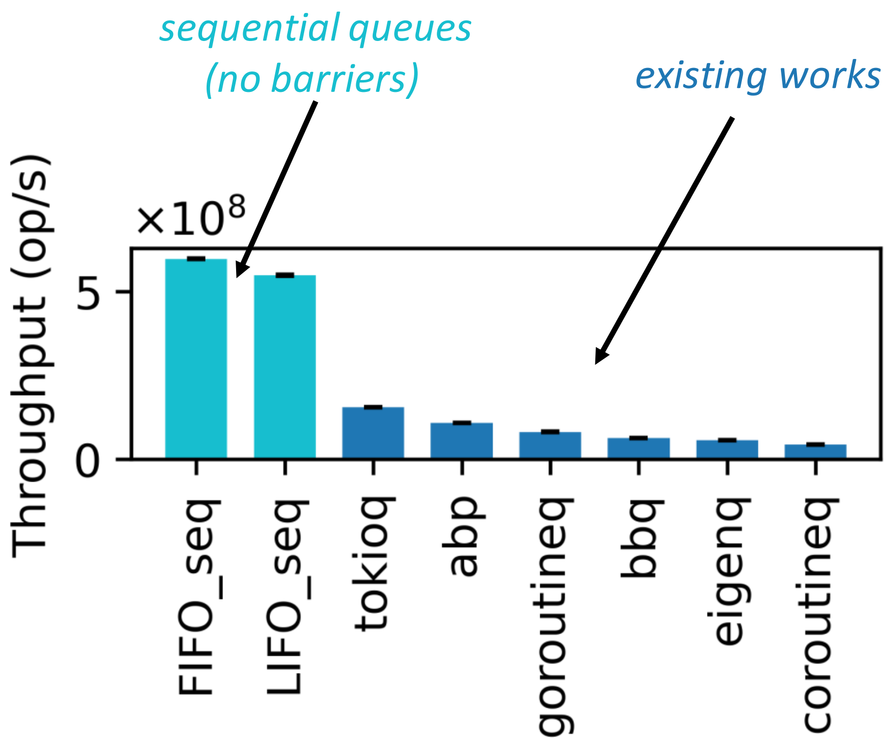

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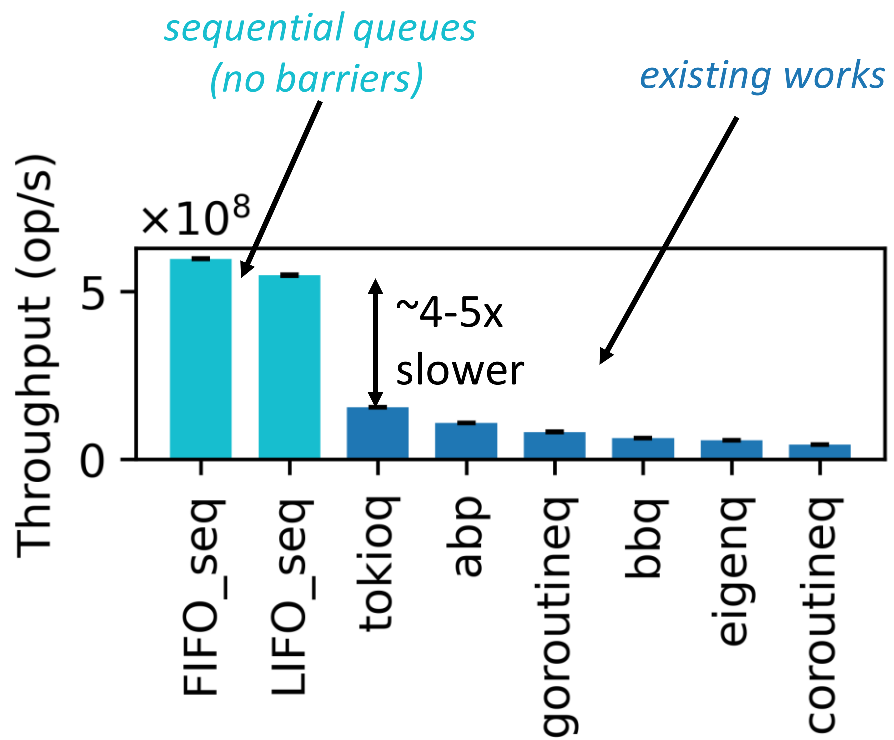

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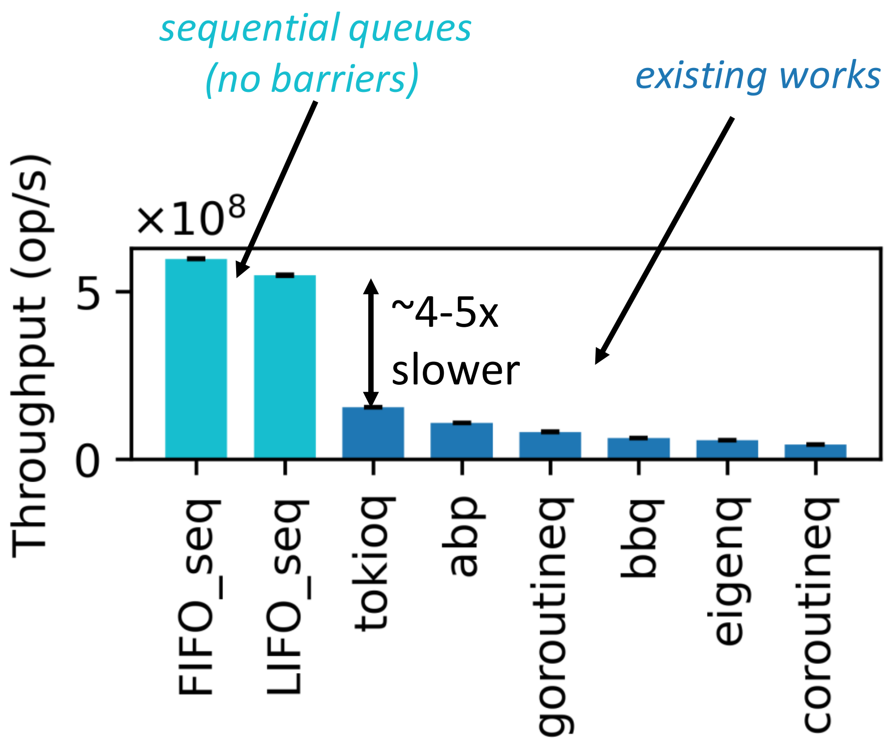
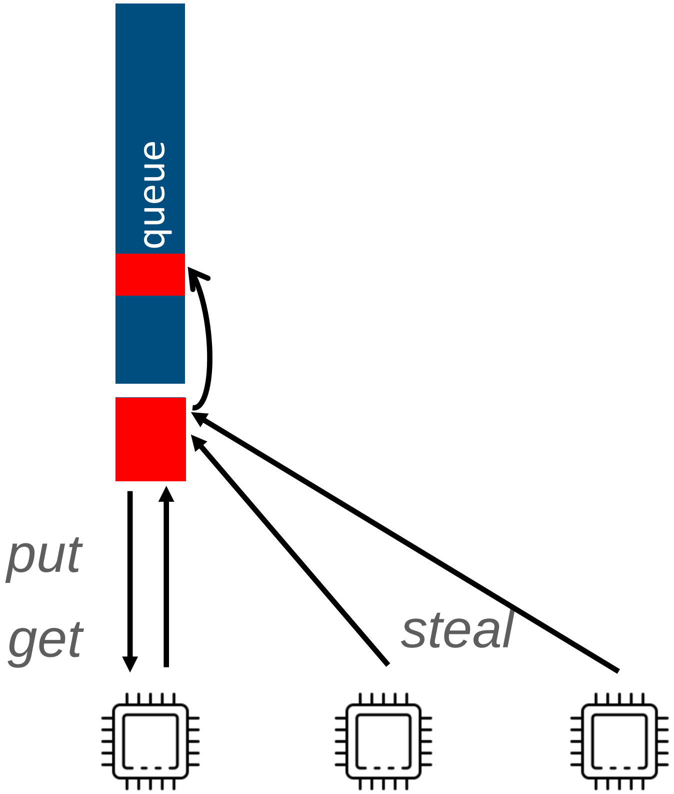


- Throughput of existing works is far away from sequential queues (theoretical upper bound)
- As steals may happen at any time strong atomic barriers are introduced

Sources of the Overhead

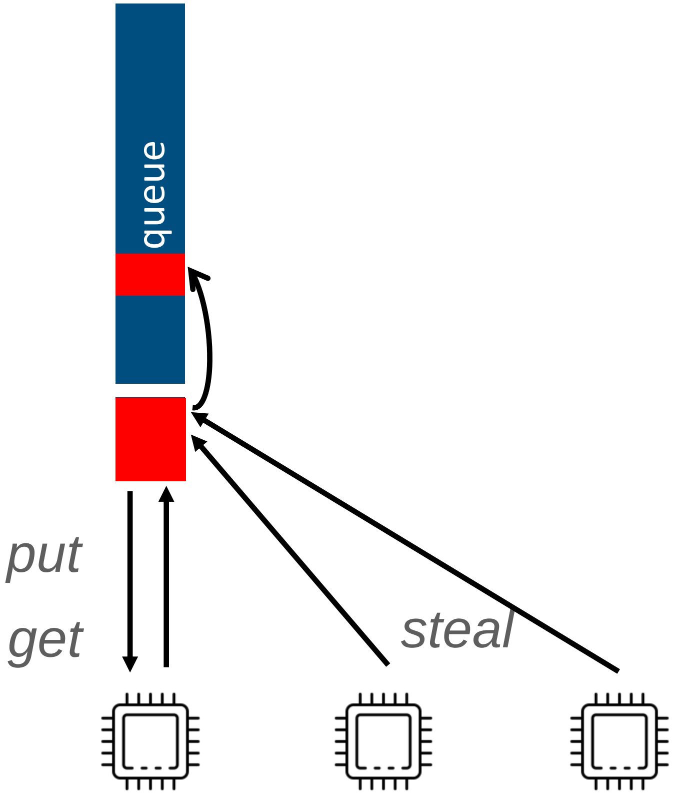
C) Cost of Interference with Thieves



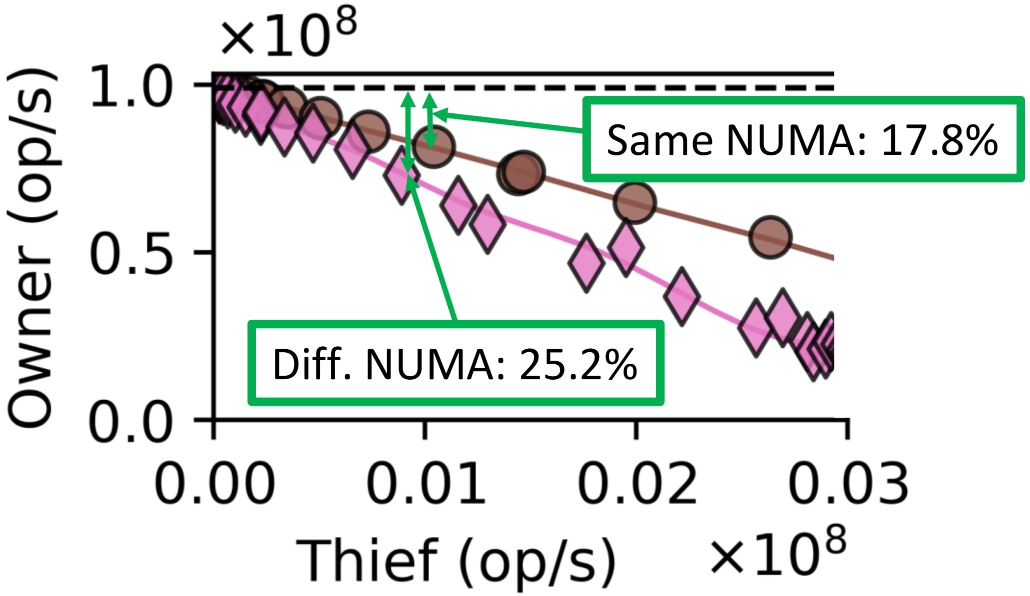
- Thieves affect the throughput of the owner

Sources of the Overhead

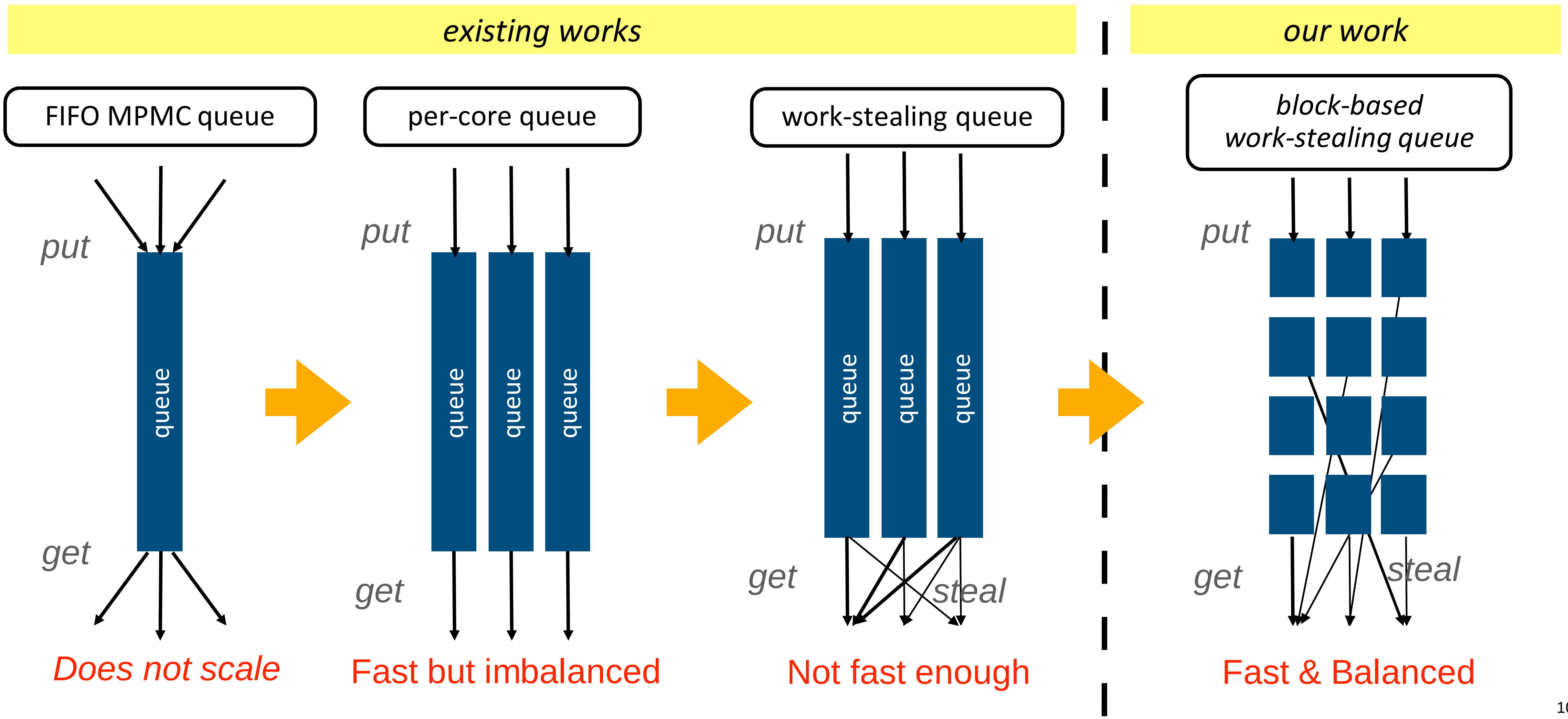
C) Cost of Interference with Thieves



- Thieves affect the throughput of the owner
- Stealing 1% of the elements:



BWoS — Block-based Work Stealing



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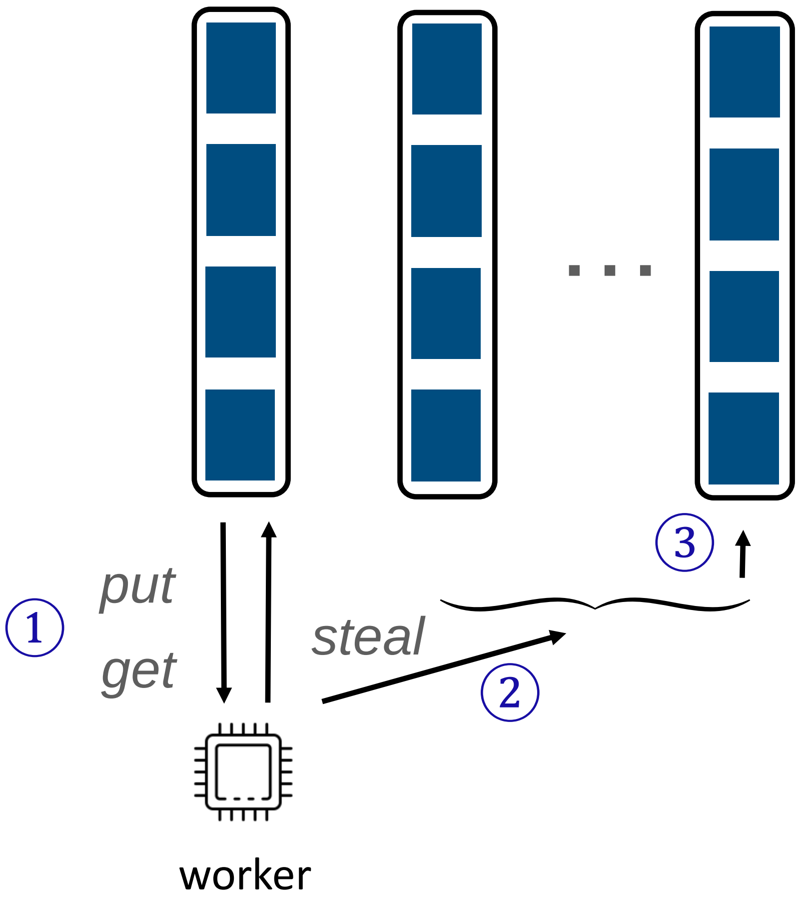

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FIFO / LIFO

Block-level synchronization: no barriers inside blocks

② When its queue is empty, it selects another queue…

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Randomized Victim Selection Policy

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No Interference when stealing from a different block

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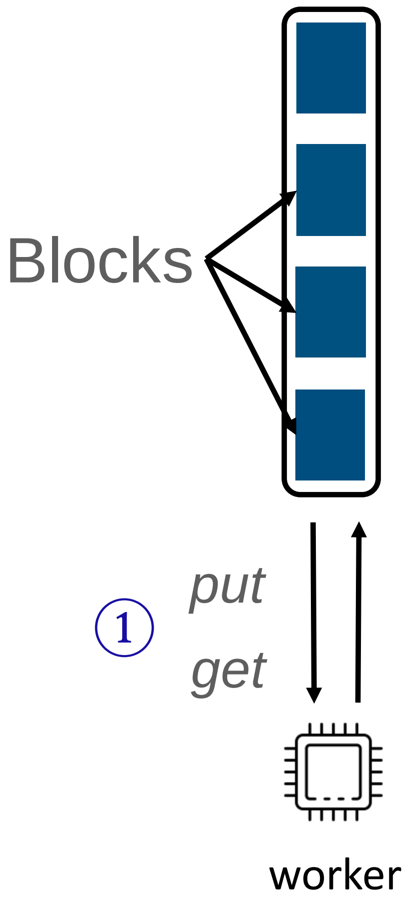

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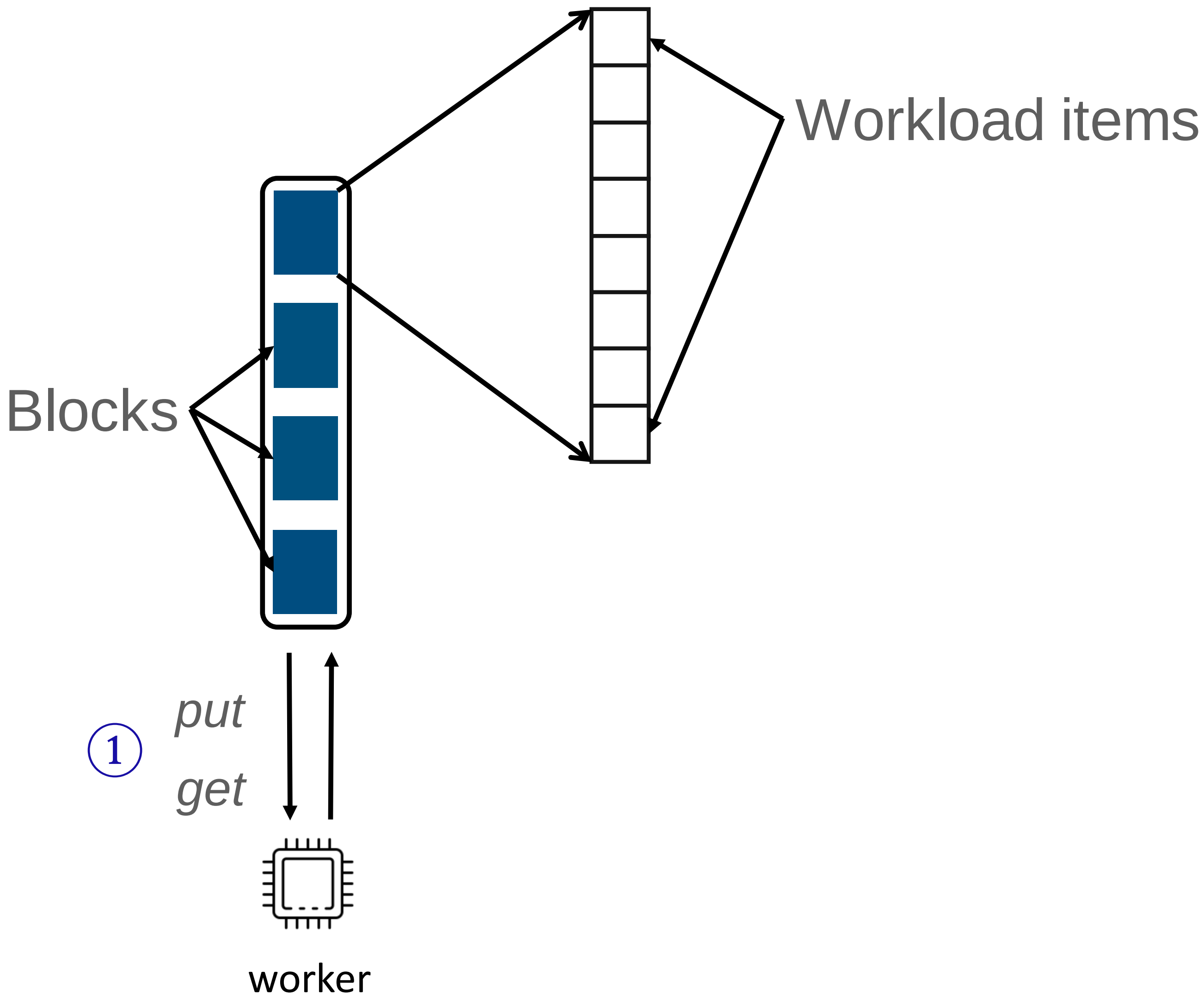

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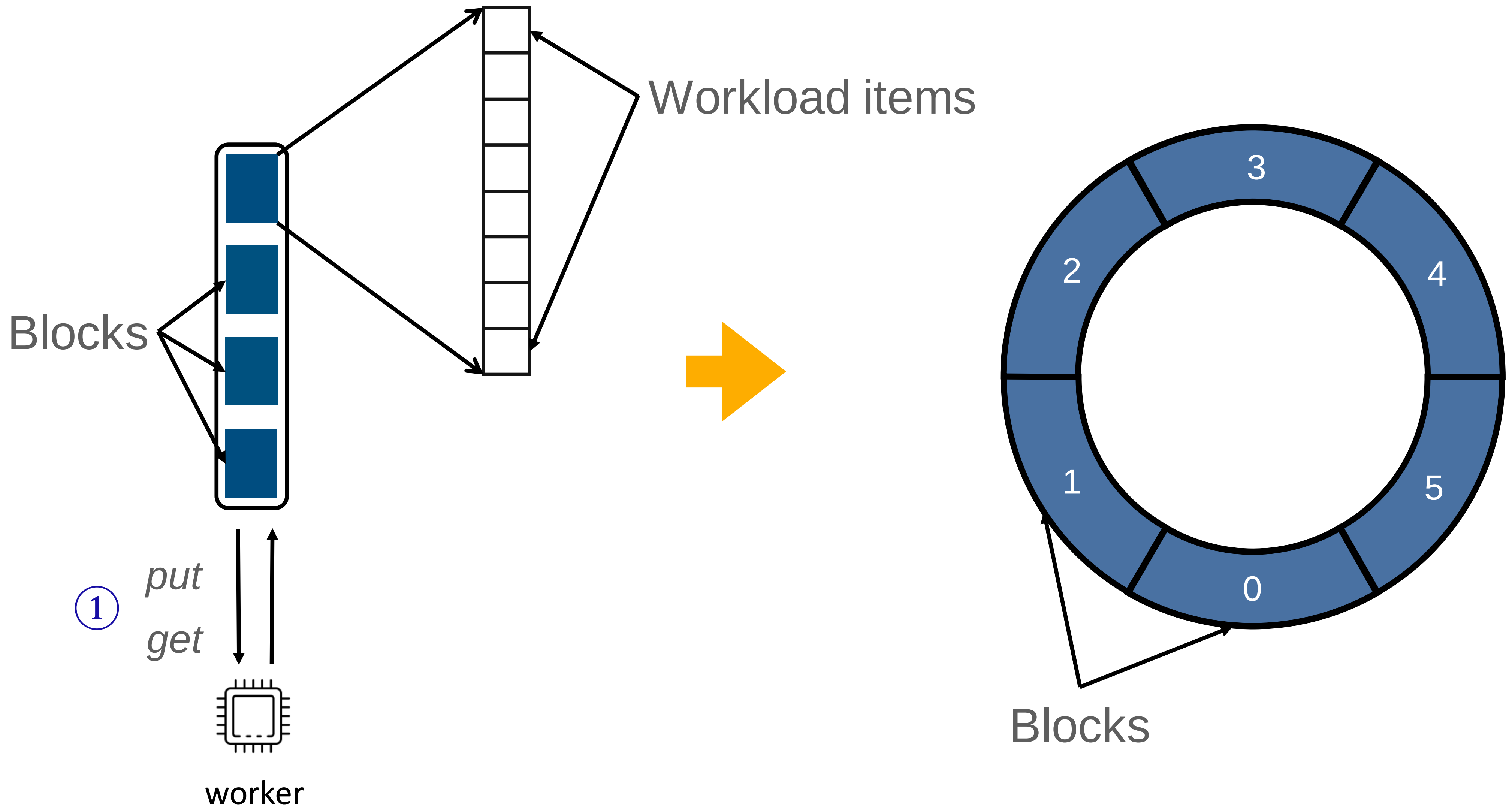

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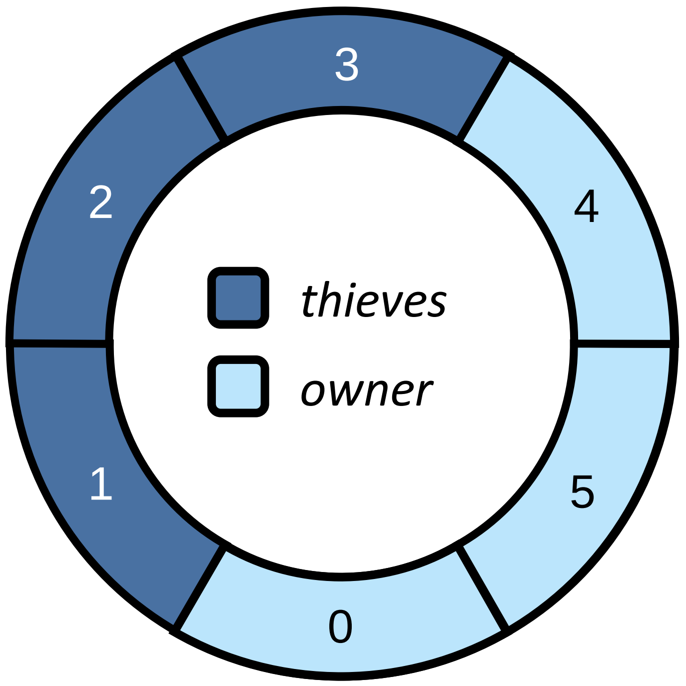

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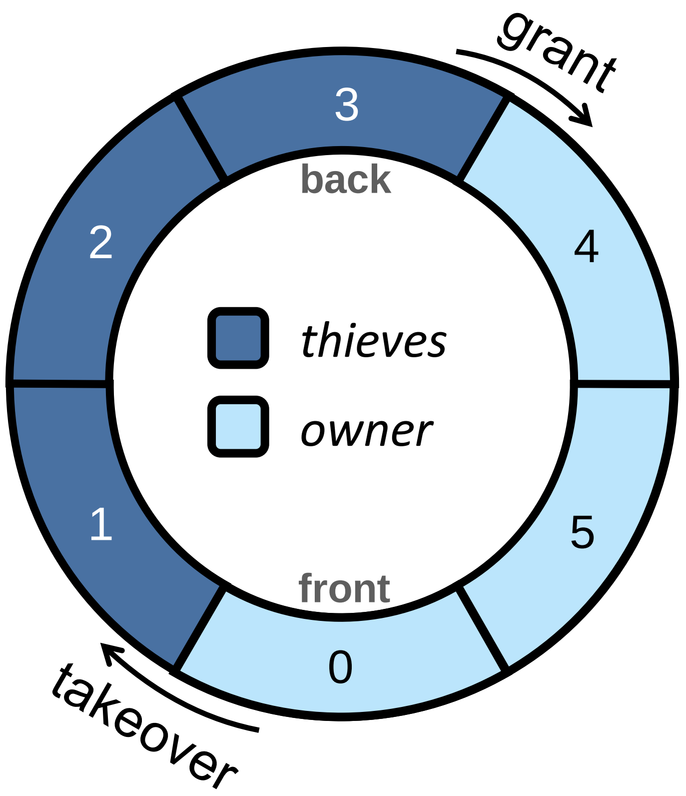

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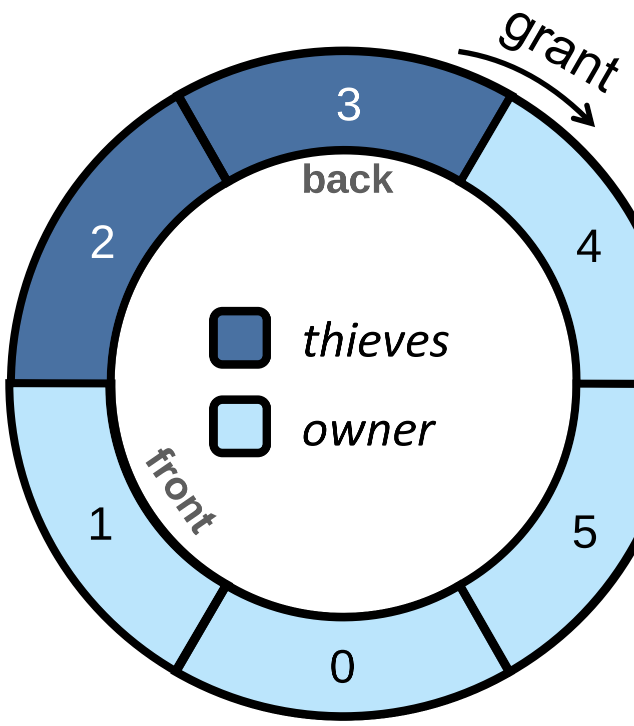

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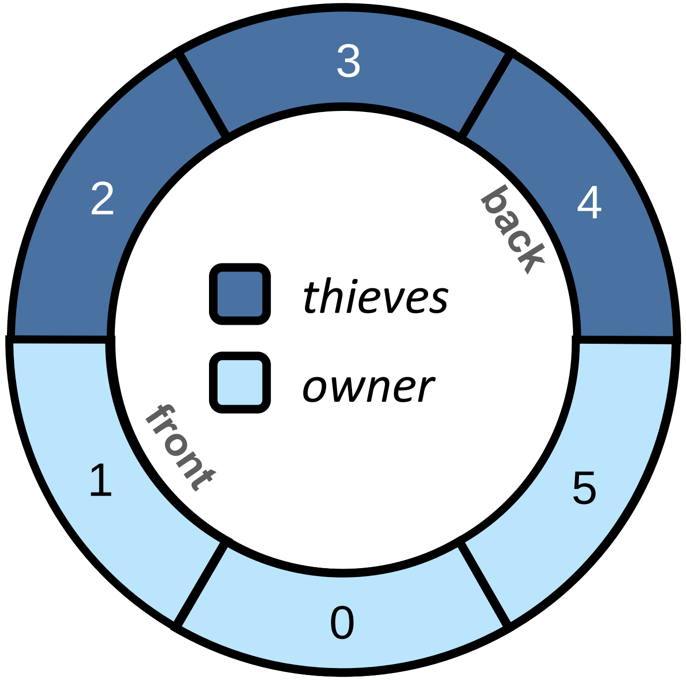

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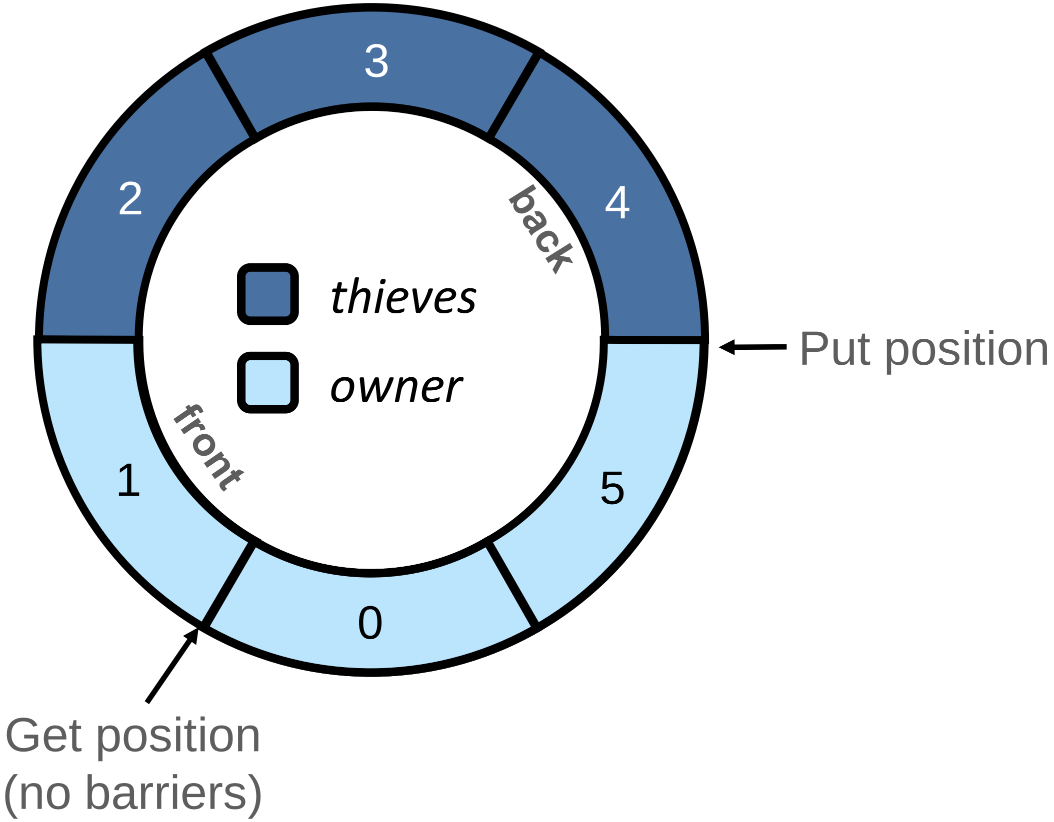

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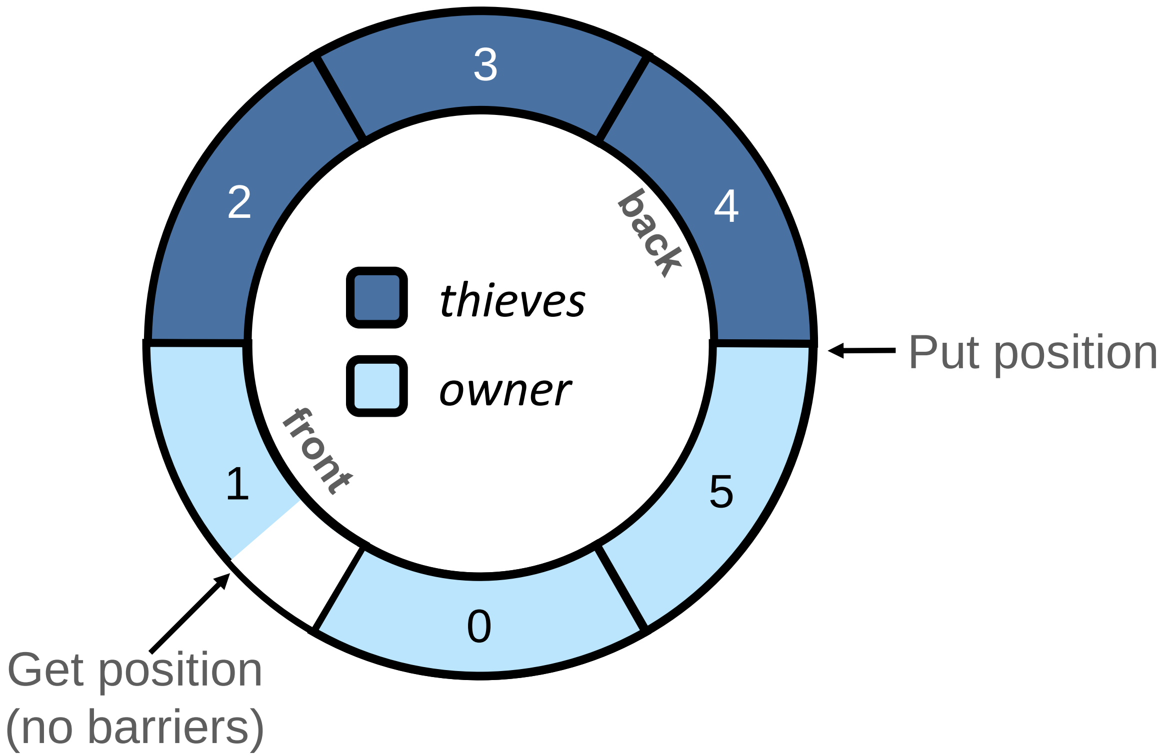

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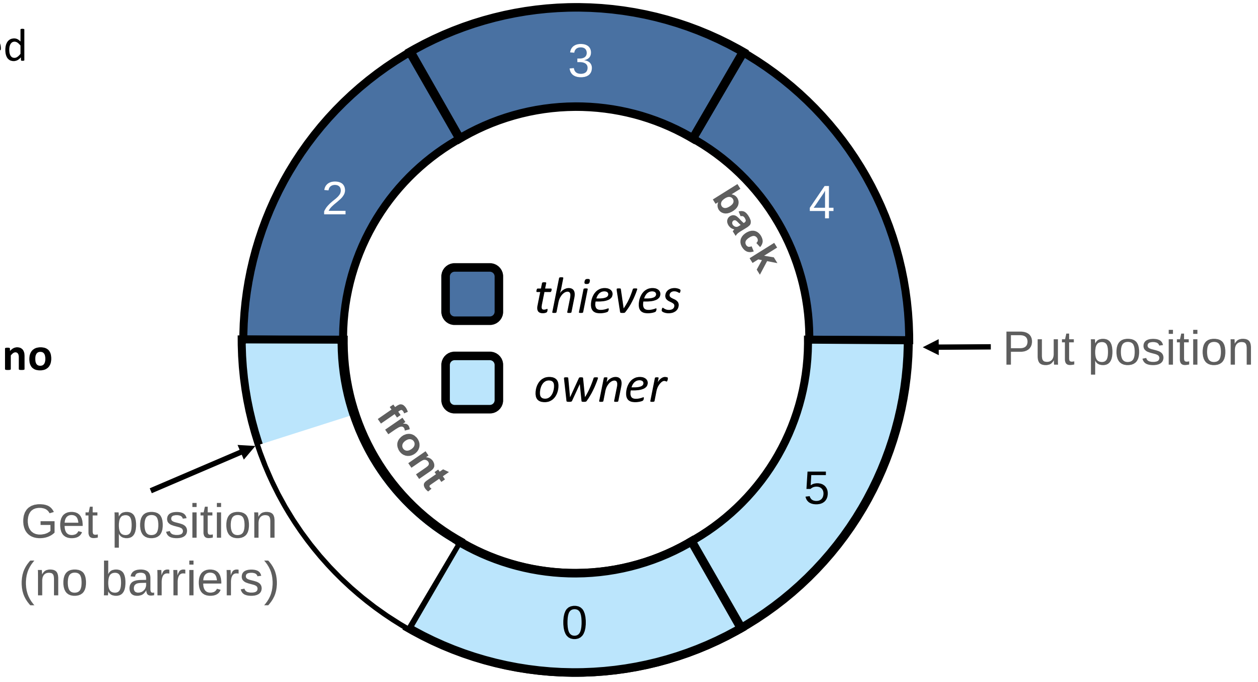

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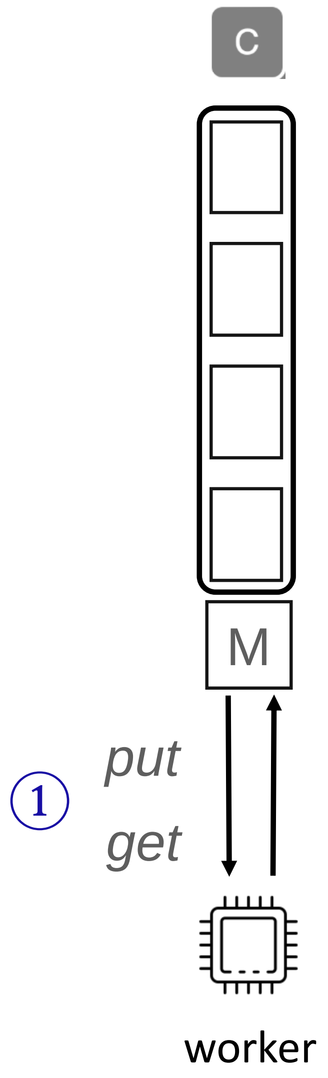

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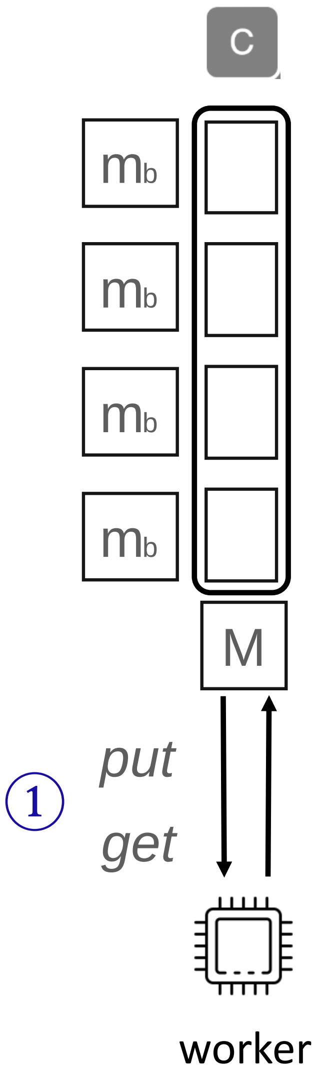

B) Overhead due to Victim Selection

- Each block has a dedicated metadata instance

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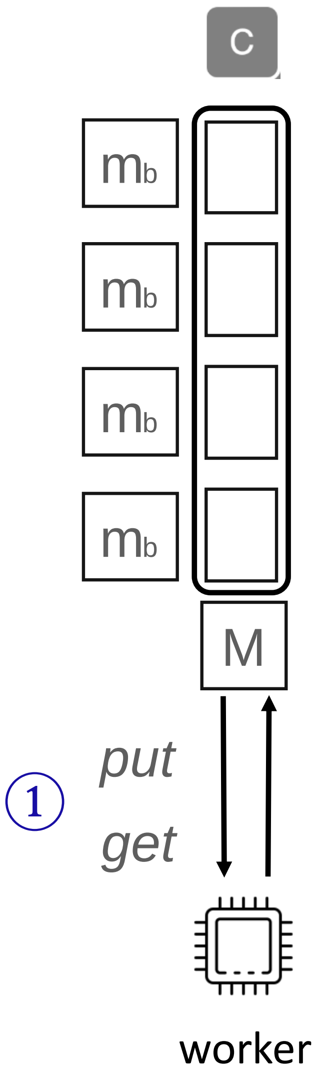

B) Overhead due to Victim Selection

- Each block has a dedicated metadata instance
- Novel probabilistic stealing policy:
  Use sampling to estimate Size/Capacity.
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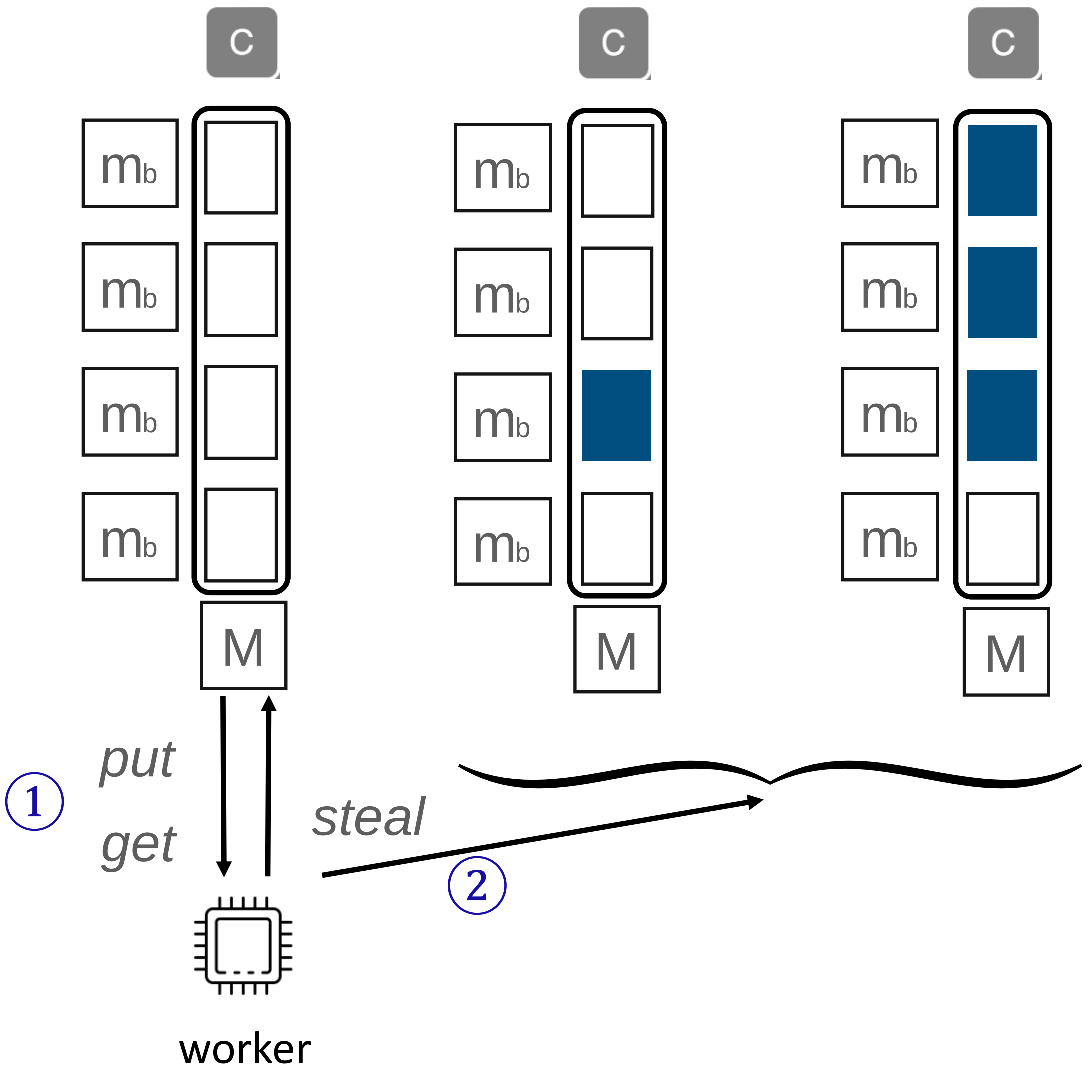

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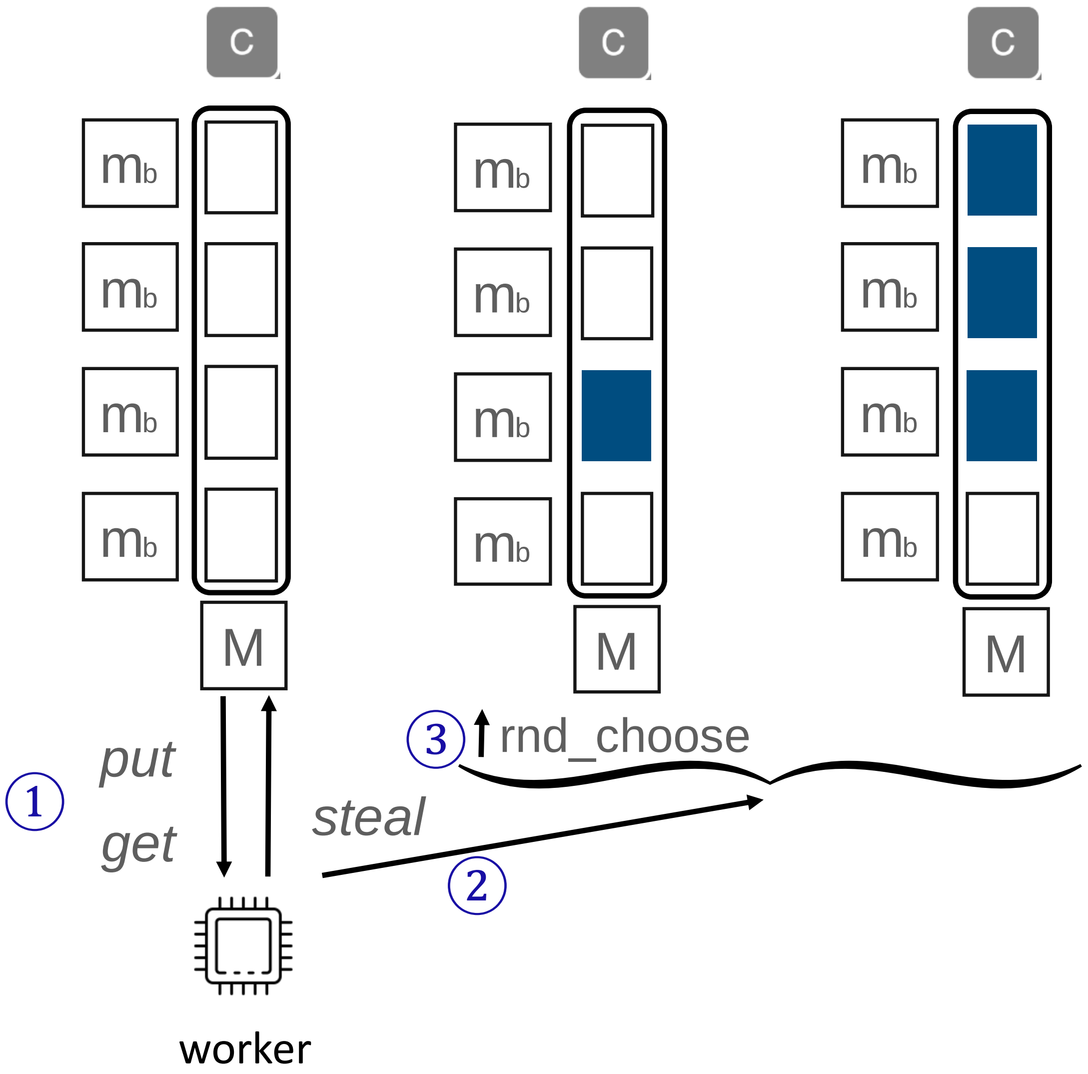

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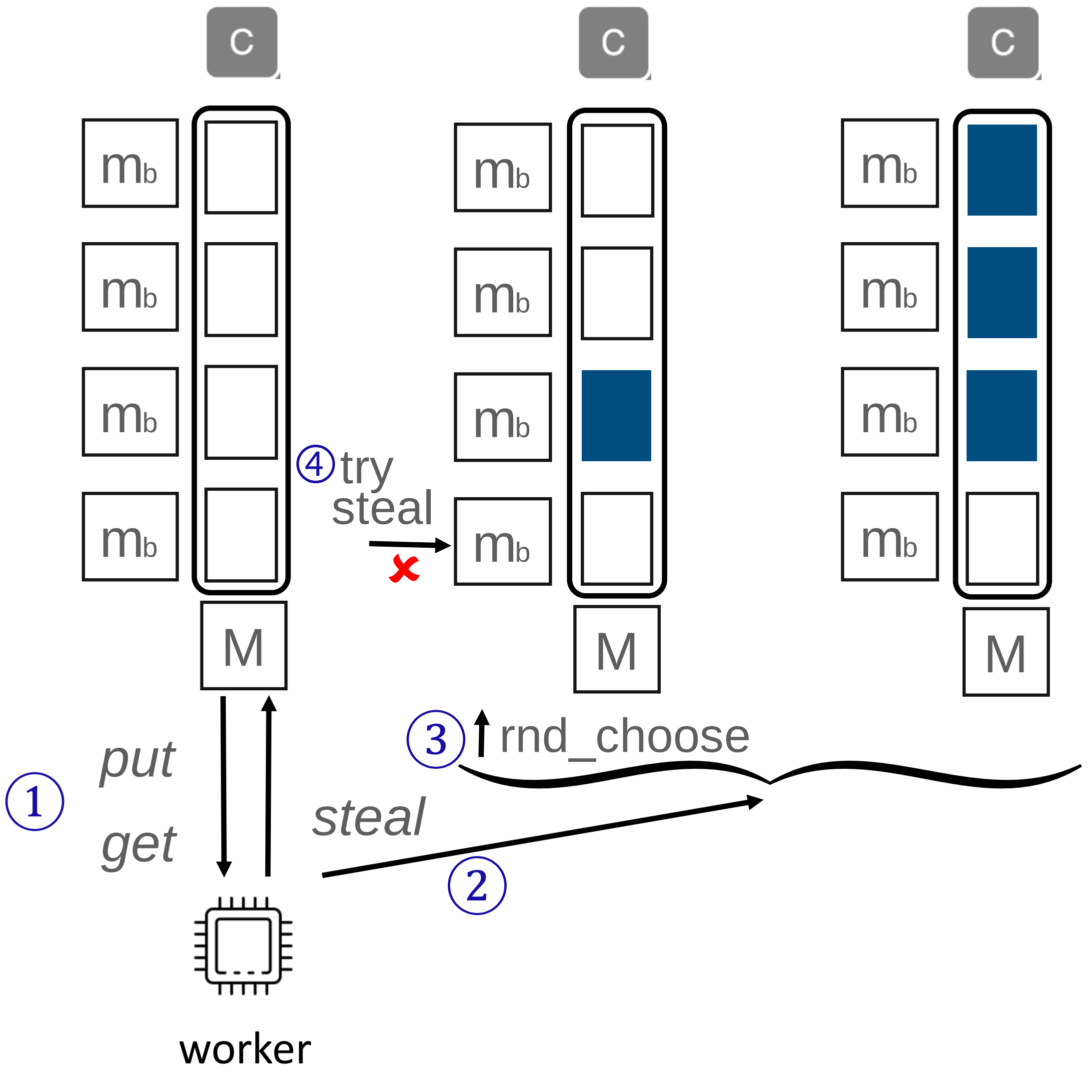

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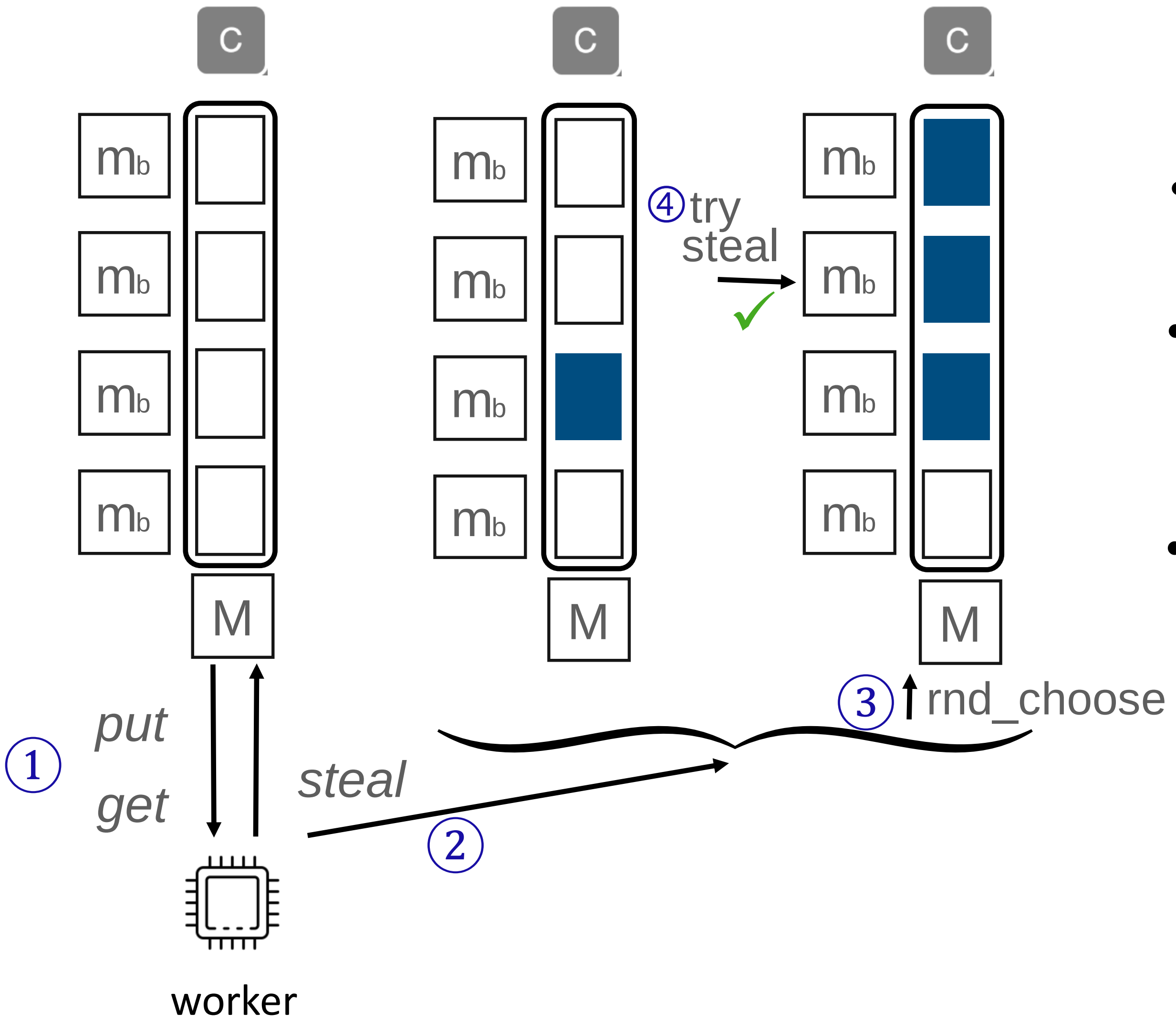

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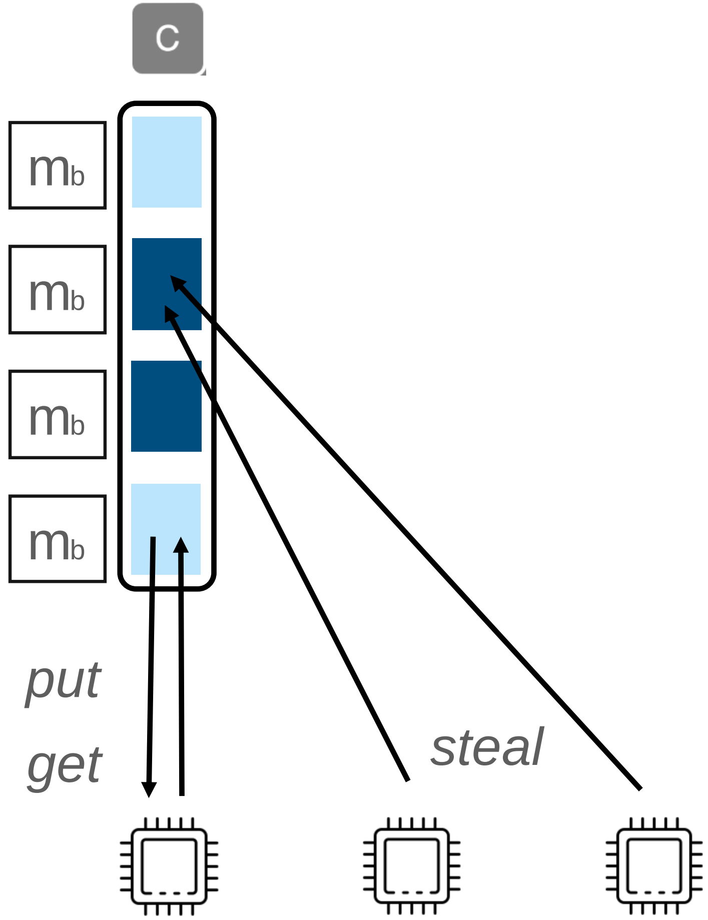

C) Cost of Interference with Thieves

- Fixed by Block-Level Synchronization and Randomized Stealing

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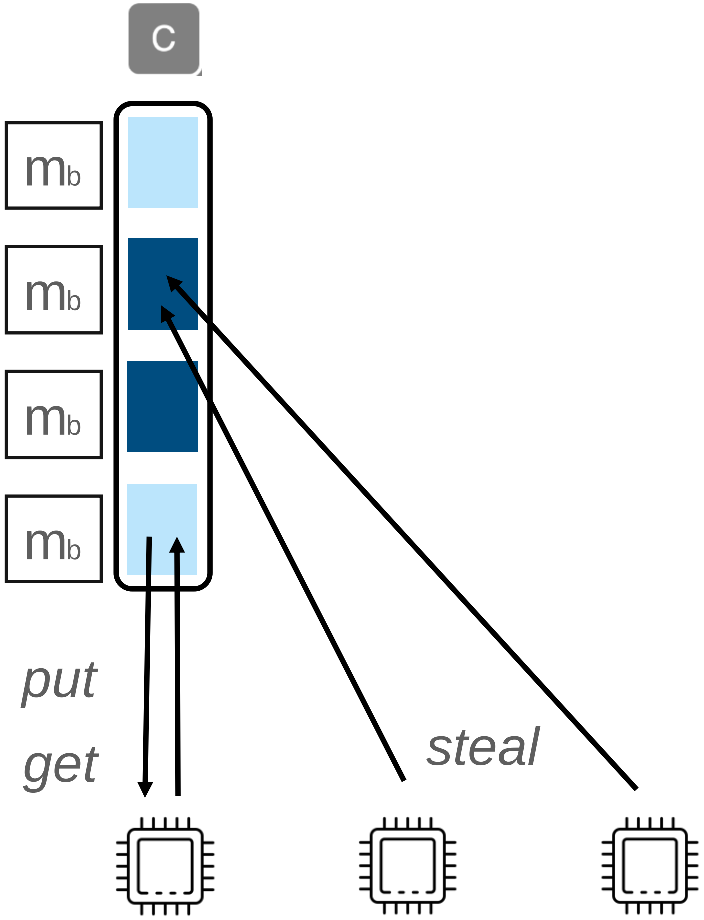
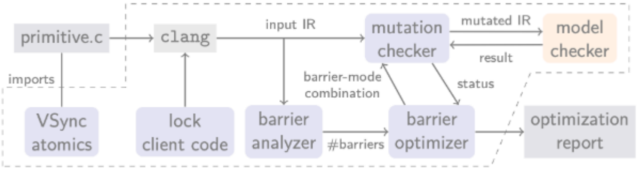


C) Cost of Interference with Thieves

- Fixed by Block-Level Synchronization and Randomized Stealing
- Thieves and the owner update different metadata, thus interference is reduced
- Thieves and the owner are likely to operate on different blocks

BWoS — Verification and Optimization

VSync Framework



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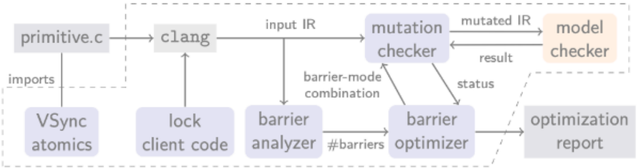
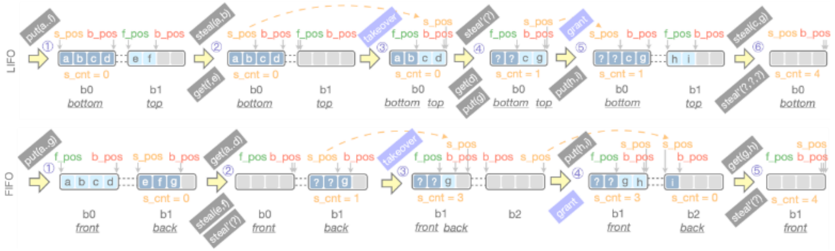


Algorithms in C



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 }
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  }
}
stat f, b, s1, s2;
queue<u64> q; // 2 * 2
T0: b.put(q)*3; f.get(q)*2;
    b.put(q)*4; f.get(q)*3;
    b.put(q)*5; f.get(q)*4;
T1: s1.steal(q);
T2: s2.steal(q)*2;
T3: while (f.get(q));
   assert (b.sum == f.sum +
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(T0 ‖ T1 ‖ T2) ; T3
```

Client Code

trigger edge cases with assertions

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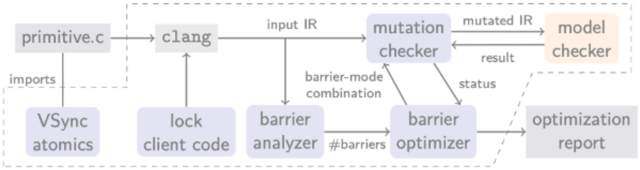

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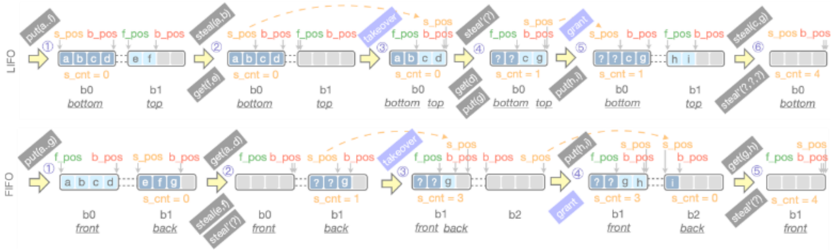

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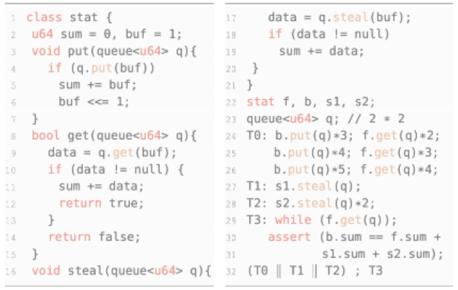

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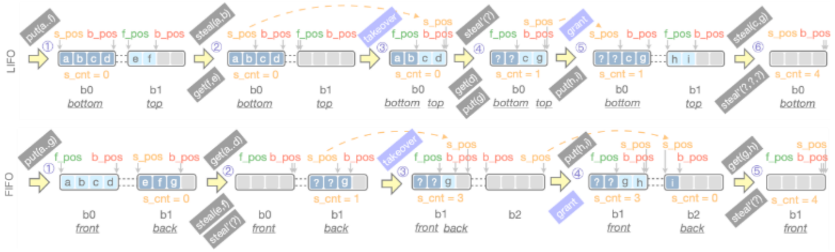

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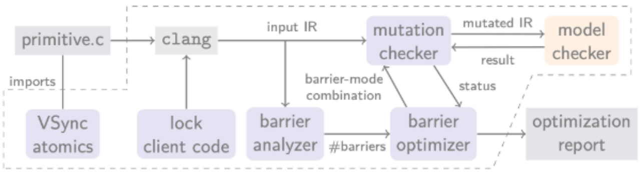

Verification

Properties:

- Memory safety
- Data race freedom
- Loop termination
- Consistency

WMM Optimization

	VERI/OPT time	memory barriers				#executions explored
		#SEQ	#ACQ	#REL	#RLX	
LIFO BWoS	62 *min.*	0	2	2	14	1.39 *M*
FIFO BWoS	53 *min.*	0	3	3	16	1.43 *M*
ABP	16 *min.*	4	3	1	7	2.05 *M*

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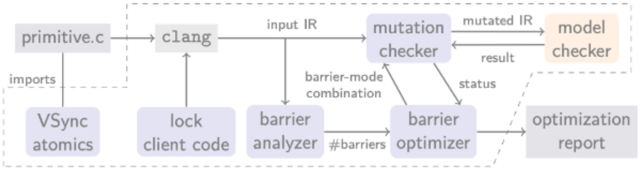
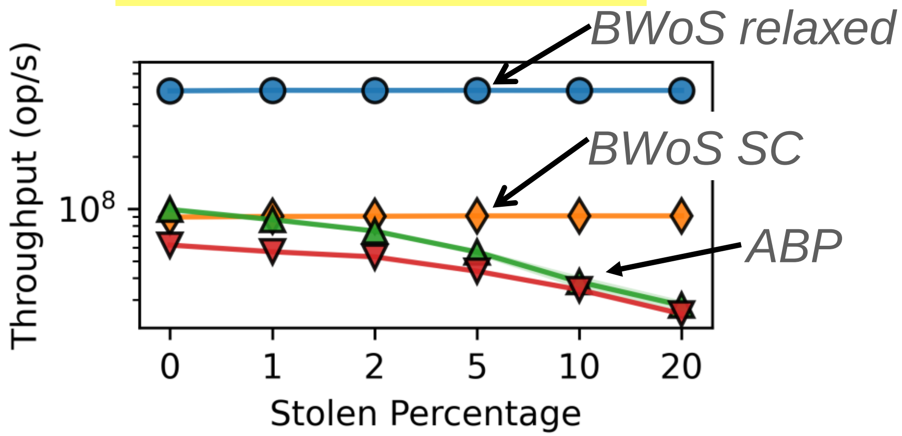


WMM Optimization Results



WMM Optimization

	VERI/OPT time	memory barriers				#executions explored
		#SEQ	#ACQ	#REL	#RLX	
LIFO BWoS	62 *min.*	0	2	2	14	1.39 *M*
FIFO BWoS	53 *min.*	0	3	3	16	1.43 *M*
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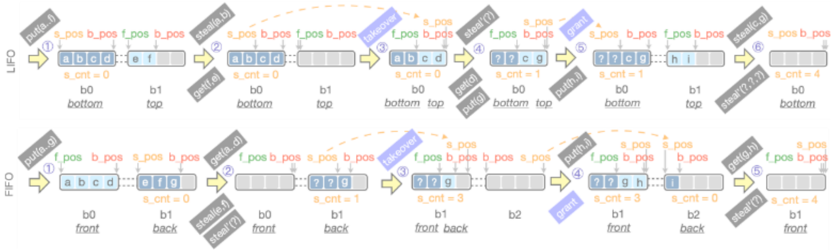
Algorithms in C



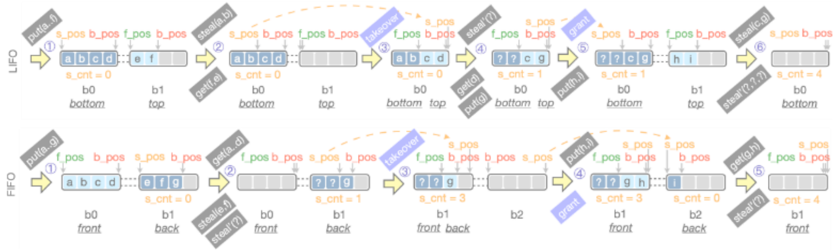
BWoS — Verification and Optimization

```
class stat {
 u64 sum = 0, buf = 1;
 void put(queue<u64> q){
   if (q.put(buf))
     sum += buf;
     buf <<= 1;
 }
 bool get(queue<u64> q){
   data = q.get(buf);
   if (data != null) {
     sum += data;
     return true;
   }
   return false;
 }
 void steal(queue<u64> q){
   data = q.steal(buf);
   if (data != null)
     sum += data;
  }
}
stat f, b, s1, s2;
queue<u64> q; // 2 * 2
T0: b.put(q)*3; f.get(q)*2;
    b.put(q)*4; f.get(q)*3;
    b.put(q)*5; f.get(q)*4;
T1: s1.steal(q);
T2: s2.steal(q)*2;
T3: while (f.get(q));
   assert (b.sum == f.sum +
           s1.sum + s2.sum);
(T0 ‖ T1 ‖ T2) ; T3
```

Client Code

trigger edge cases with assertions

Algorithms in C



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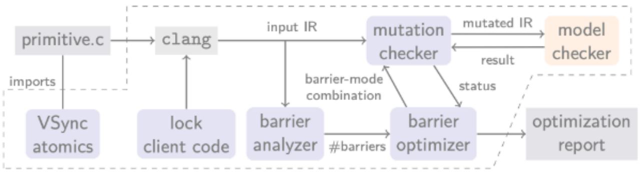

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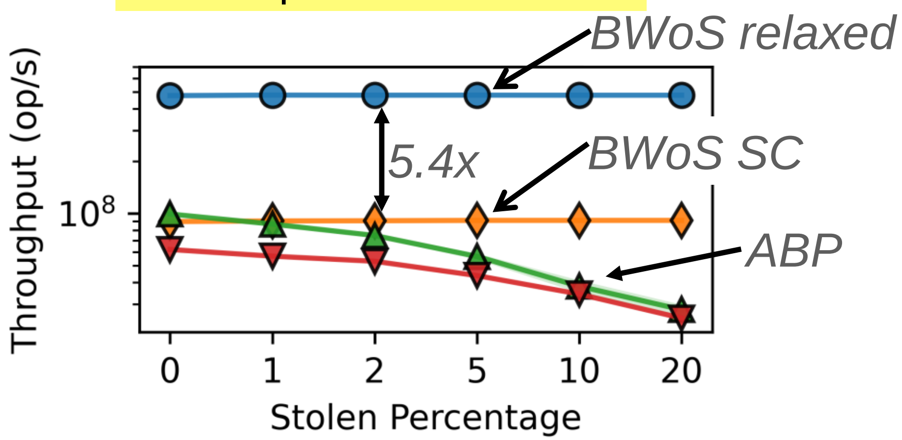

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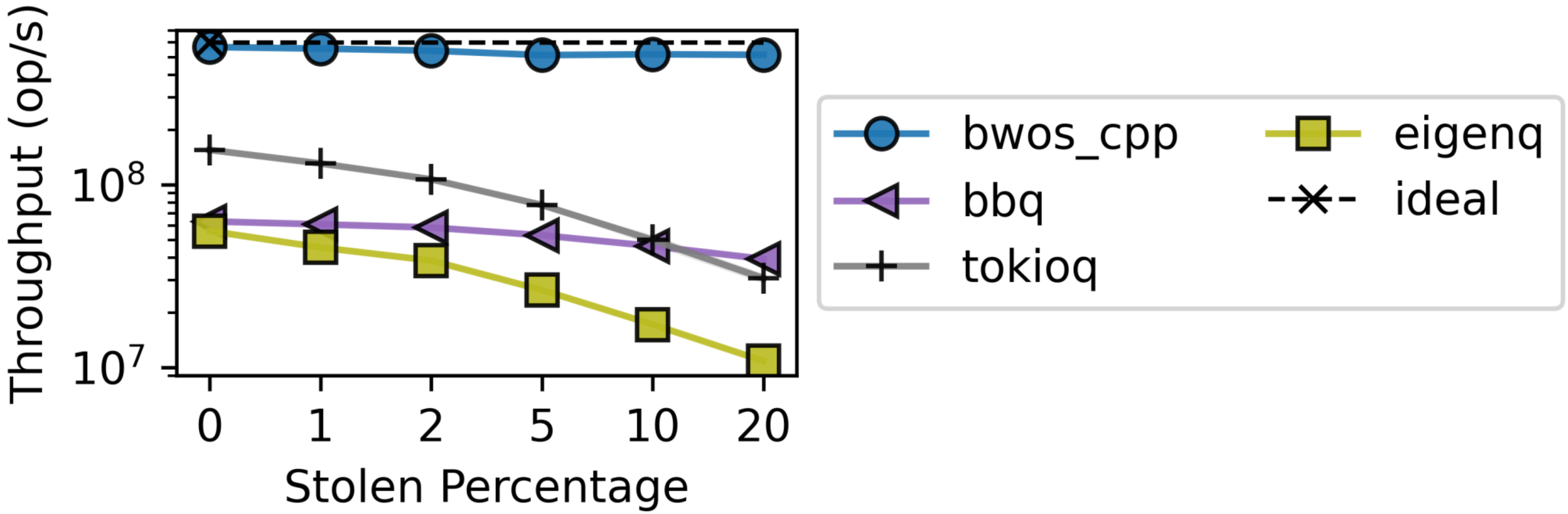
Micro-benchmark Results

Compared against state-of-the-art work-stealing queues

Each queue has a capacity of 8k entries, with 8-byte data items; BWoS is configured to have 8 blocks.



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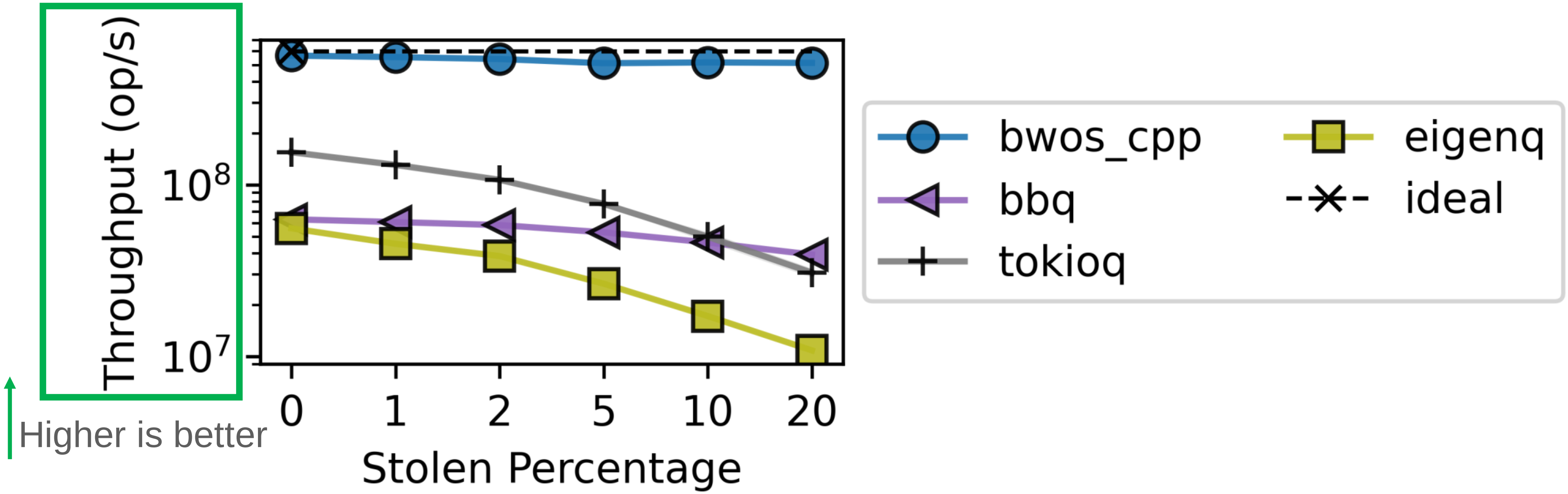

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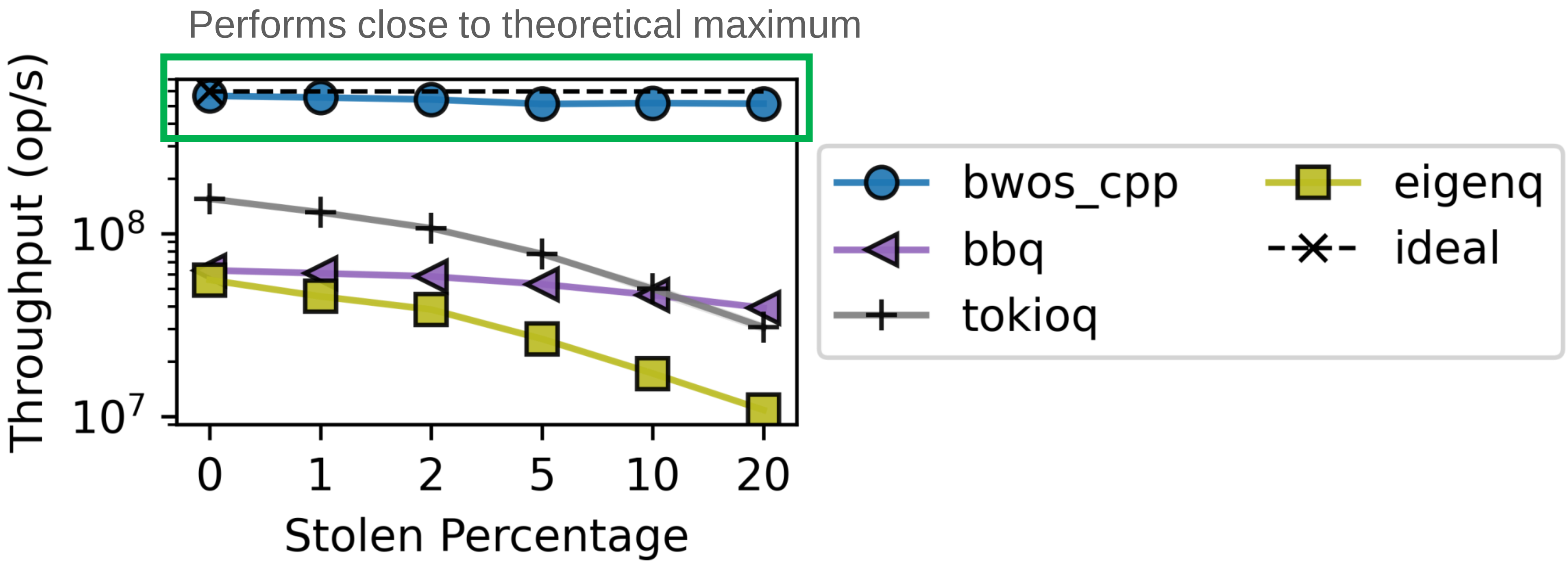

Micro-benchmark Results

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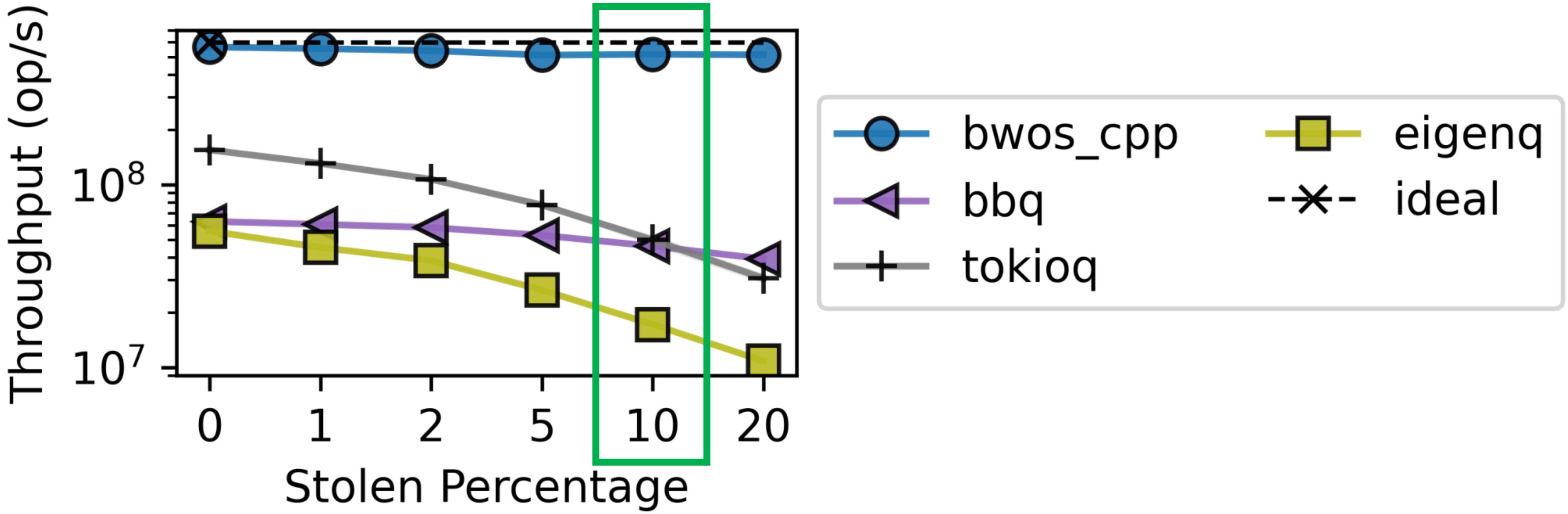
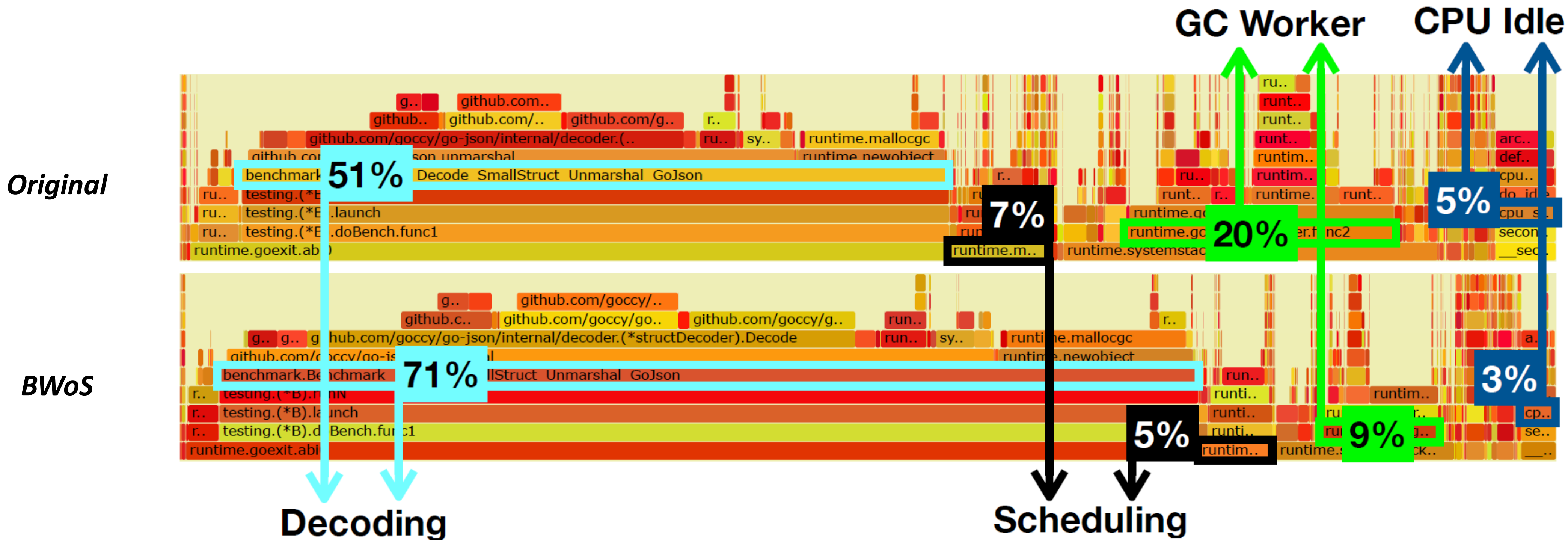
10% stolen: up 30x throughput



Summary: BWoS outperforms state-of-the-art queues by
1.6x – 10x without thieves, 1.6x - 30x with thieves.

BWoS in Go’s Runtime

GoJson Object Decoding Benchmark

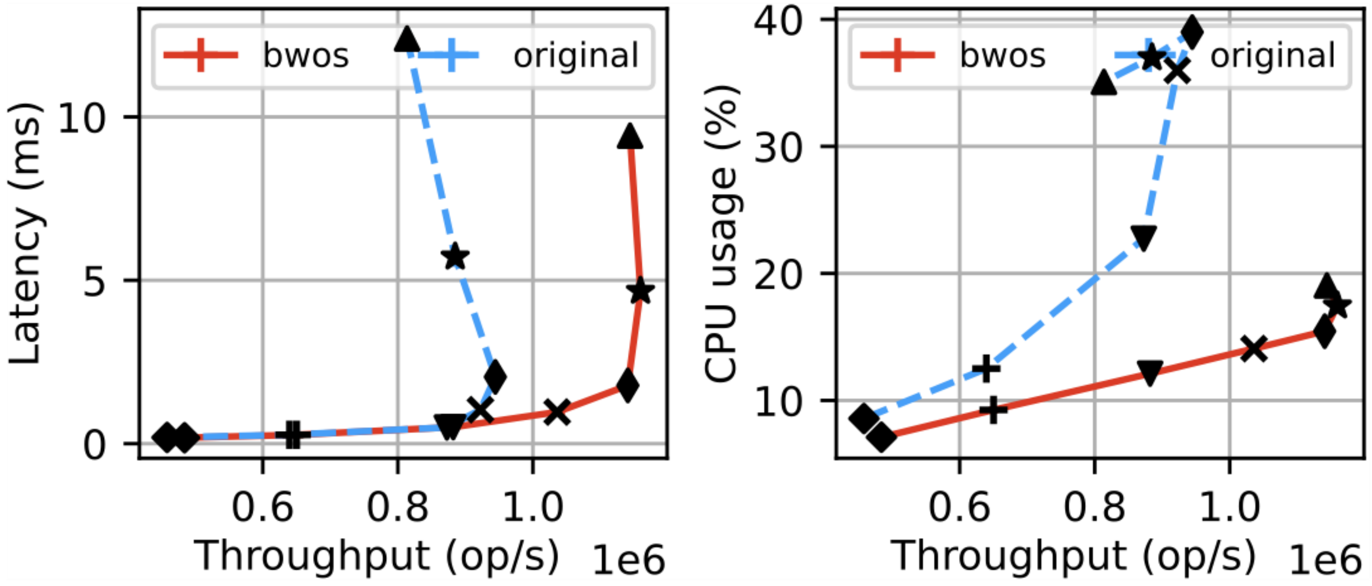


Summary: GoJson benchmarks experience 28.2% speedup on average for Arm (see paper).
BWoS improves performance of real-world computational workloads.

BWoS in Rust Tokio Runtime

We replace the run queue in Rust Tokio with FIFO BWoS

Hyper HTTP server, 1k connections



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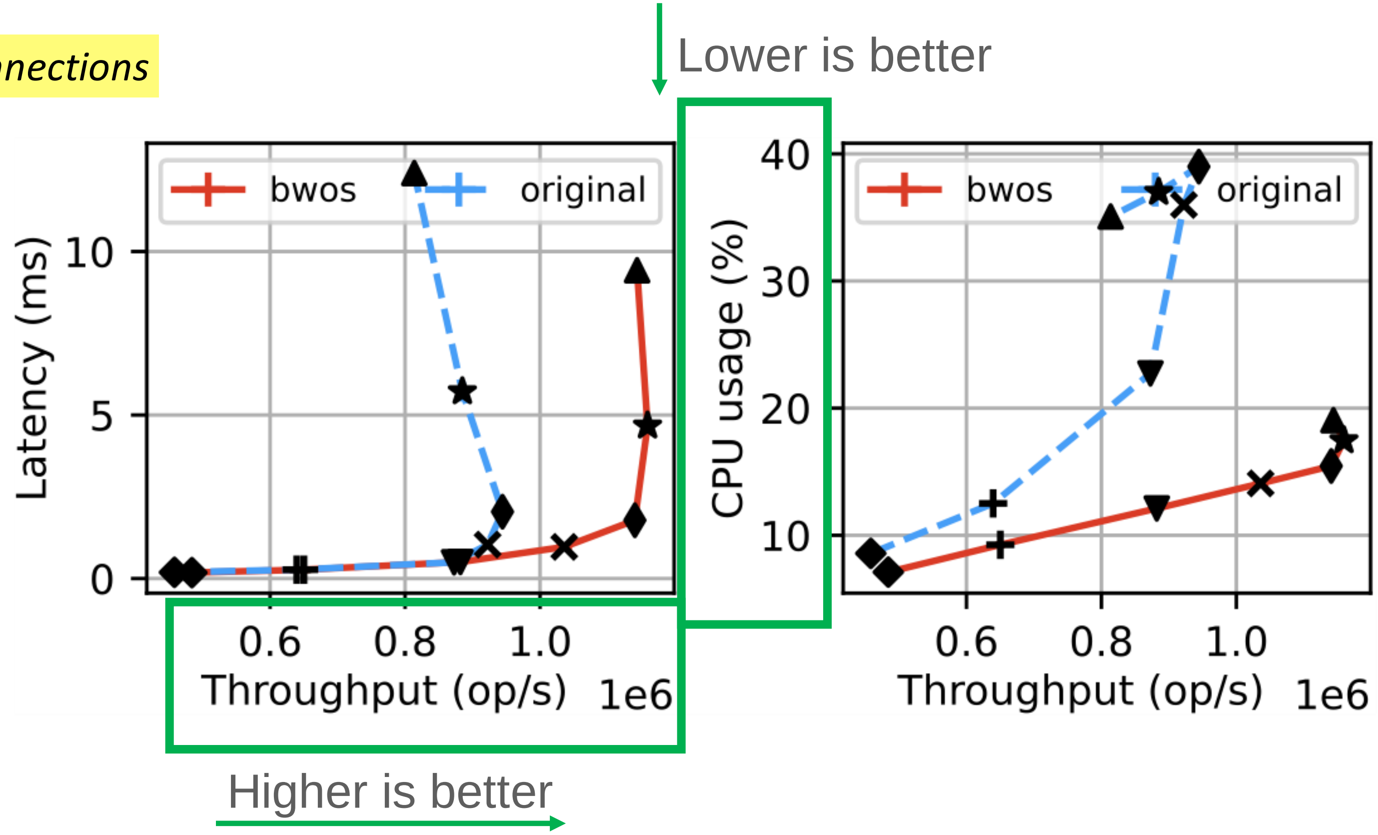

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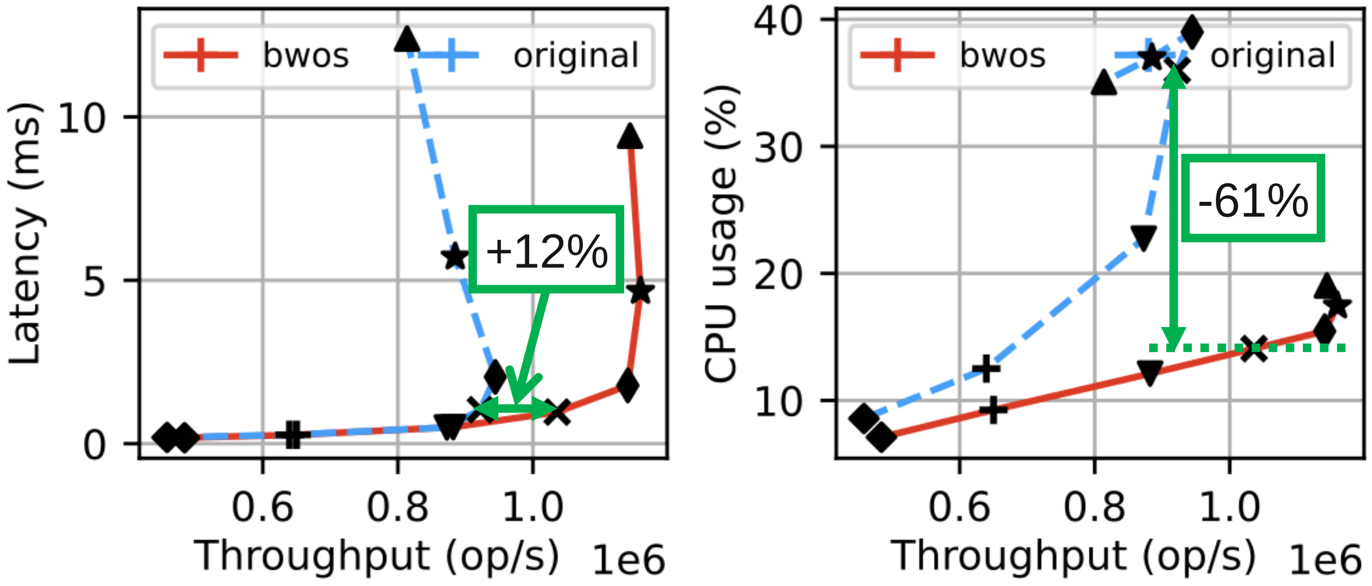

Summary: BWoS increases throughput by 12% with 7% lower latency and 61% lower CPU utilization.
BWoS improves performance of real-world IO servers.

We have published our changes for the Tokio runtime: https://github.com/tokio-rs/tokio/pull/5283

Summary

- The benefit of the block-based design is manyfold, and can be applied in many concurrent algorithms:
  - BWoS: Work Stealing (this work)
  - BBQ: Producer-Consumer Queues (ATC’22)

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Thanks!