New Locks for the Old Kernel

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Outline

1. **Background**: Locks, Locks in the Kernel, NUMA
2. **CNA**: Compact NUMA-aware Lock
3. **BRAVO**: Biased Reader-Writer Locking
4. **Conclusion**

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Locks: Quick Background

- Protect access to the shared data

- Remain the most popular synchronization technique
- … and the topic of extensive research

- Performance of parallel software often depends on the efficiency of the locks it employs

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Locks: Quick Background (cont.)

- Many flavors:
  - exclusive / reader-writer
  - spinning / blocking
  - strictly fair / unfair / long-term fair
  - …

- Evolve with the evolution of computing architectures
  - we live in the era of multi-socket architectures with NUMA effects → we need *NUMA-aware* locks

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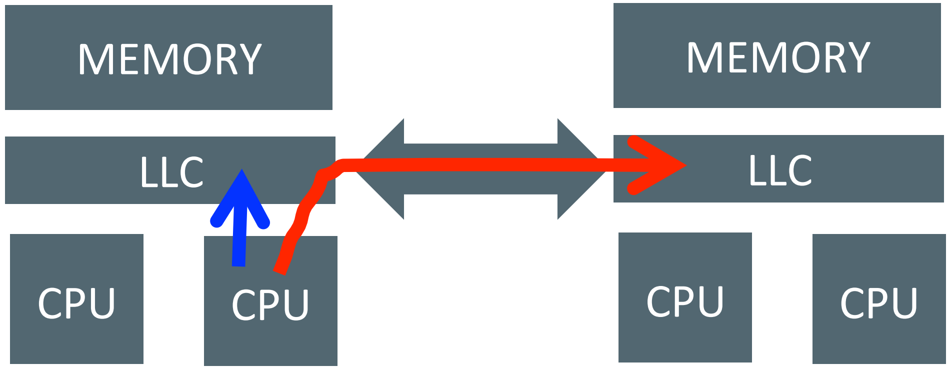
NUMA-aware Locks



- Access by a core to a local memory or local cache is faster that accesses to a remote memory or remote cache
  - known as Non-Uniform Memory Access (NUMA) effect

- Keep the lock ownership ***within the same node***
  - decrease remote cache misses and inter-node communication
  - non-FIFO and unfair over the short term
  - ➢ trade-off short-term fairness for better performance

Locks in the Kernel

- Keep evolving
  - spinlocks: test-set → ticket → MCS (sort-of)
- Fail to keep up with the latest and greatest
  - e.g., spinlocks are not NUMA-aware, read-write locks use a shared counter
- Very specific requirements
  - compact
    - spinlock state must occupy at most 4 bytes
  - fair
  - good low thread-count performance

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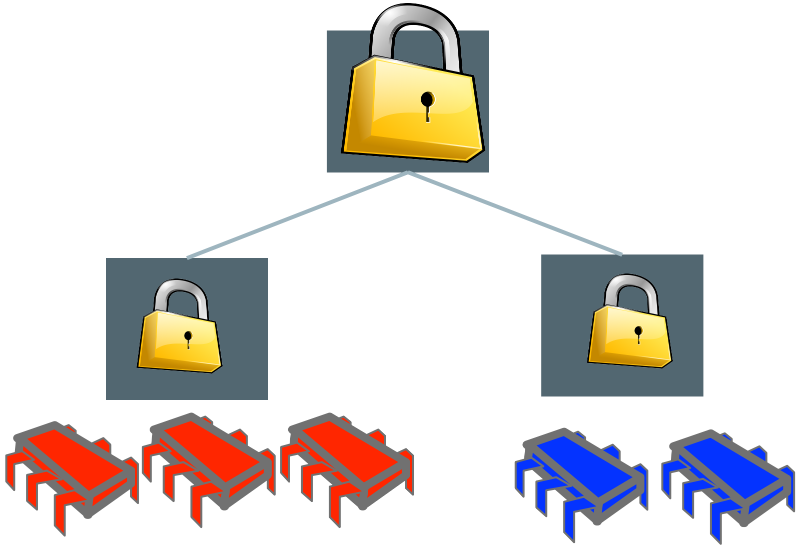
Hierarchical NUMA-aware Locks

- Multiple (2+) layers of lock hierarchy



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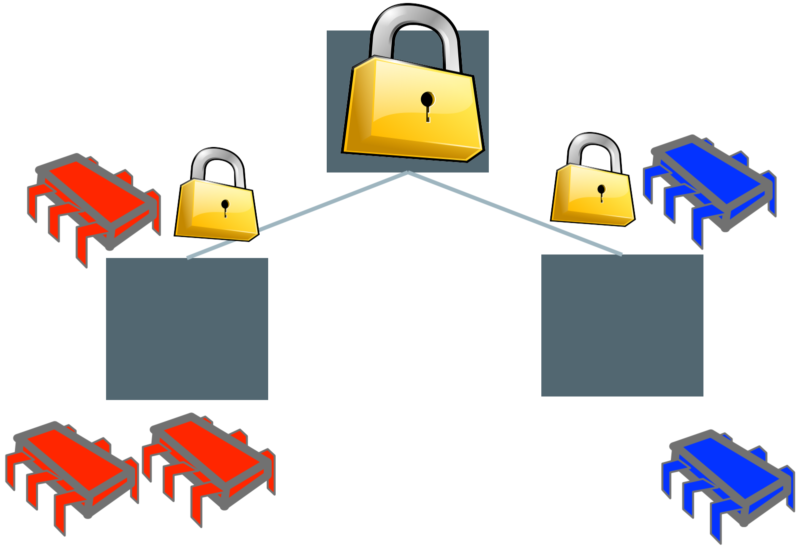
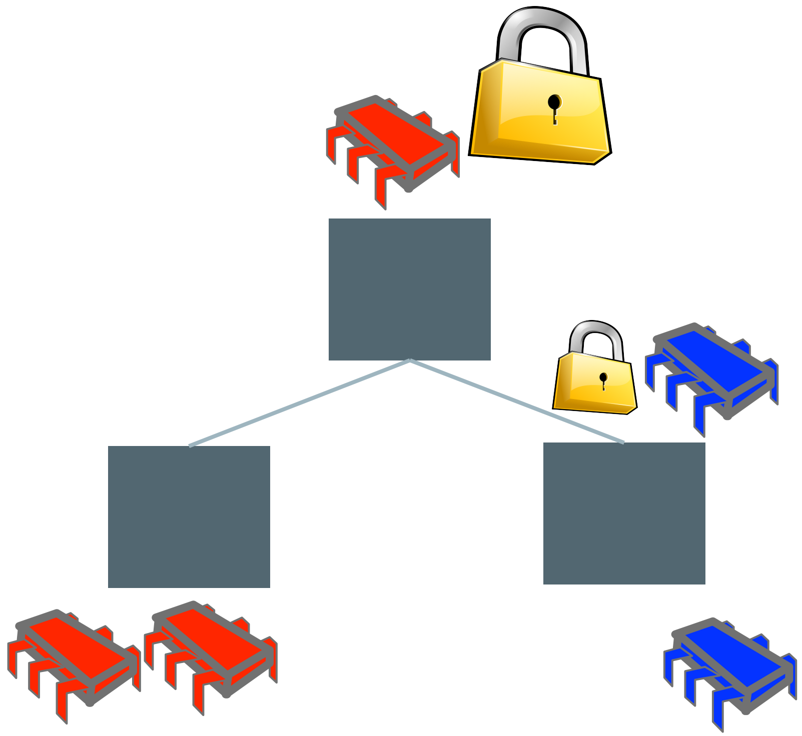


Hierarchical NUMA-aware Locks

- Multiple (2+) layers of lock hierarchy
- Acquire intra-node lock(s) first, then compete for the root lock
- The root lock stays locked by threads running on the same socket
  - passing the intra-node lock passes the ownership



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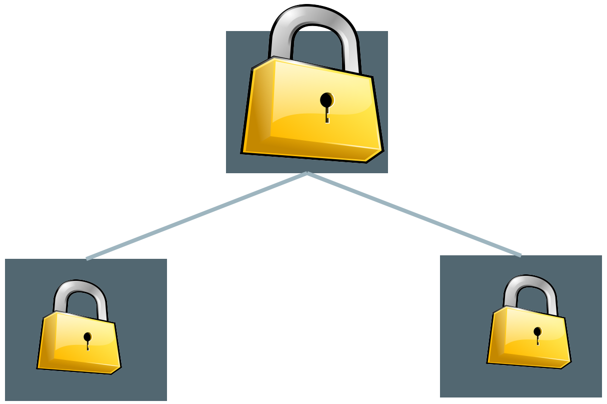
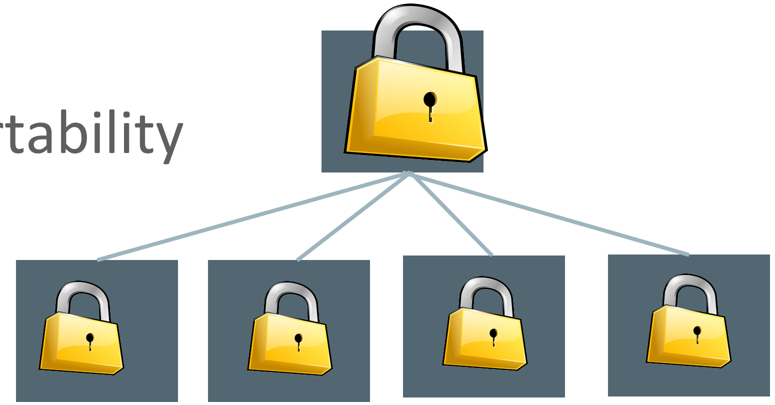
The Pitfalls of the Hierarchical Approach

- Longer acquisition path
  - multiple atomic instructions



- Require dynamic initialization to ensure portability
  - but the lack of standard API to query topology hinders portability



- SIZE: space proportional to #nodes
  - to make matters worse, each low-level lock has to be placed on a separate cache line

Where (and Why) Size Matters?

- Concurrent data structures with one lock-per-node/entry
  – E.g., binary search trees, linked lists, etc.

- Systems with millions+ of locks
  – E.g., Linux Kernel
    - spinlocks are embedded in every inode and page structure
    - ➢ one lock per file and per physical page
    - ➢ strict limit of 4 bytes (32bits) on the spinlock size

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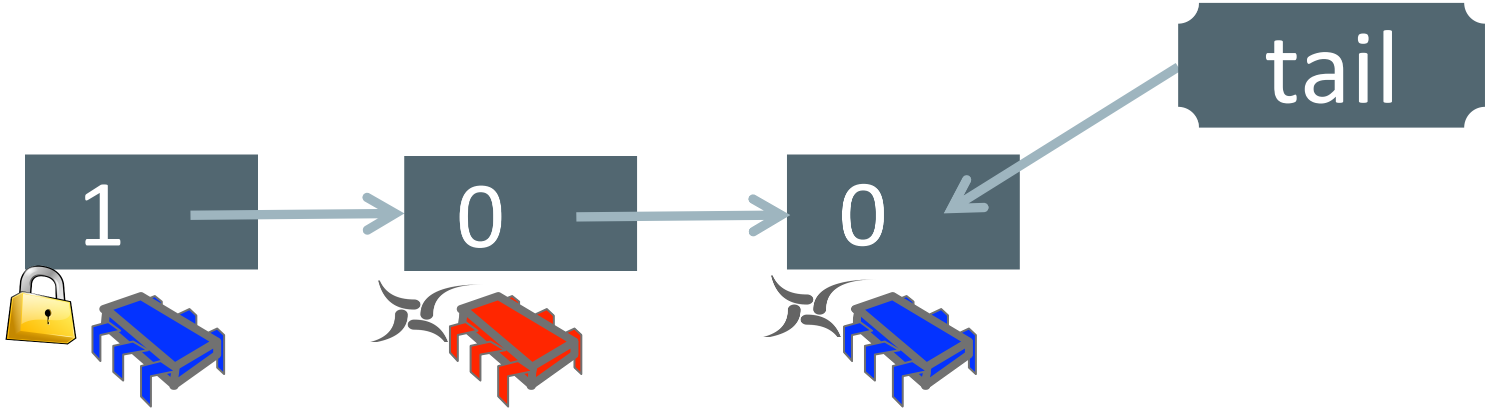
CNA: Compact NUMA-aware Lock

- Requires one word of memory
- Variant of a (NUMA-oblivious) MCS lock
  - inherits its performance features
    - local spinning, one atomic operation per acquisition, …
- Performance on-par with MCS under no contention, on-par with state-of-the-art hierarchical NUMA-aware locks when contended

MCS (Mellor-Crummey and Scott) Lock

- Organizes waiting threads in a FIFO queue
- The shared state is a pointer to the tail of the queue
- Each thread has a record that it inserts into the queue …
- … and then spins locally on a flag inside the record



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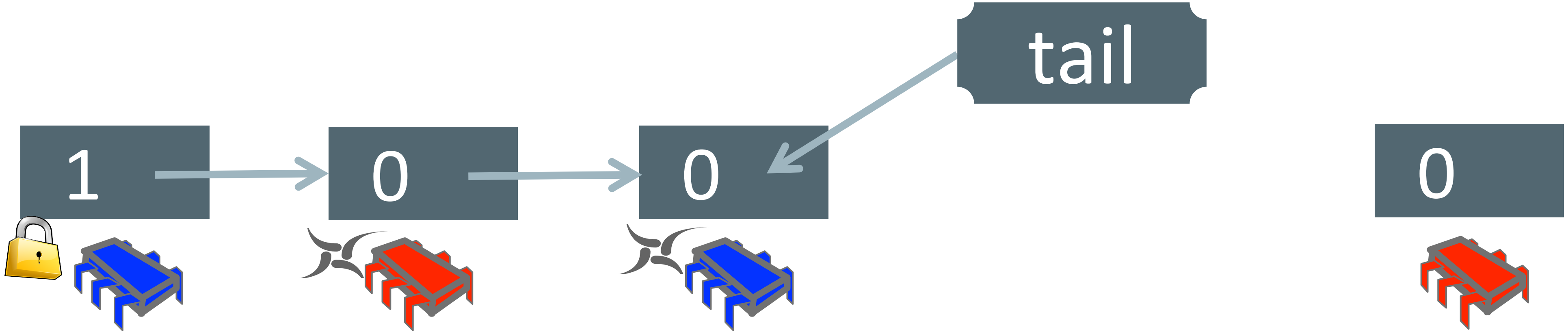

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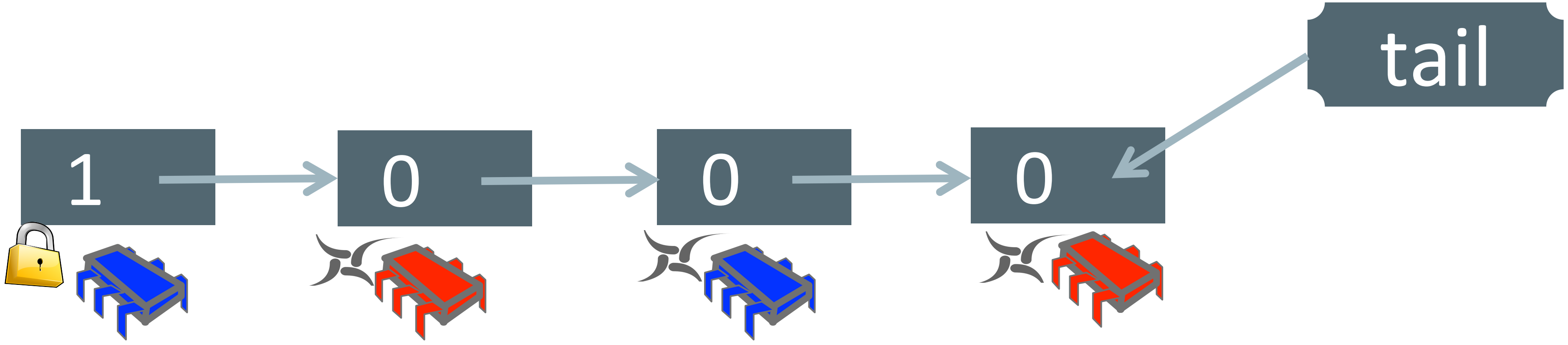

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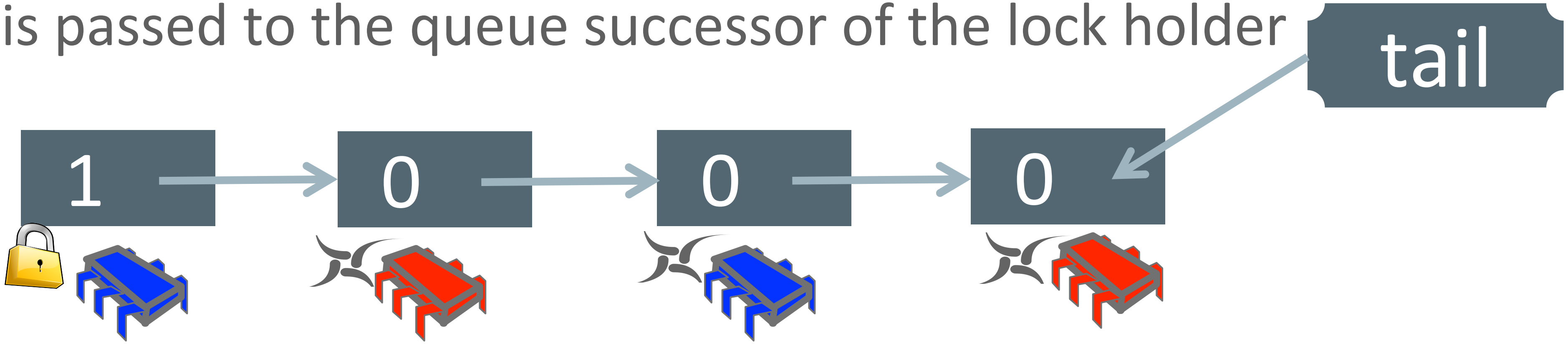

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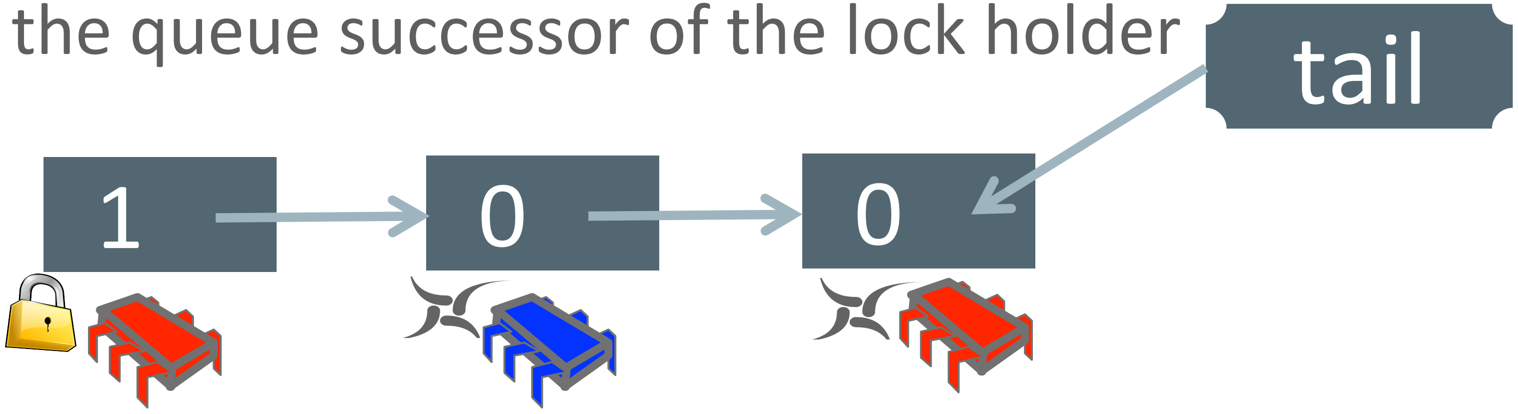

CNA: a NUMA-Aware Variant of MCS

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- Organizes waiting threads in **two queues (“main” and “secondary”)**
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- … and then spins locally on a flag inside the record
- The lock is passed to the queue successor **running on the same node as the lock holder**
  - **waiting threads between the lock holder and its new successor are moved to the secondary queue so they do not interfere in subsequent lock handovers**

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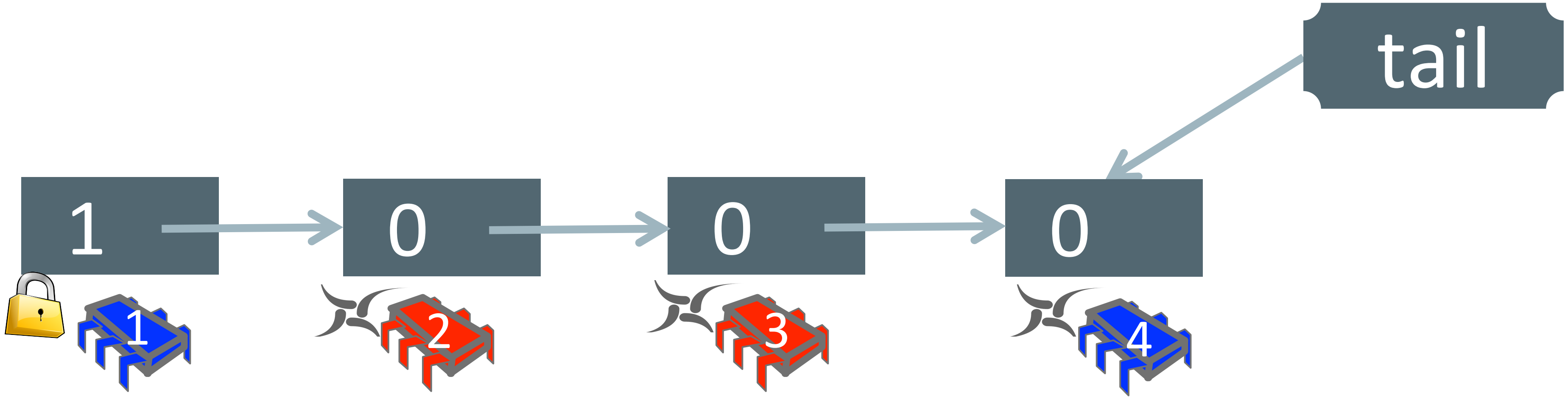
CNA in Action



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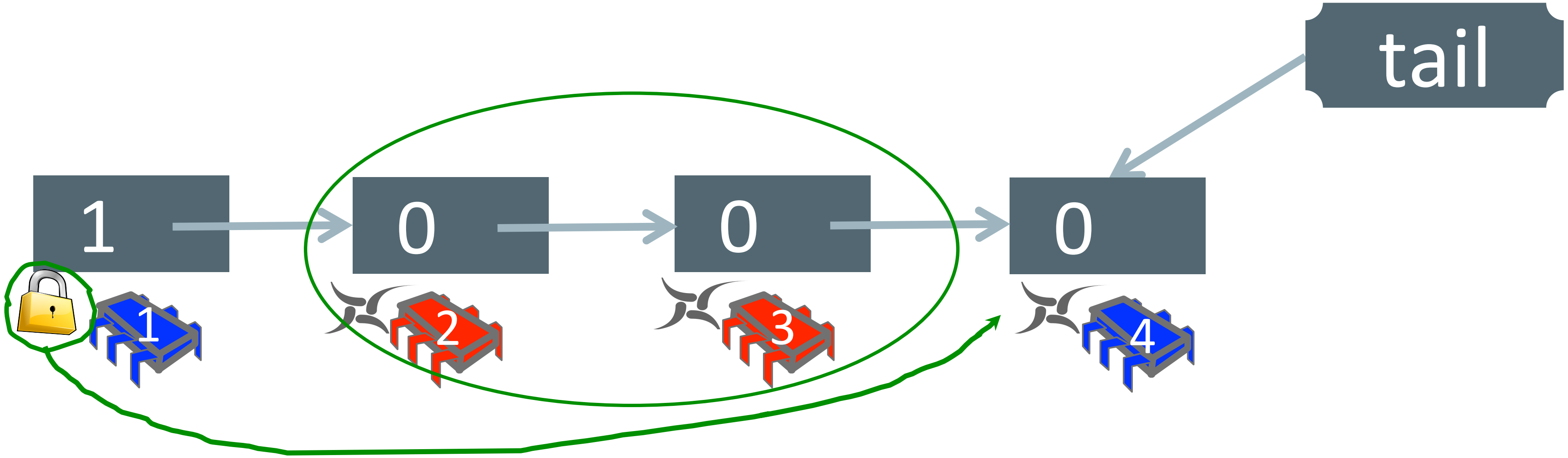

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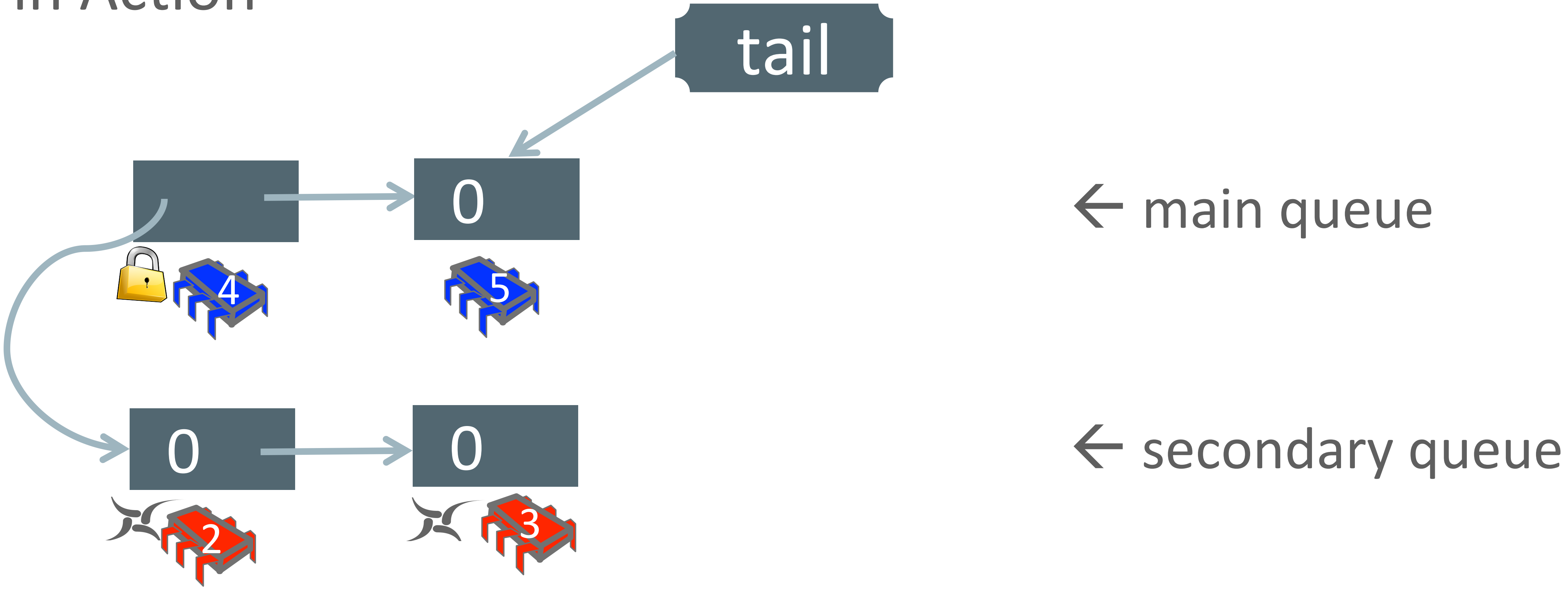
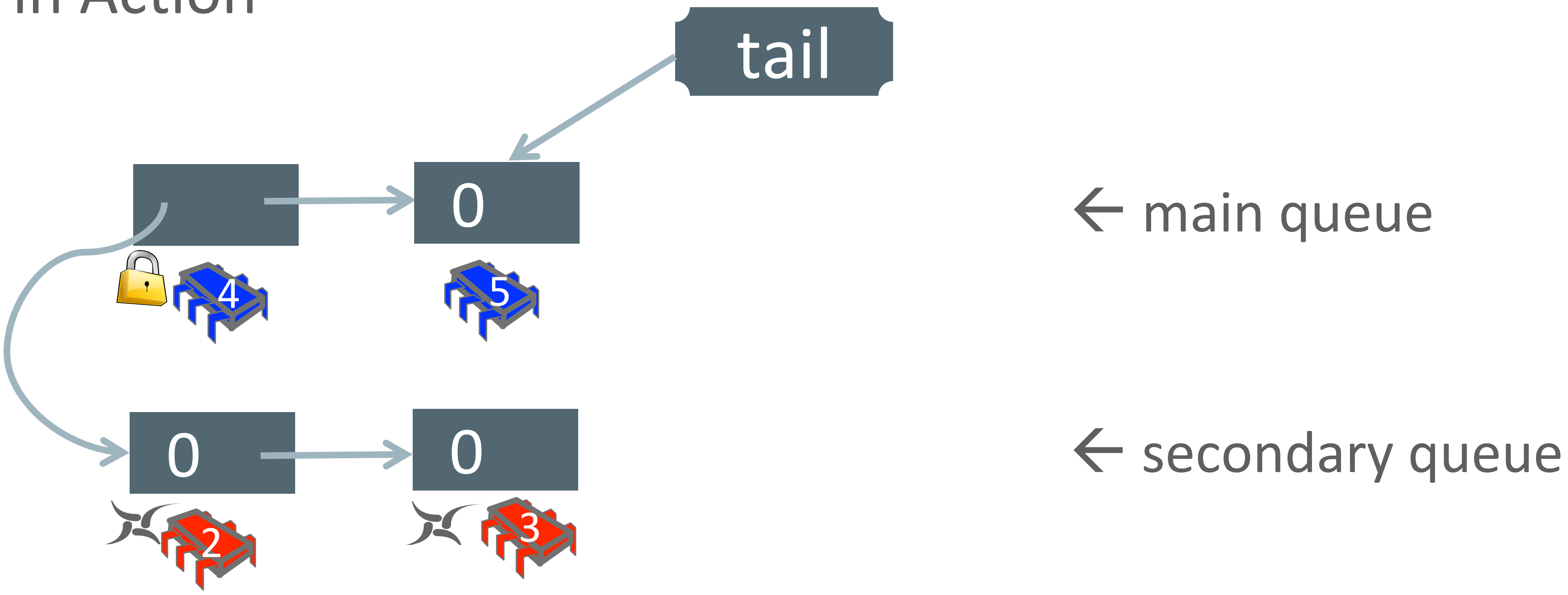


Thread 4: unlock()

CNA in Action



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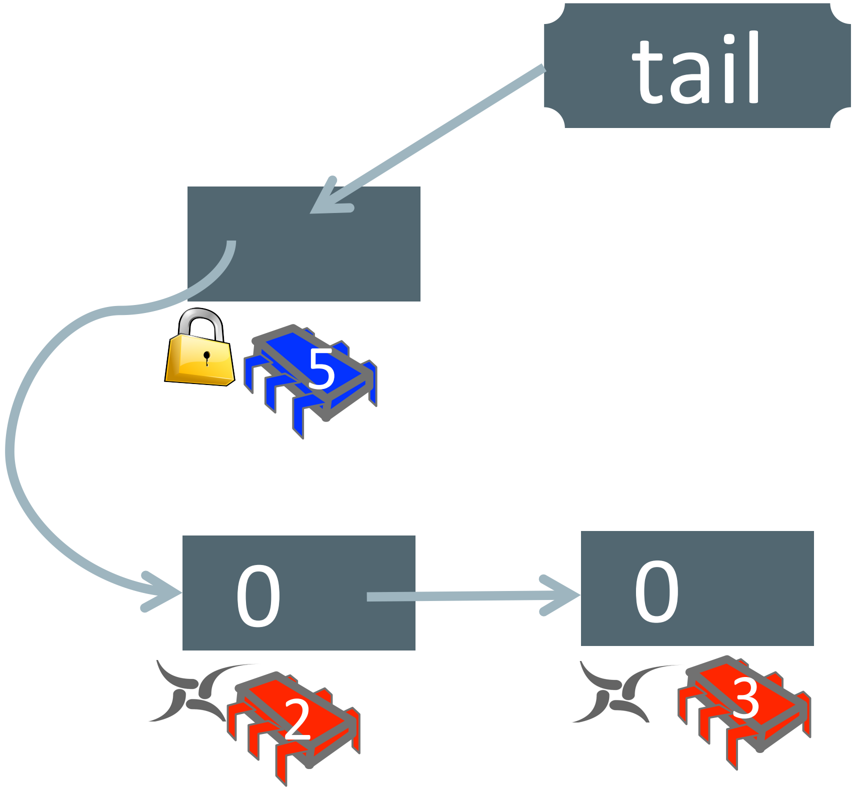

← main queue

← secondary queue

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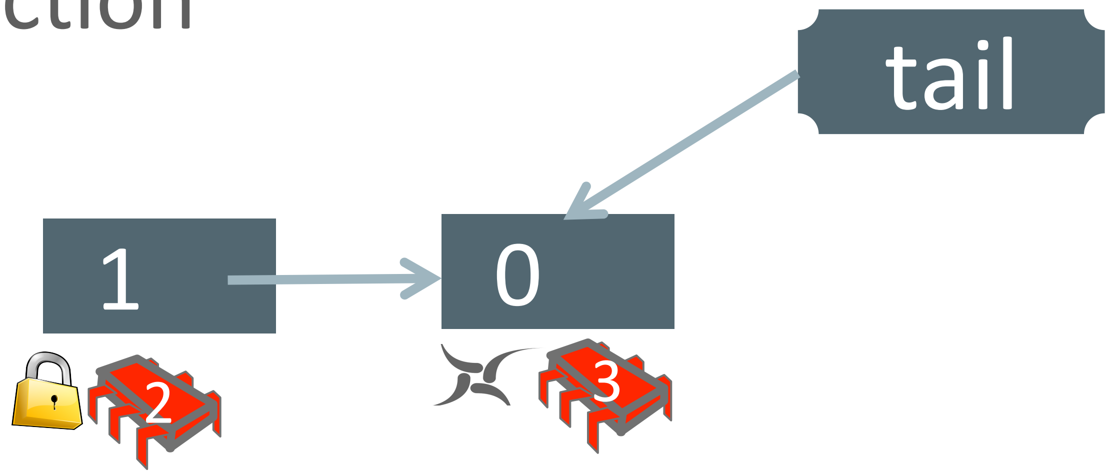

Avoiding Starvation

Move waiting threads back from secondary to main queue

1. When the main queue is empty / does not have threads on the same node as the lock holder

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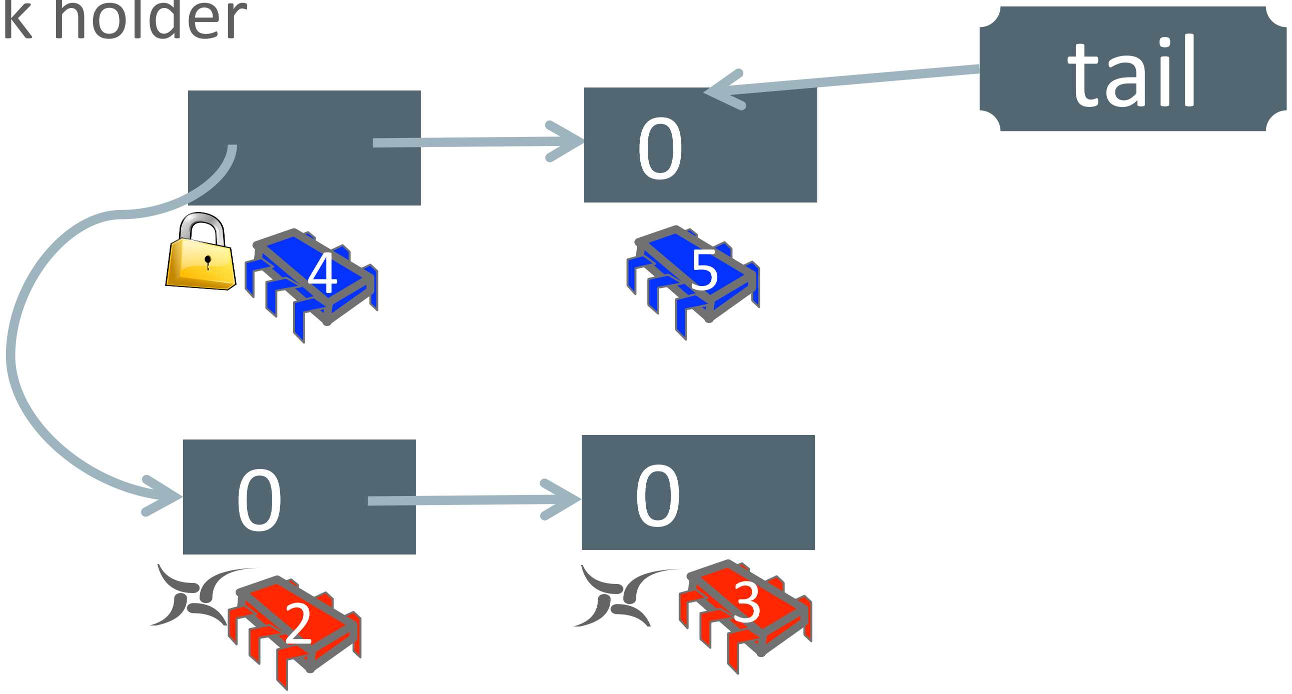

Avoiding Starvation

Move waiting threads back from secondary to main queue

1. When the main queue is empty / does not have threads on the same node as the lock holder
2. After a certain number of “intra-node” handovers
   - scan the main queue with high probability rather than always
   - can count deterministically, but incurs more overhead (cache misses to update count)
   - threshold controls fairness-VS-throughput trade-off

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Performance Evaluation

User-space:

- Implemented CNA as a user-level library
- Compared to MCS, cohort locks (C-BO-MCS), HMCS lock

Kernel-space:

- Integrated into the slow path of qspinlock, Linux kernel spin-lock

HW: 4-socket x86 machine, with 18 hyper-threaded cores per sockets

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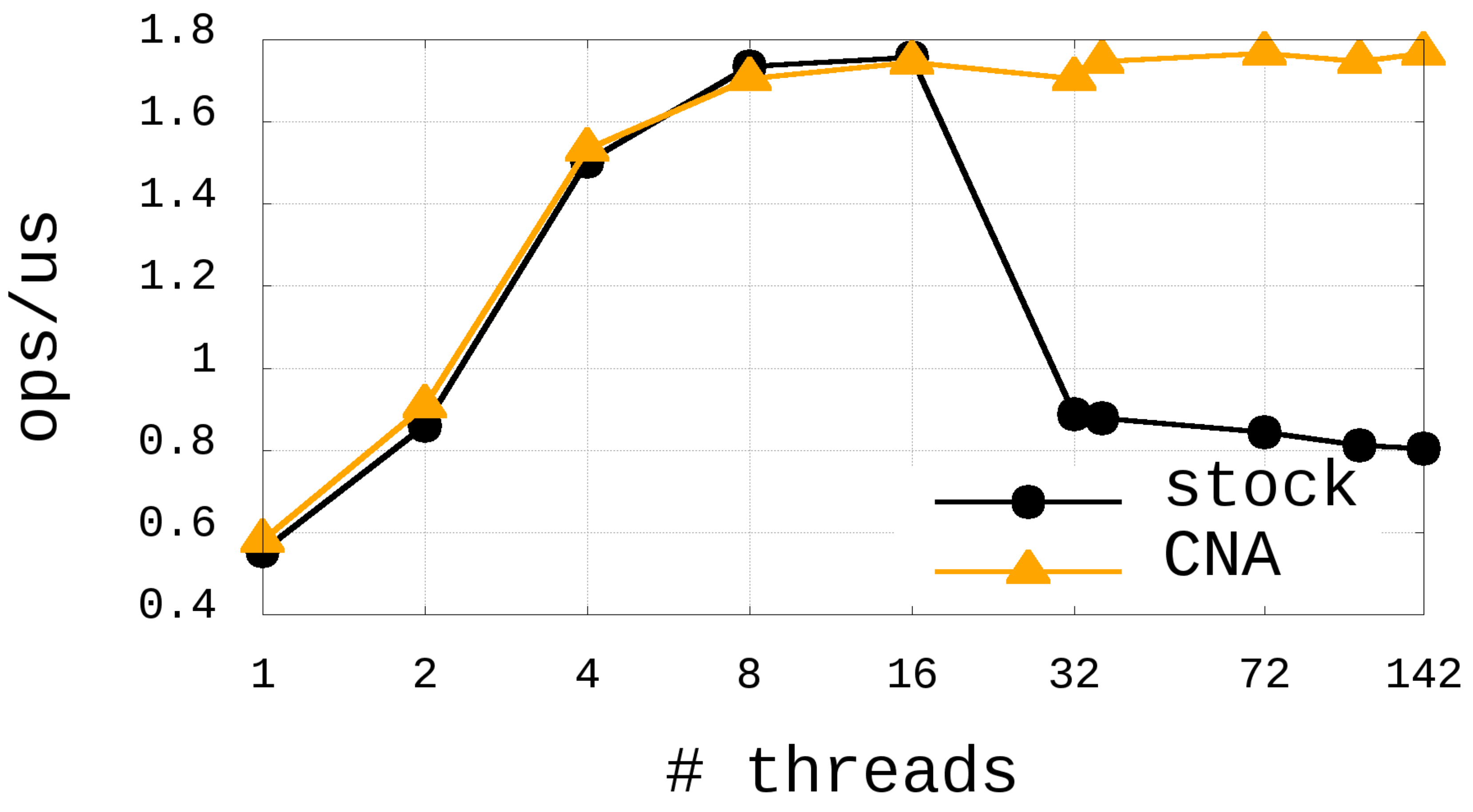
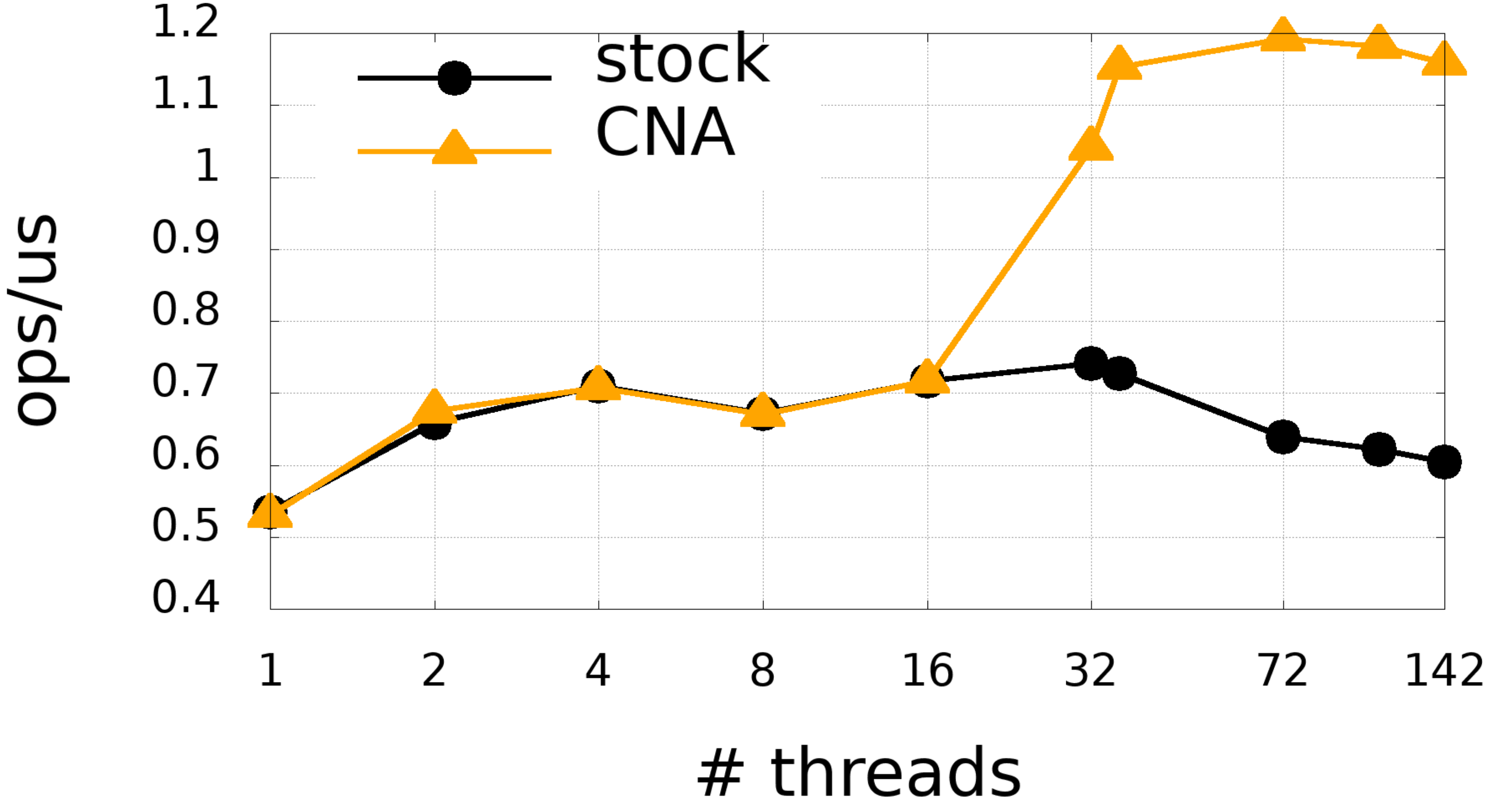
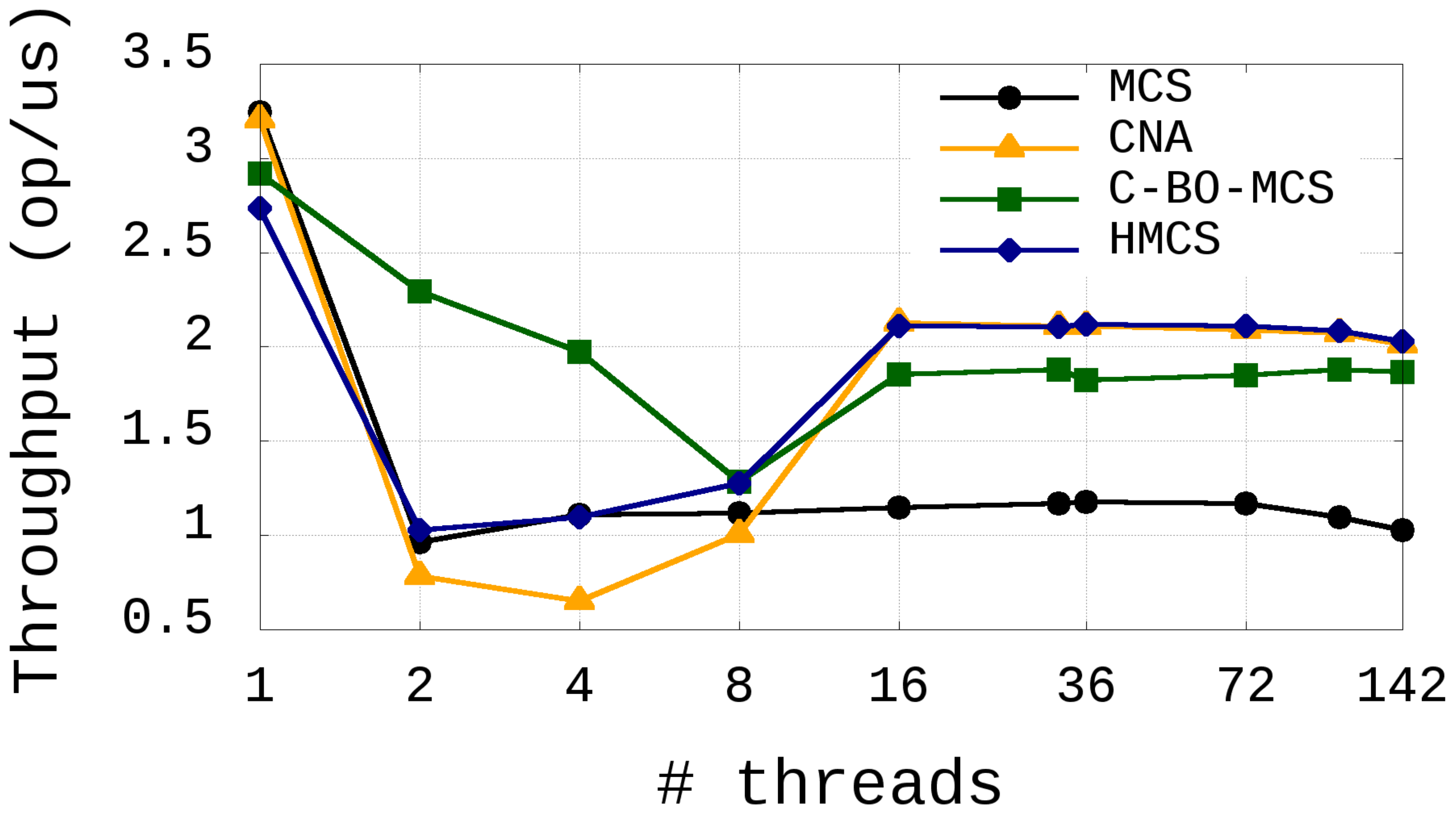
will-it-scale/open1_threads



LevelDB/readrandom



User-space: LevelDB



Shuffle Reduction Optimization

- Under light contention, waiting threads can be moved back and forth between two queues
  - creates overhead without reaping the benefit of locality
- Solution: when the secondary queue is empty, scan the main queue with low probability rather than always
  - reduces the amount of unnecessary shuffling when the contention is low, while responding fast enough when the contention is high

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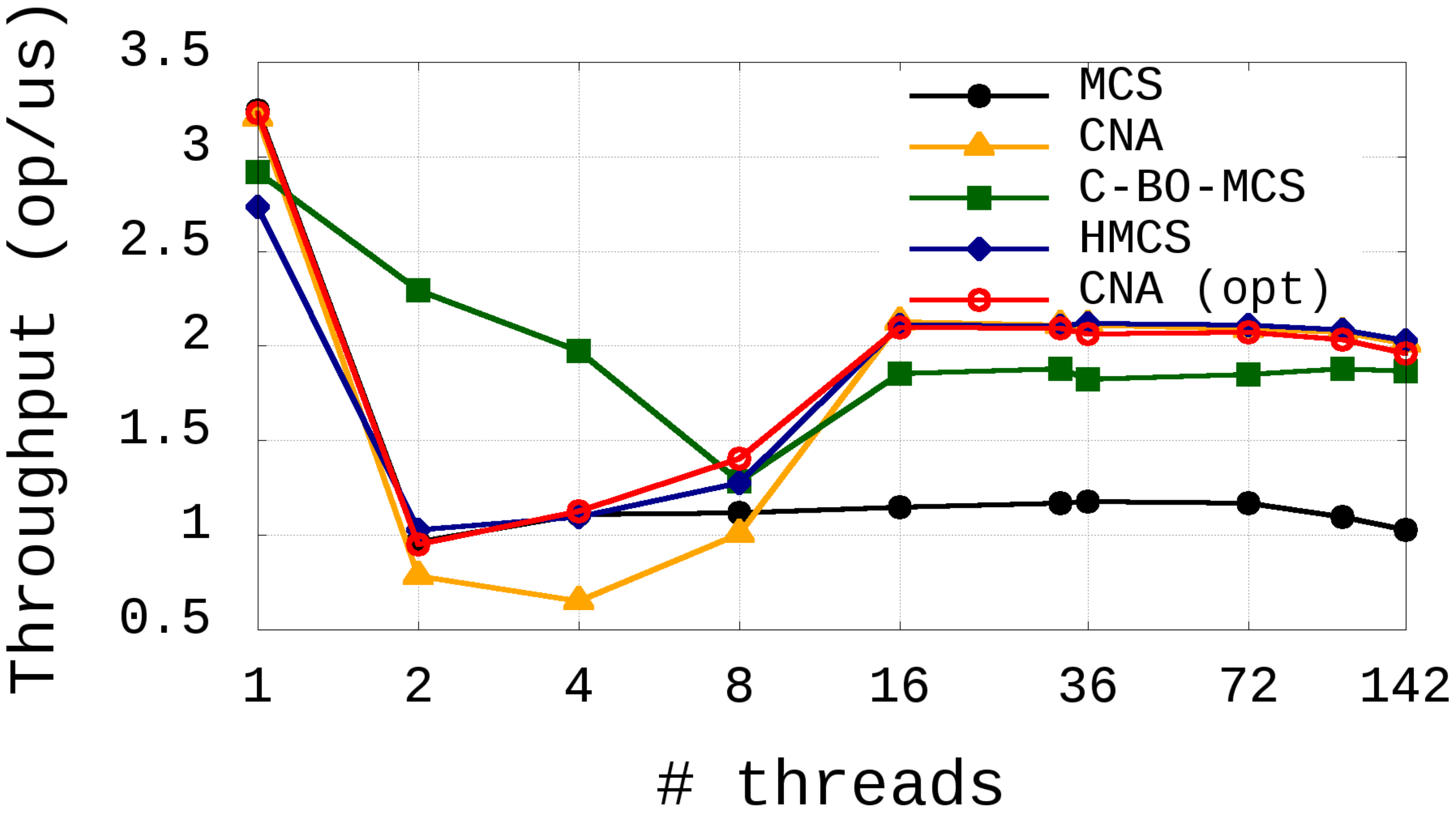
User-space: LevelDB



Wrap-up: CNA

CNA achieves the best of both worlds:

- as efficient as MCS at low contention
  - but better at high contention by 40-100%
- as performant as state-of-the-art NUMA-aware locks at high contention
  - but its state requires only one word of memory
- Reduces #remote cache misses while preserving long-term fairness

- Linux kernel patch is publicly available

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Reader-Writer Locks: Quick Background

- Allow shared access for read-only use of a resource
- Ubiquitous in modern systems

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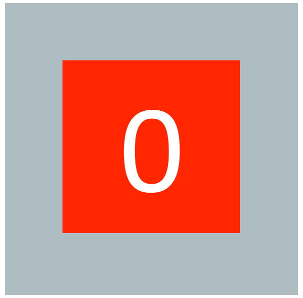
- Allow shared access for read-only use of a resource
- Ubiquitous in modern systems

- Have to keep track of the presence of active readers

The “shared counter” approach



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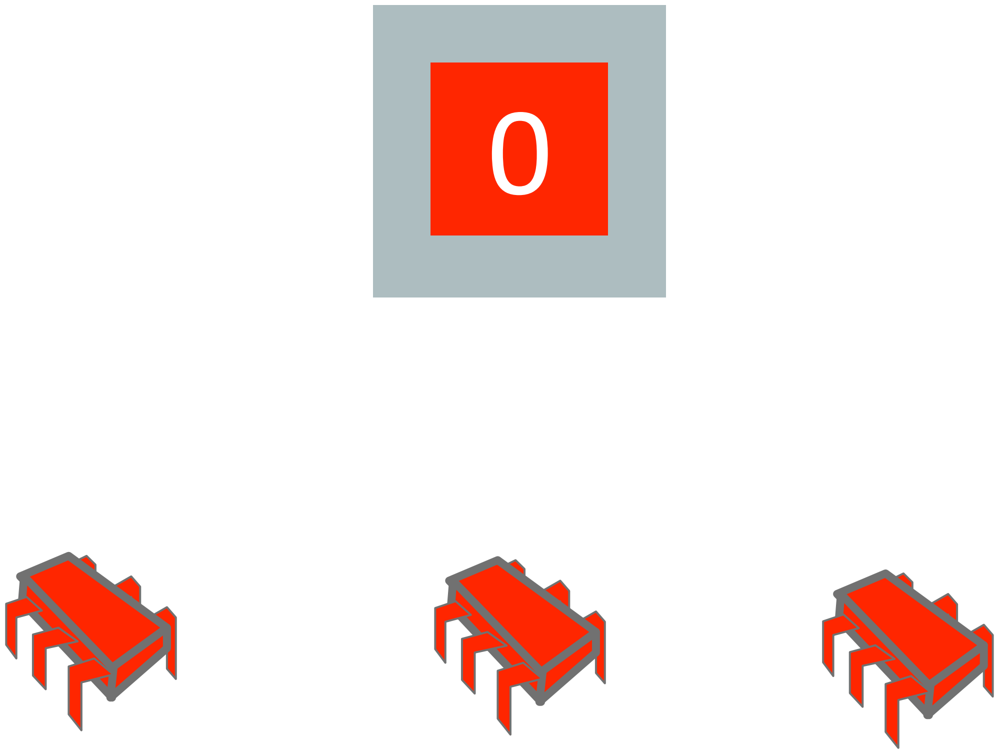

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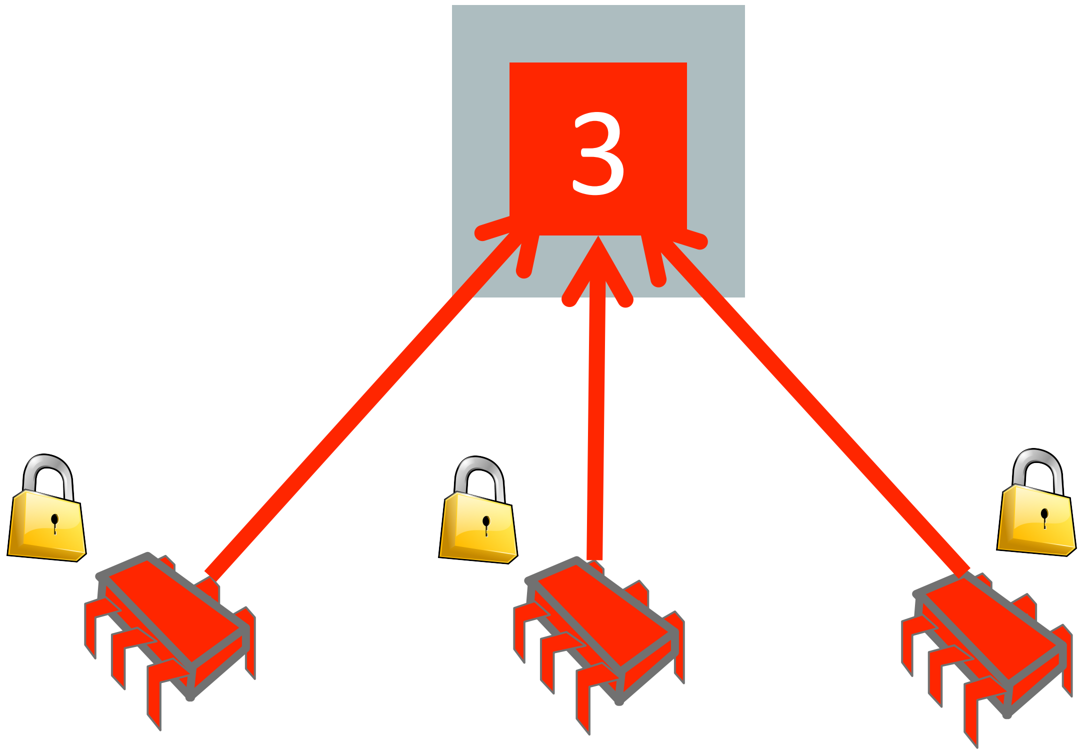

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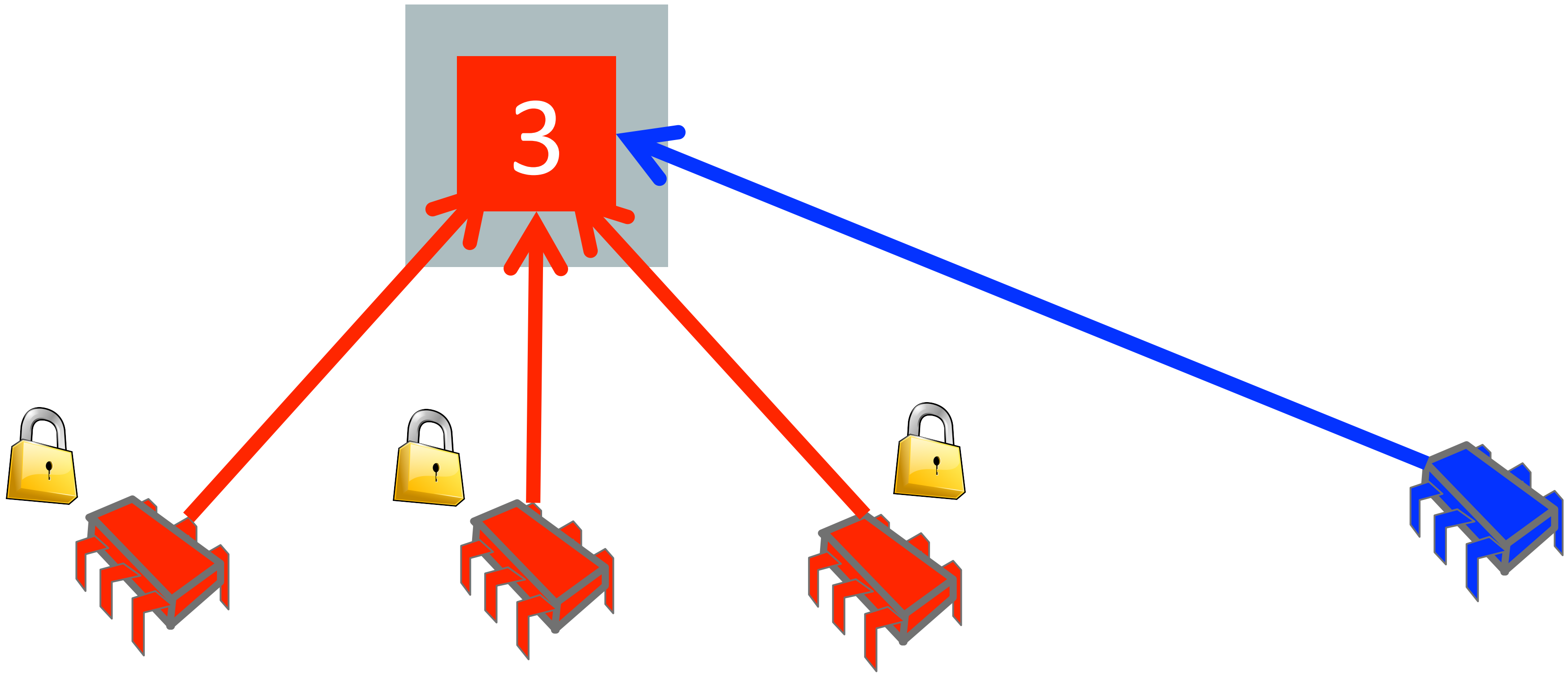

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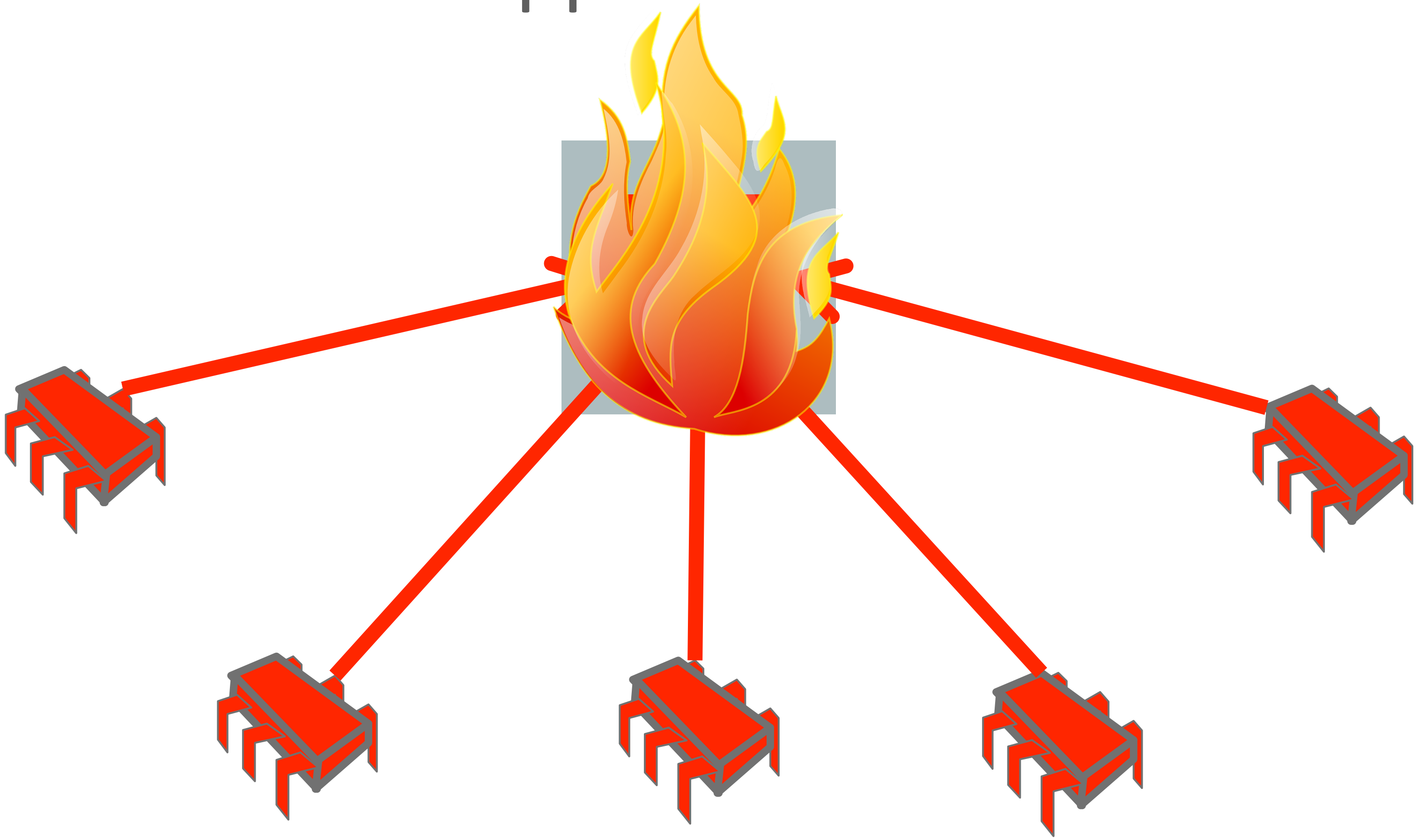

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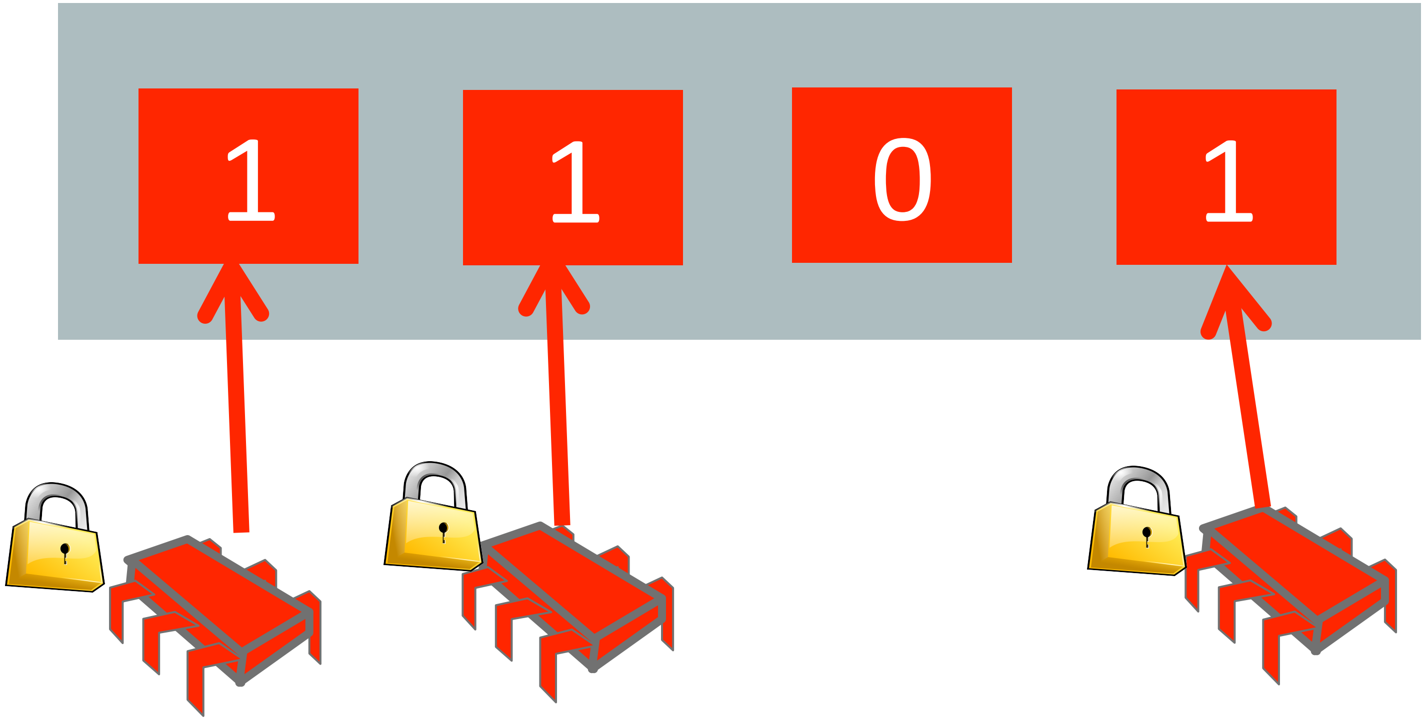

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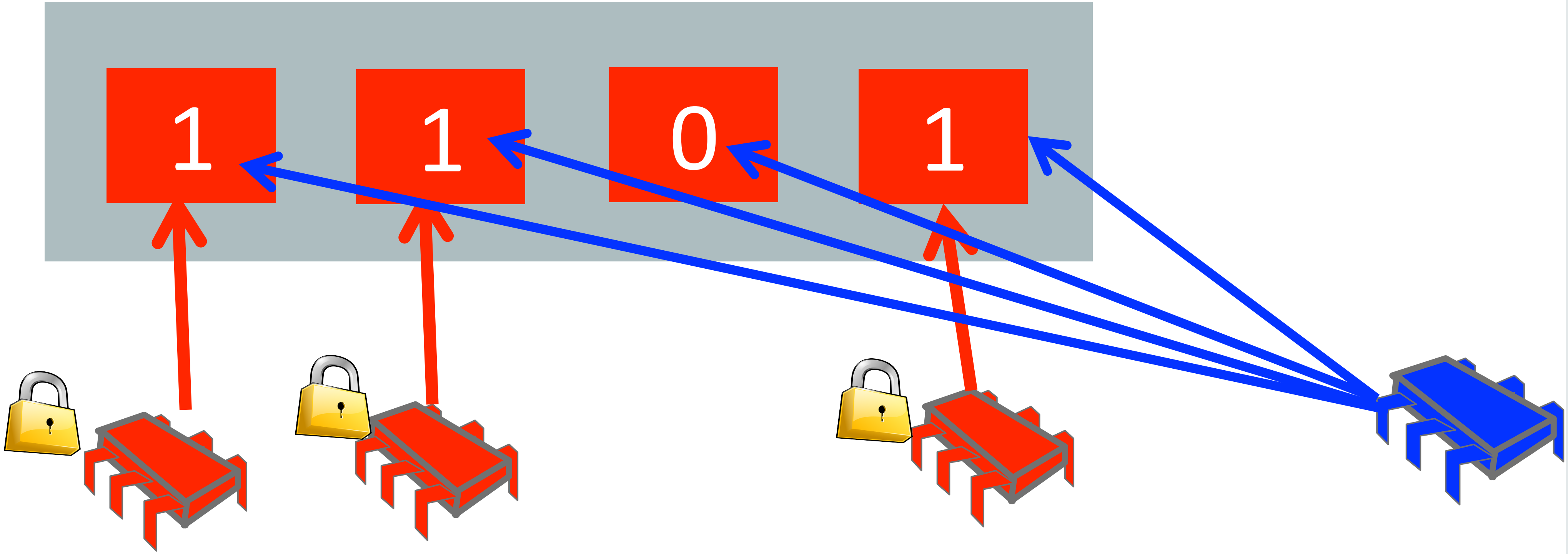
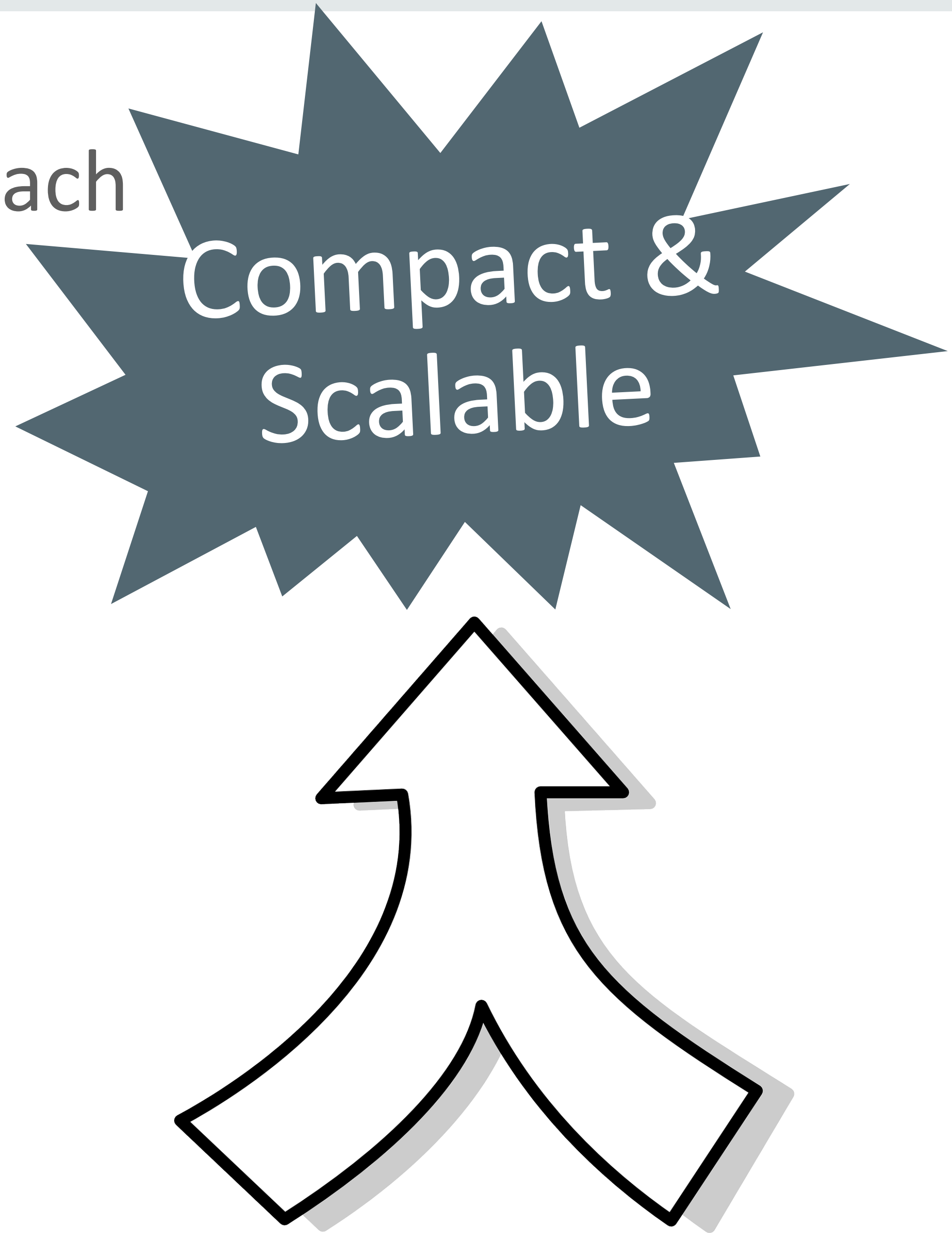


The Scalable "Reader Indicator" Dilemma

The BRAVO approach



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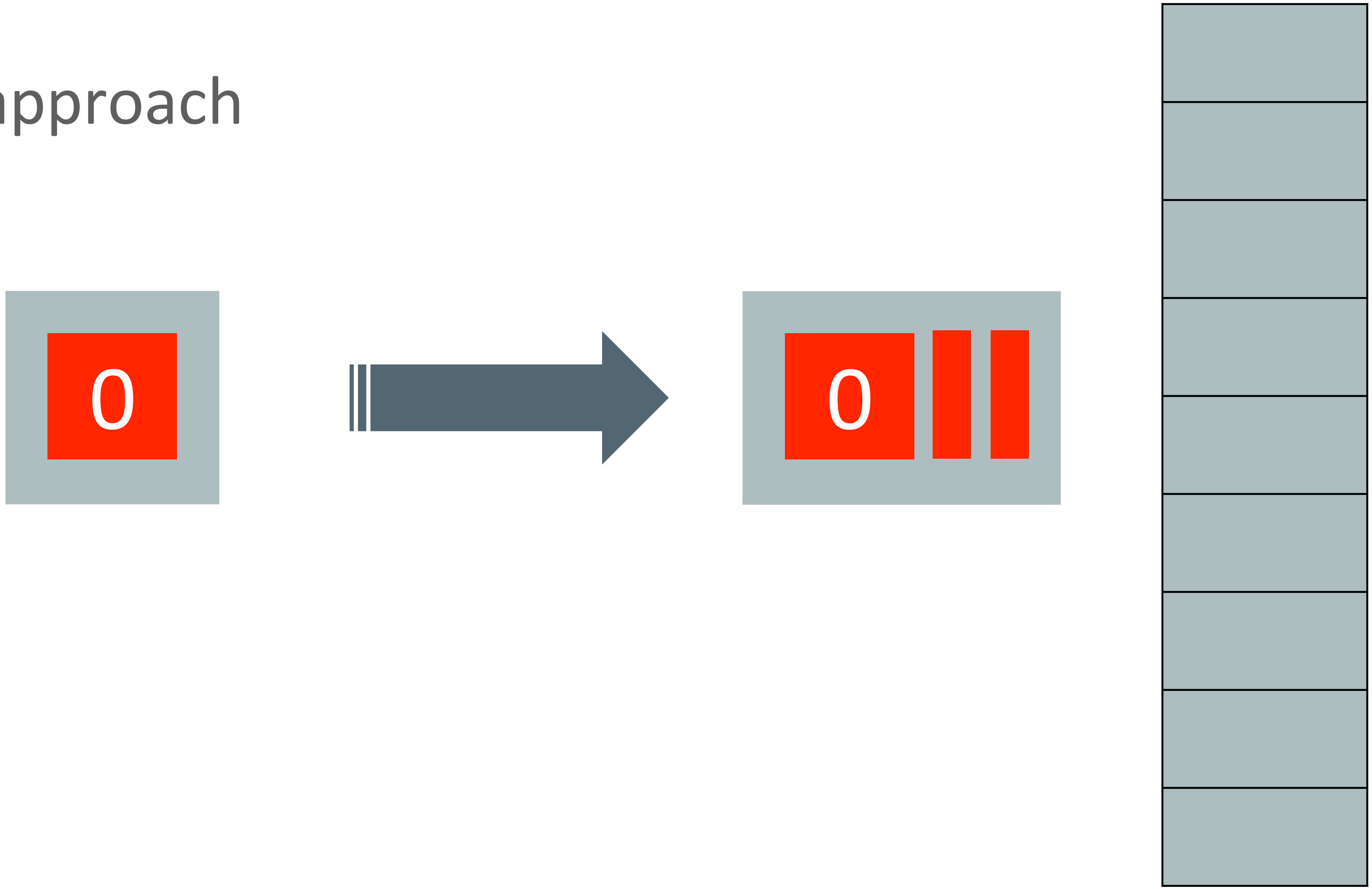

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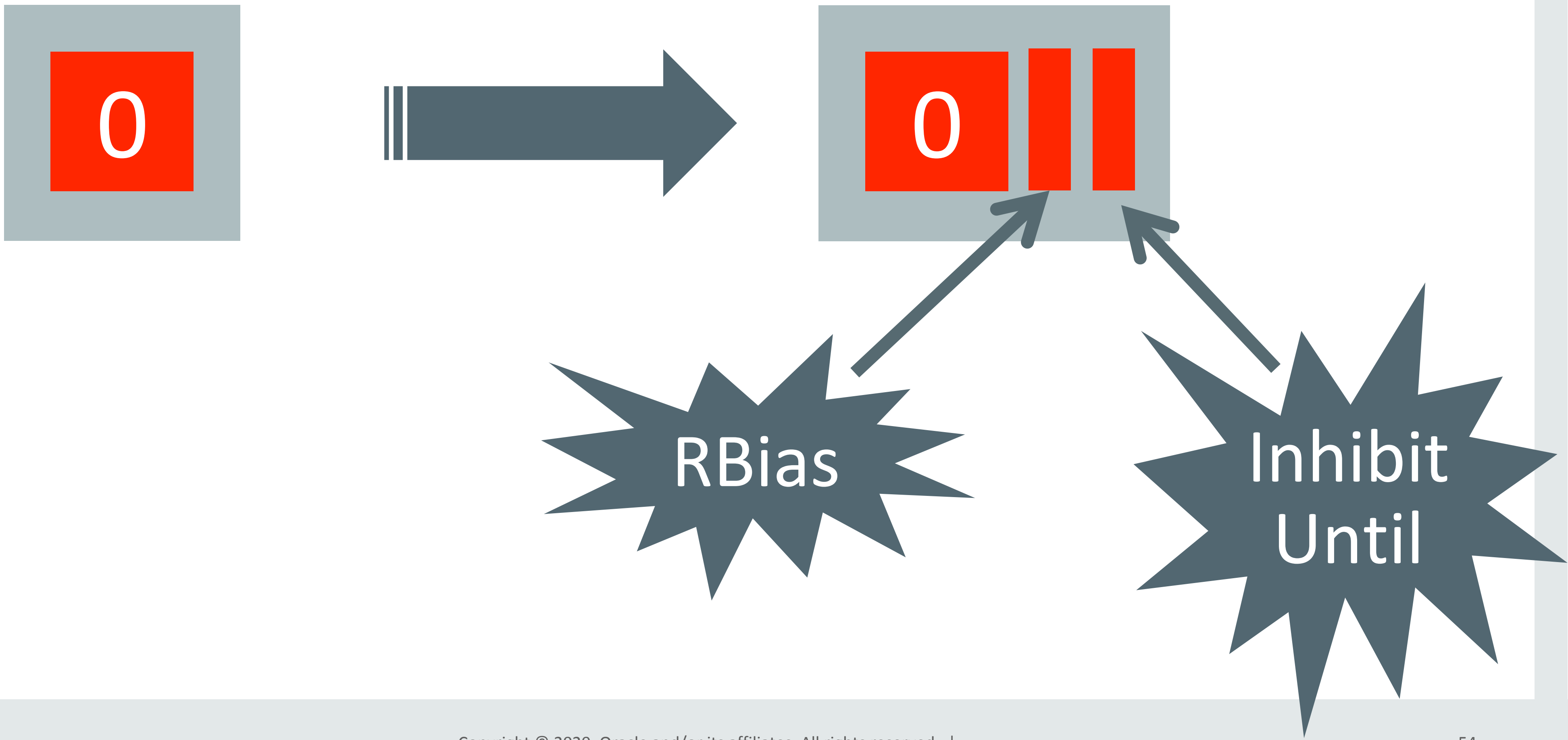

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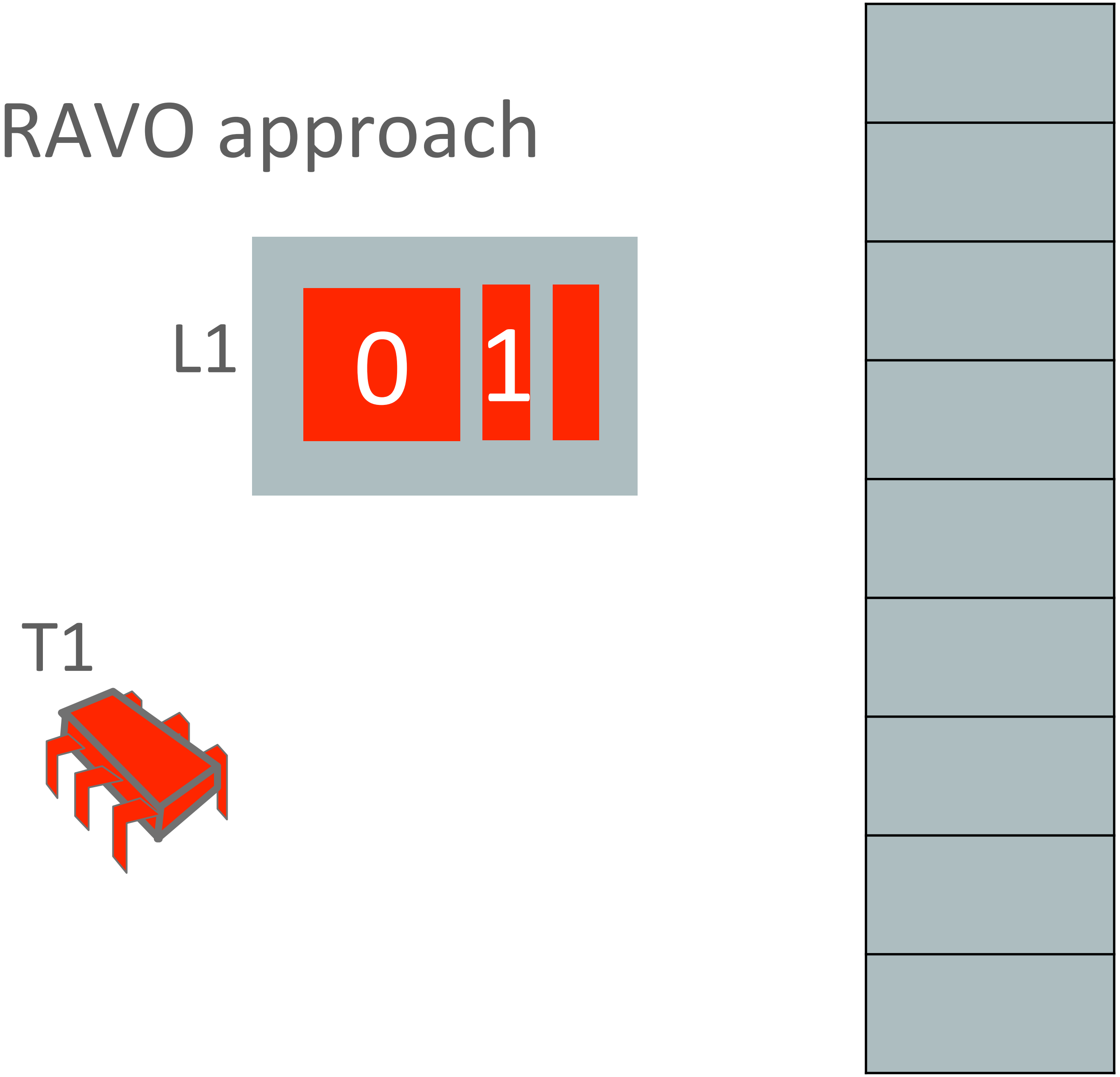

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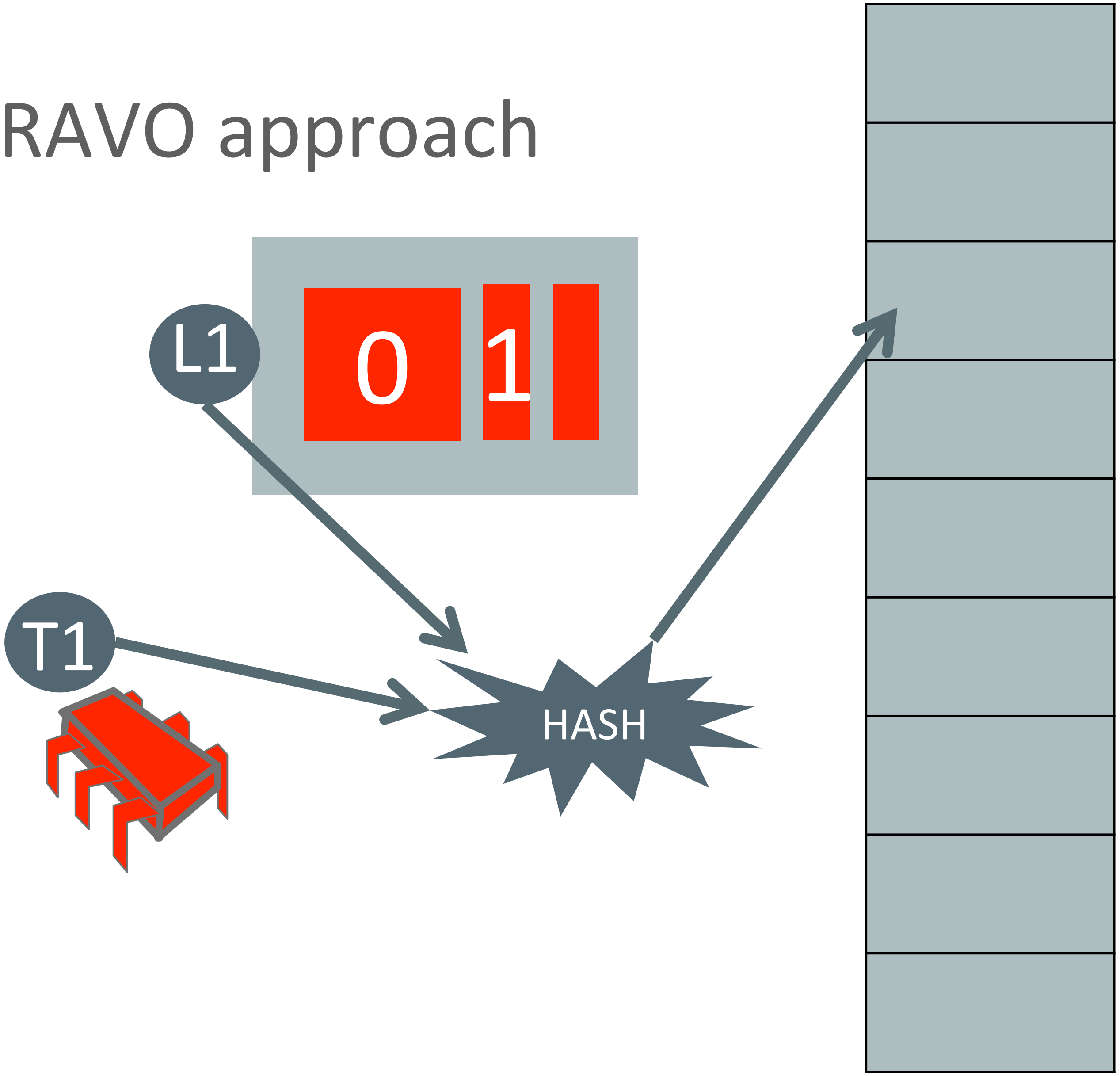

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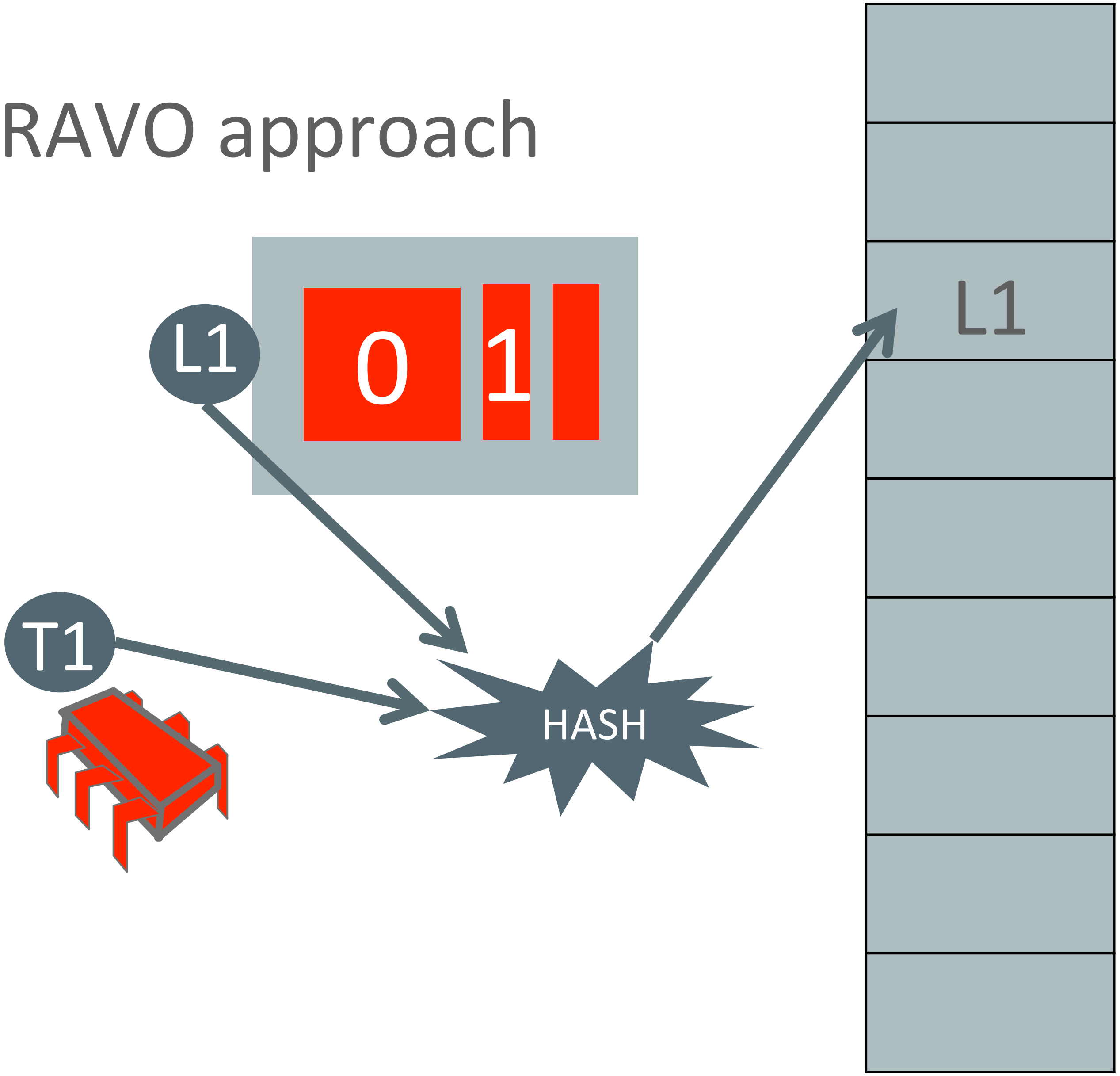

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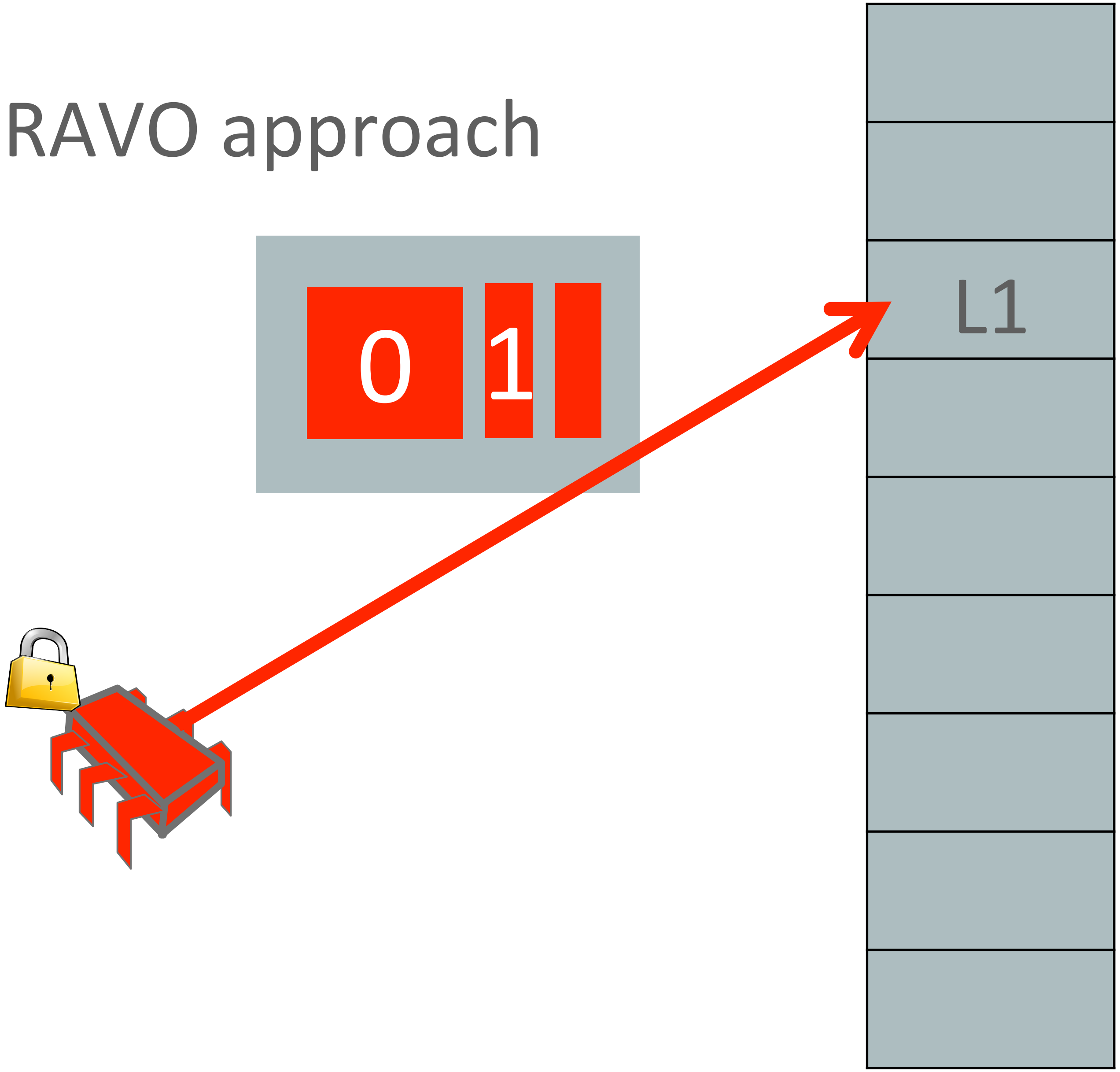

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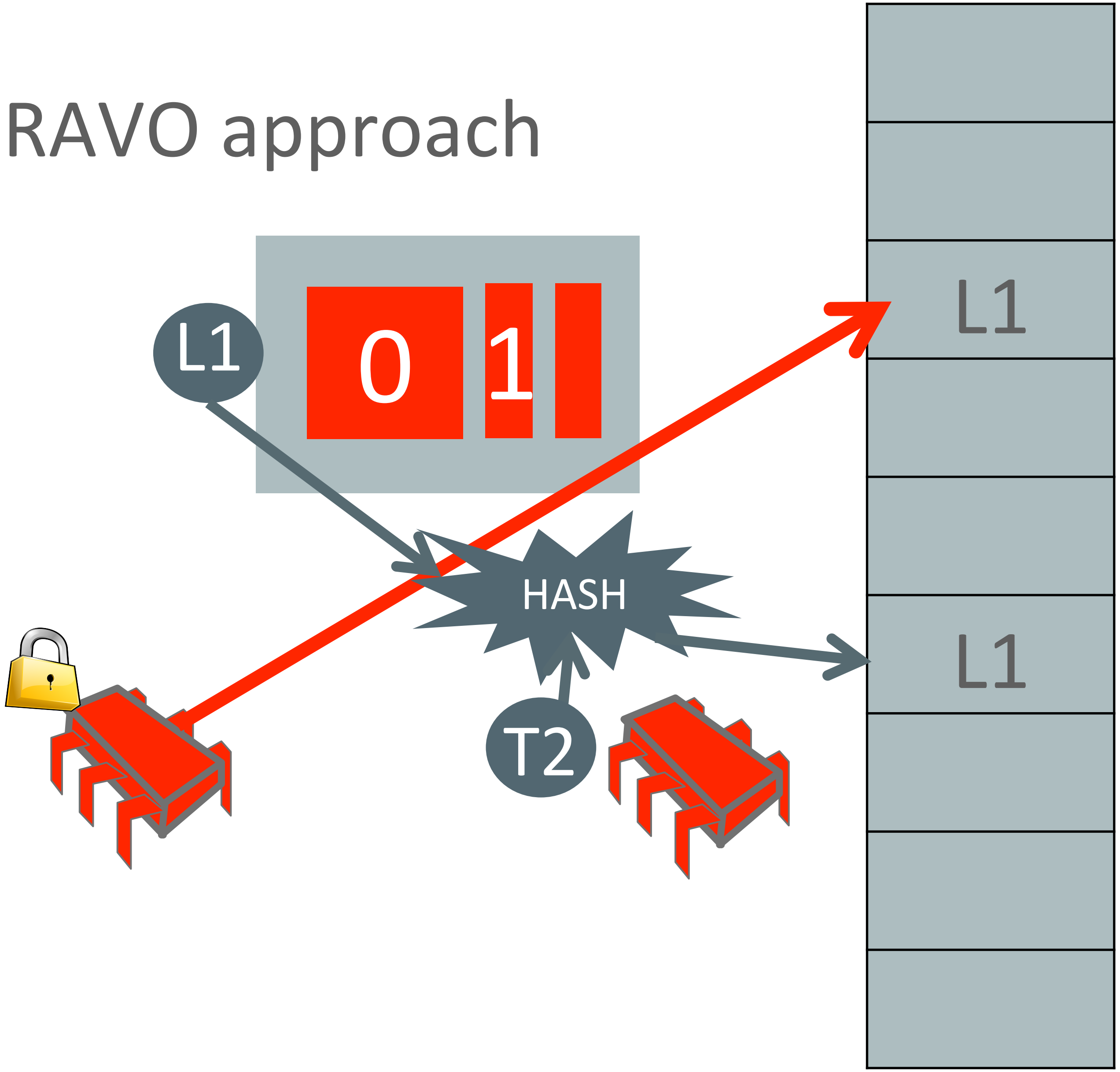

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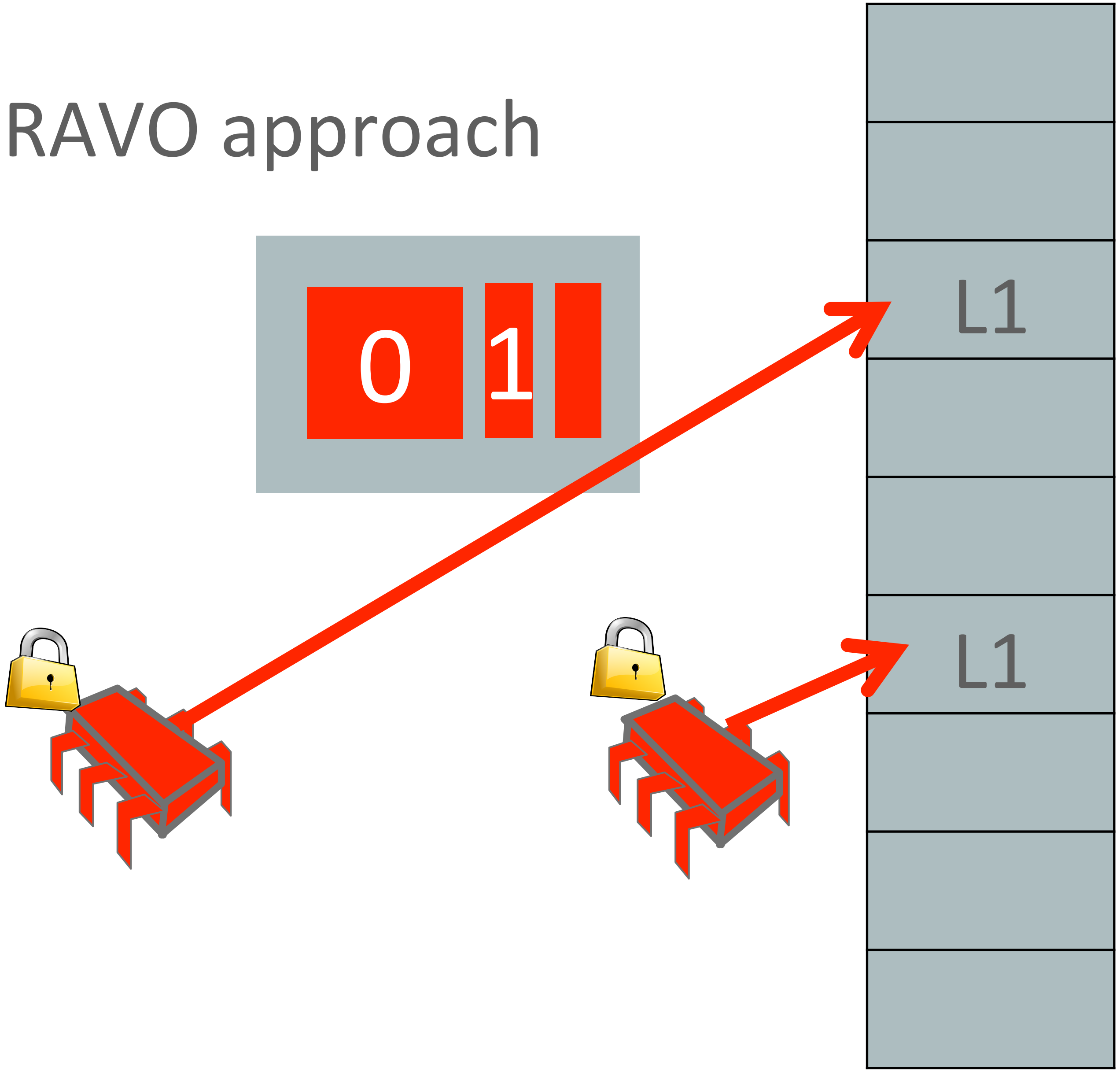

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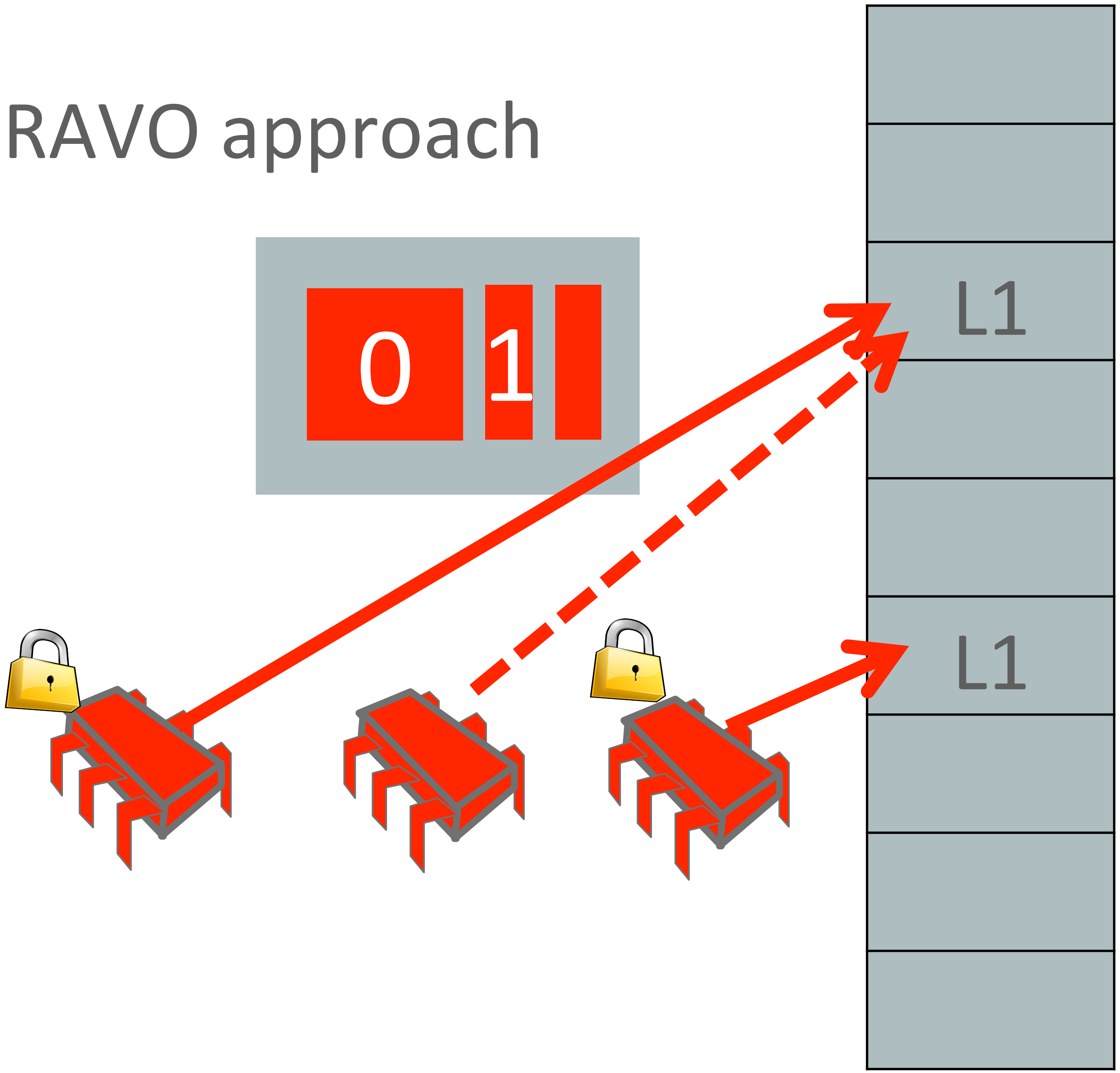

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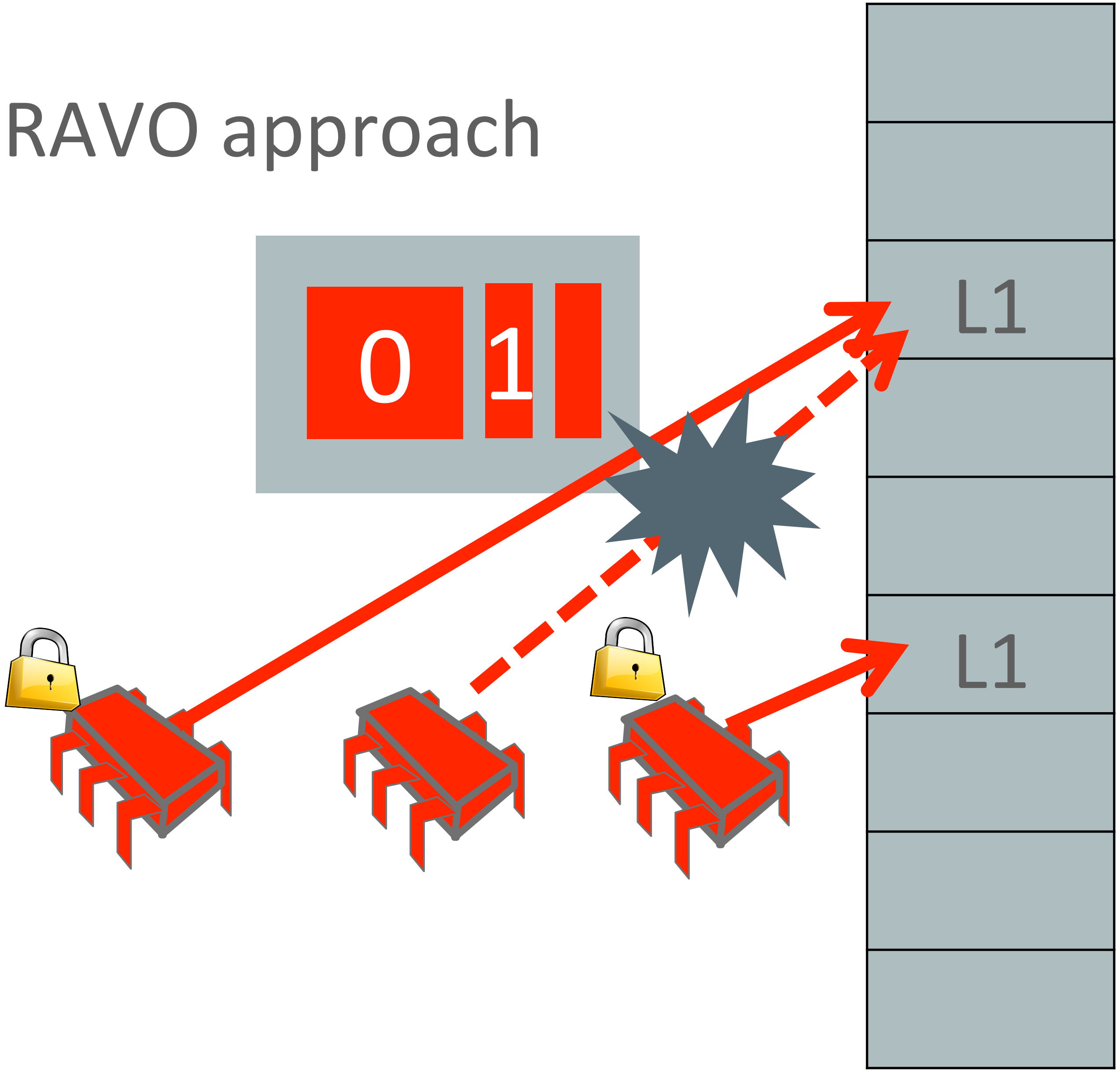

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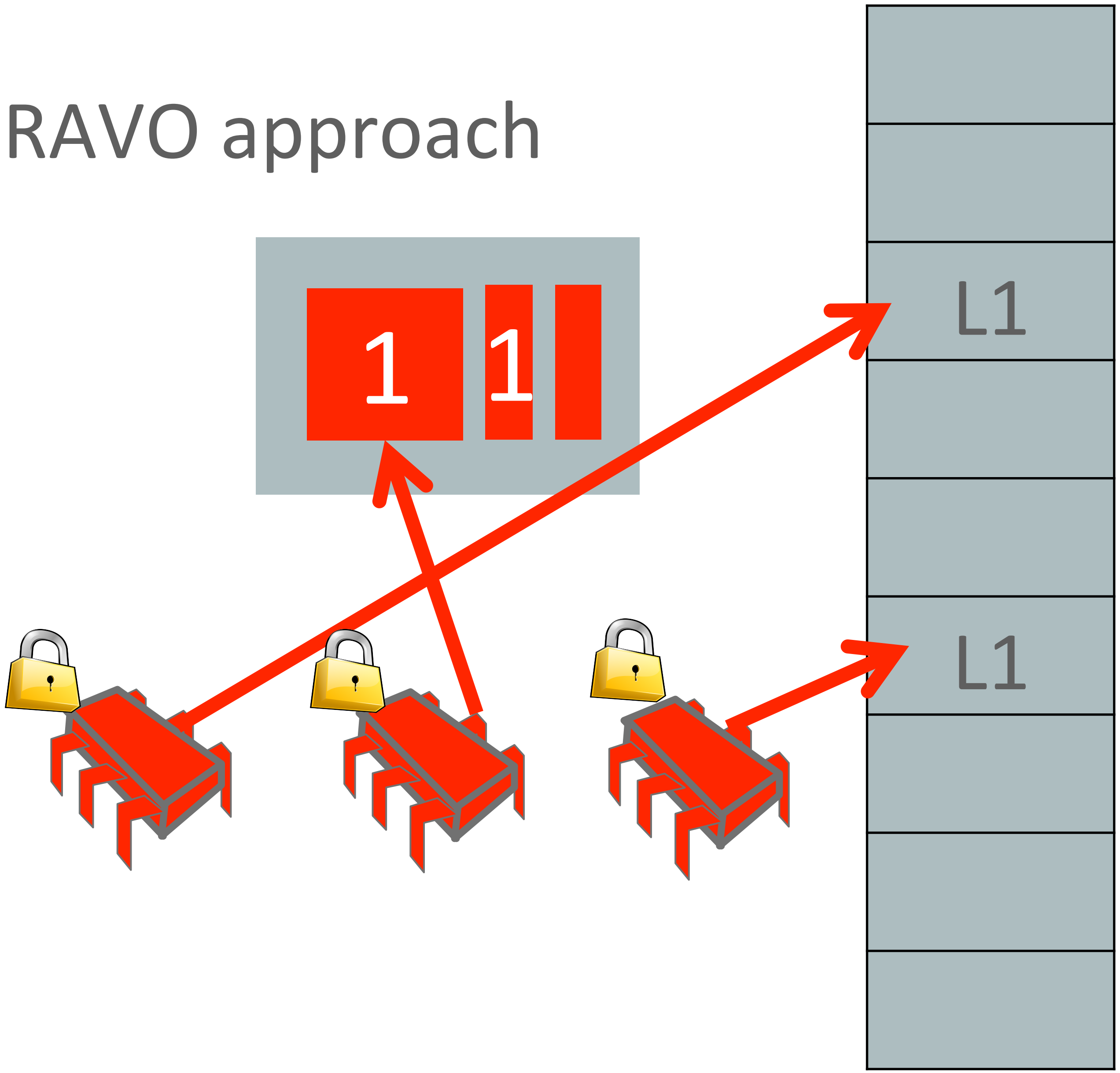

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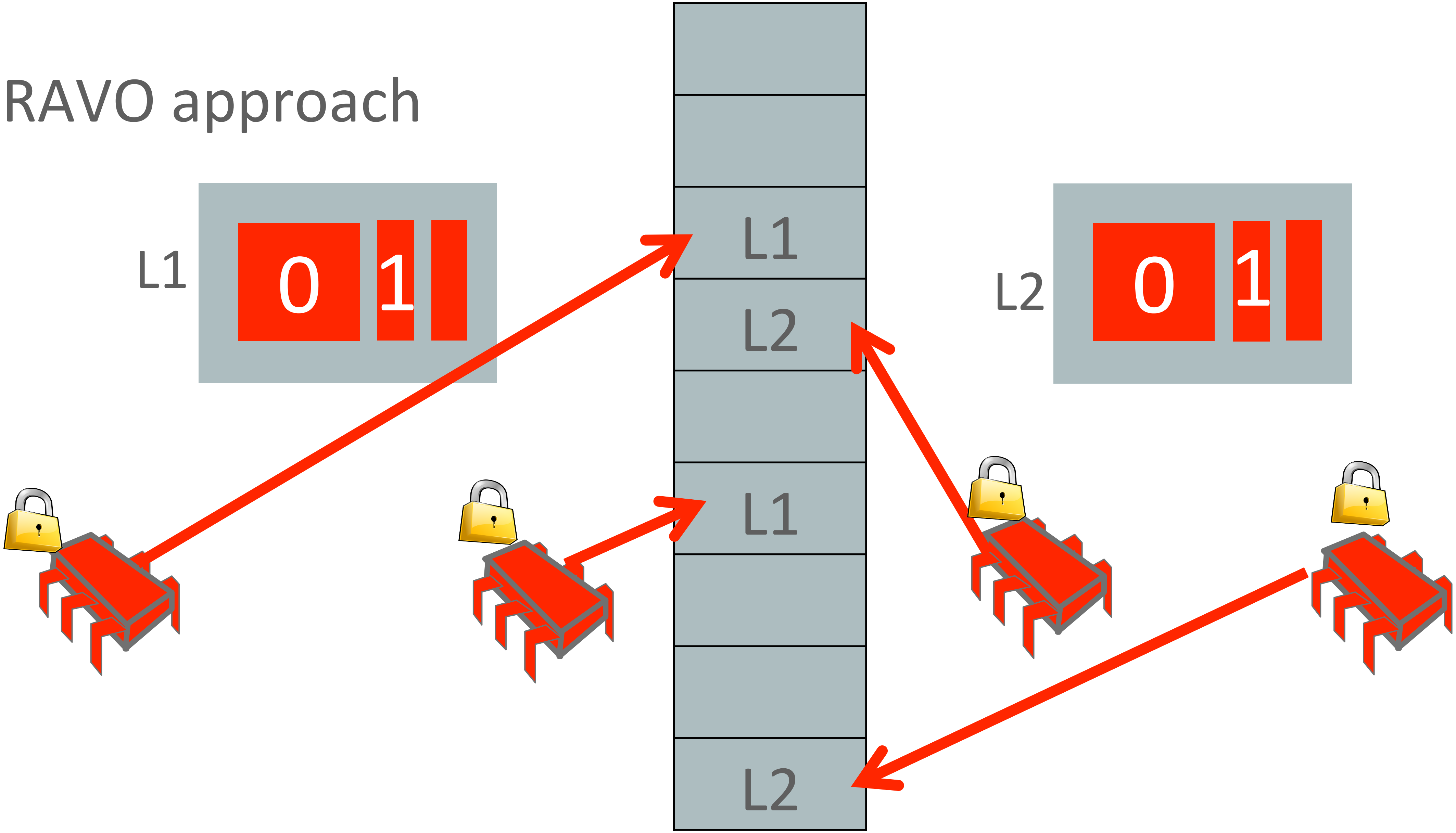

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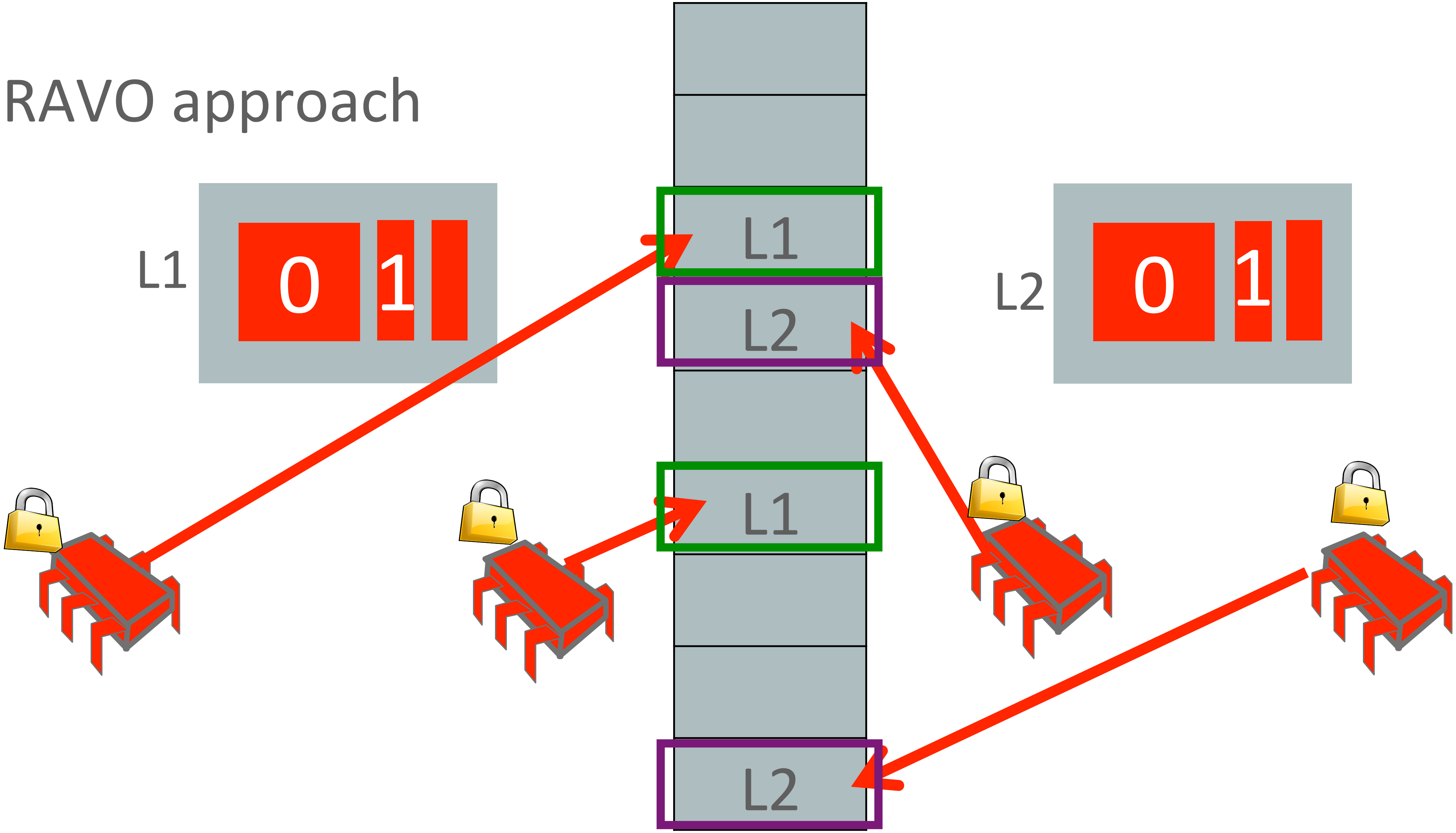

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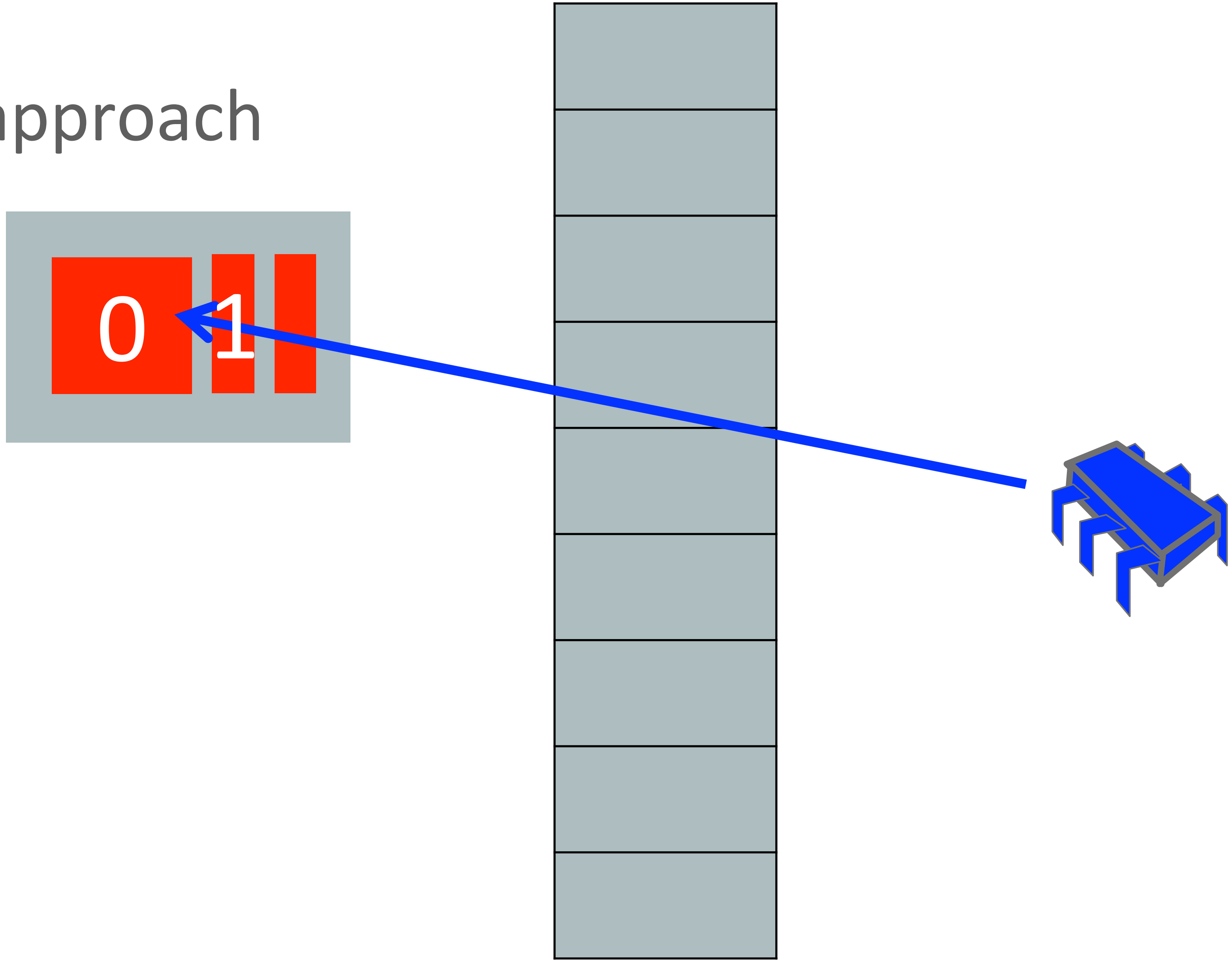

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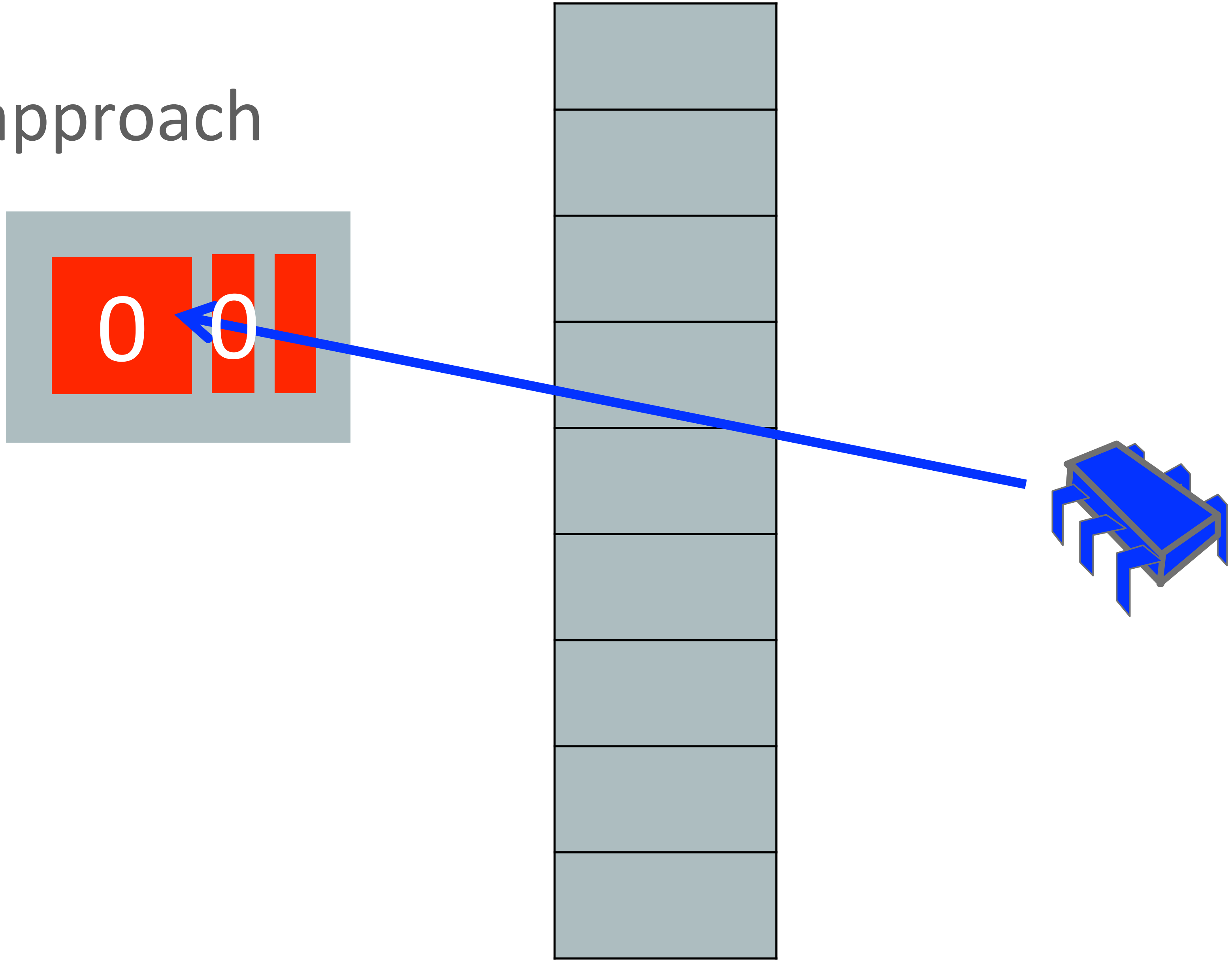

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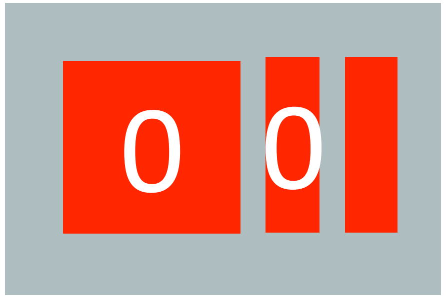

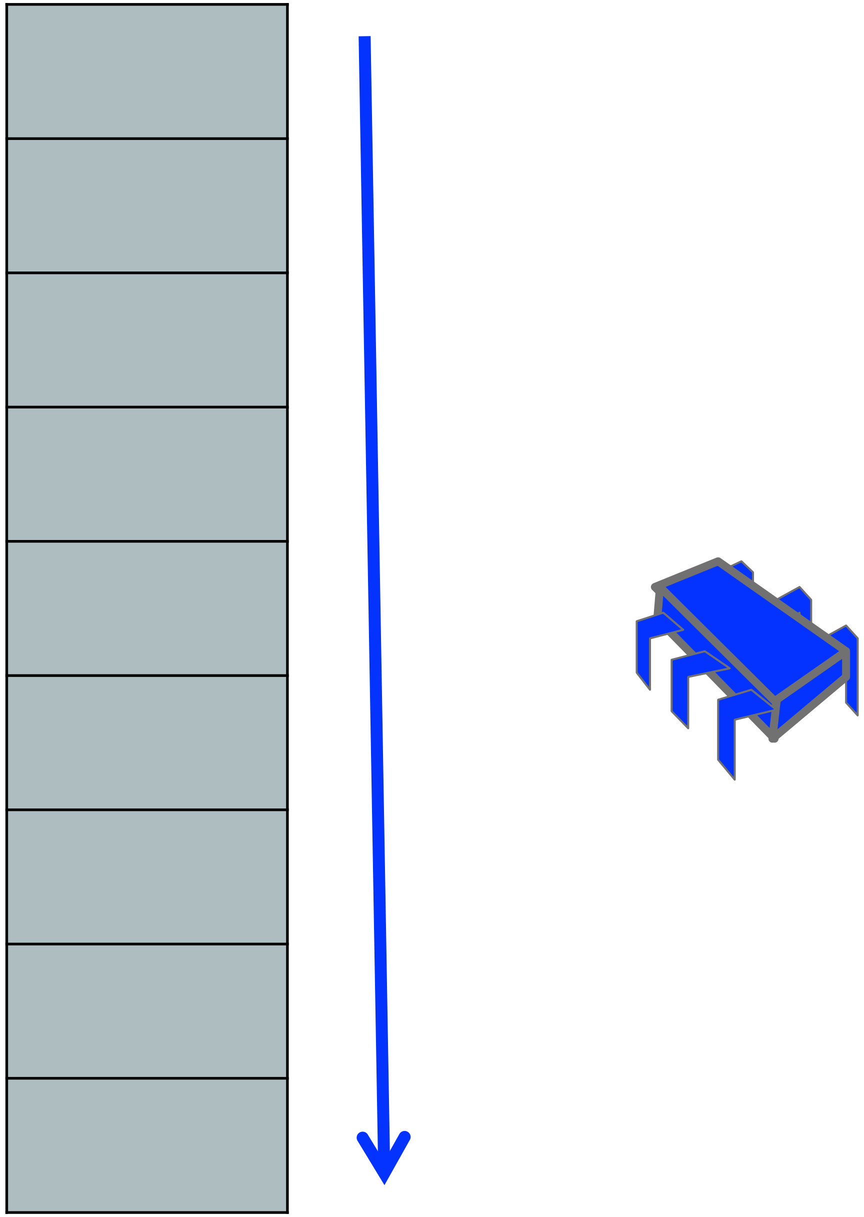

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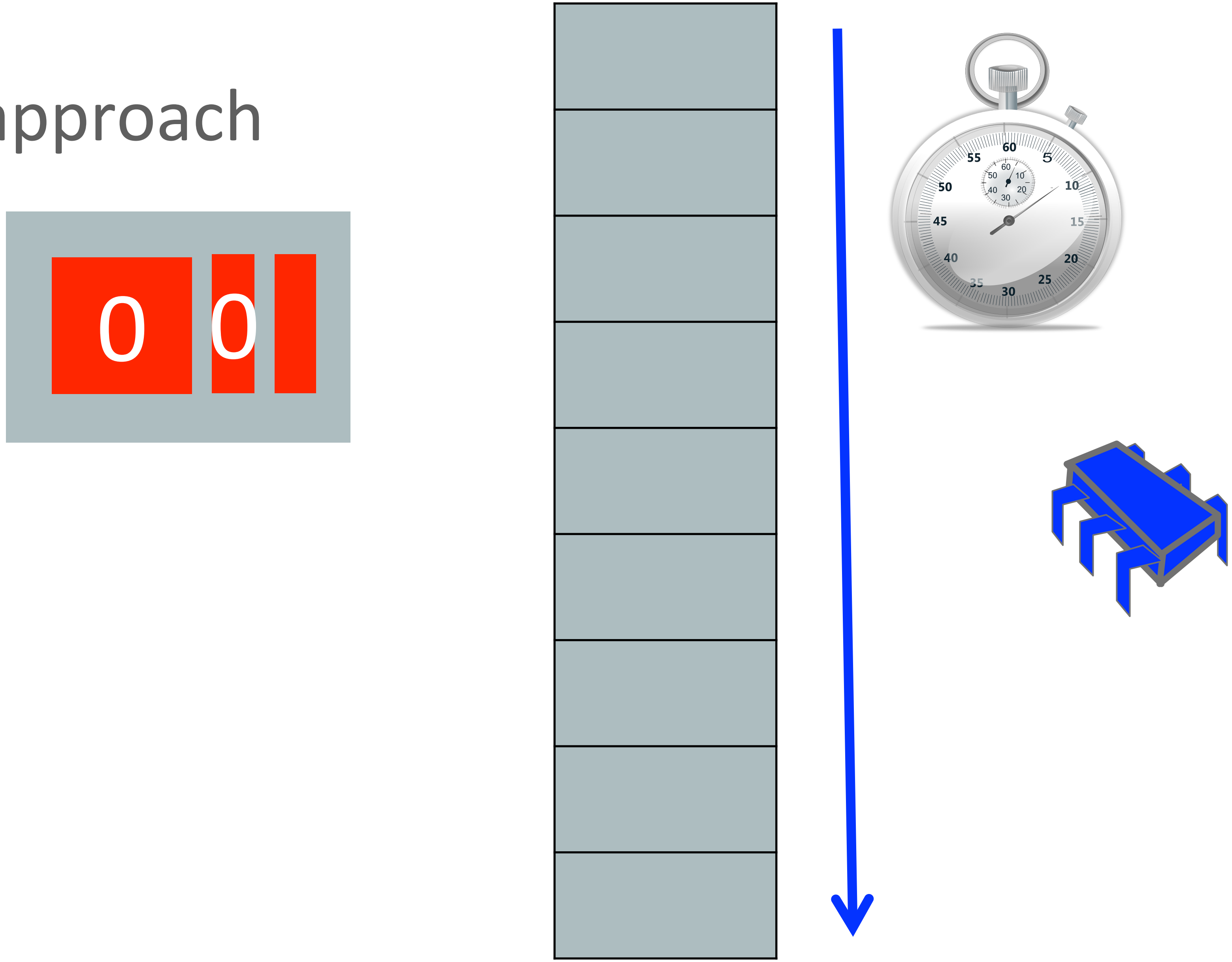

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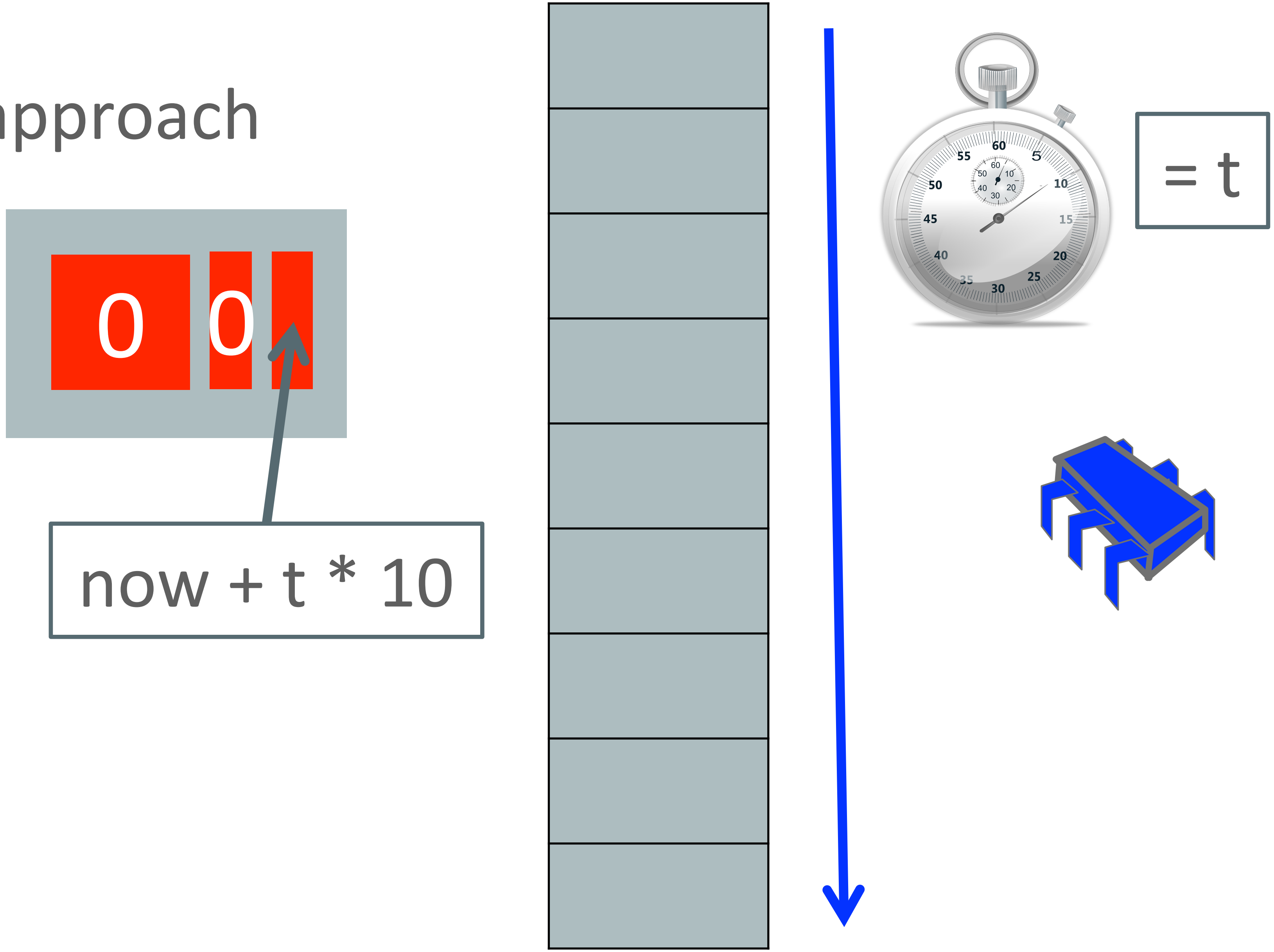

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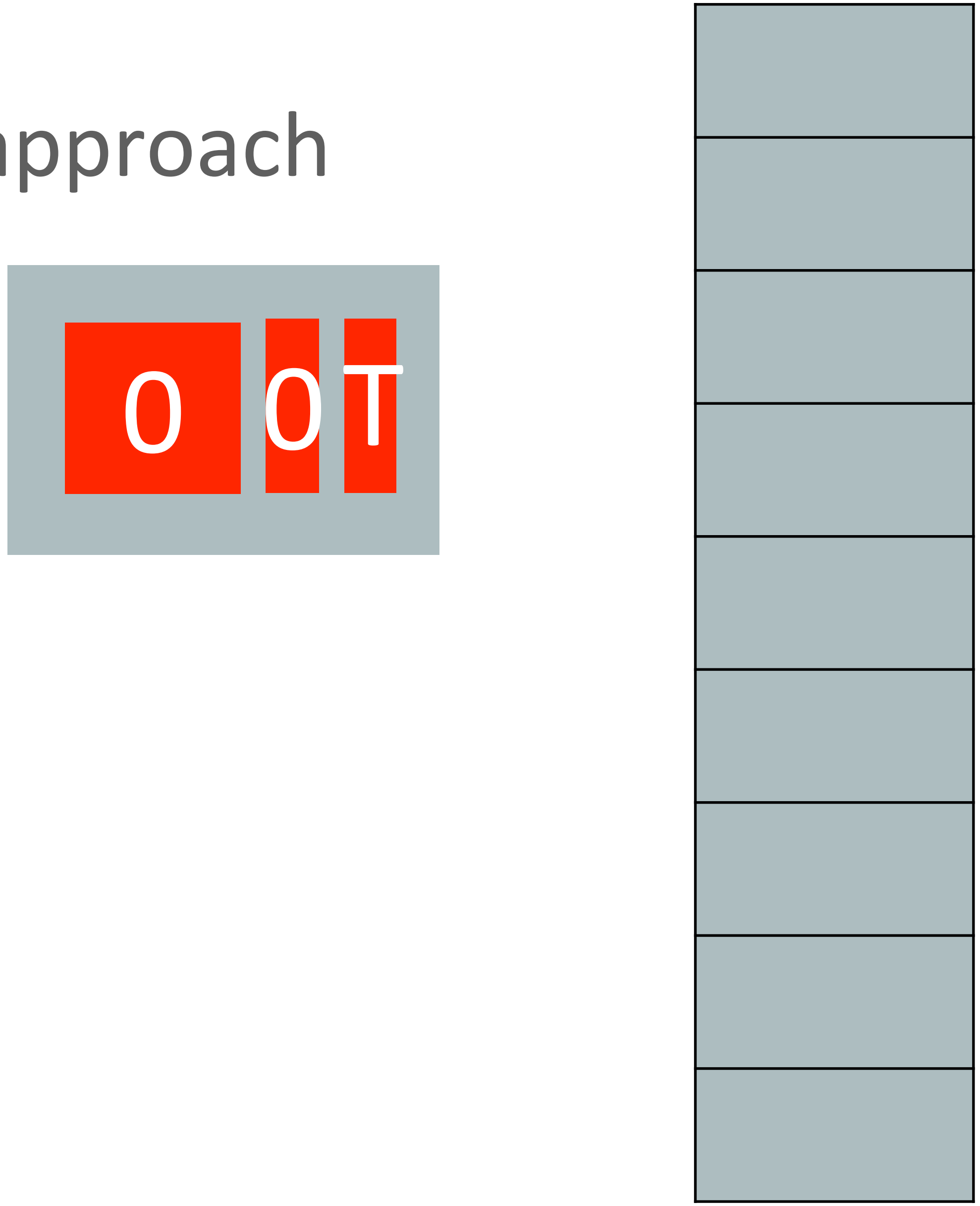

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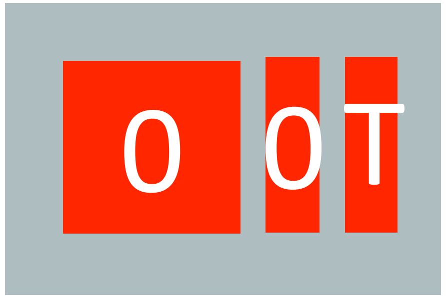
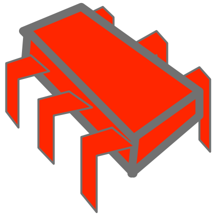
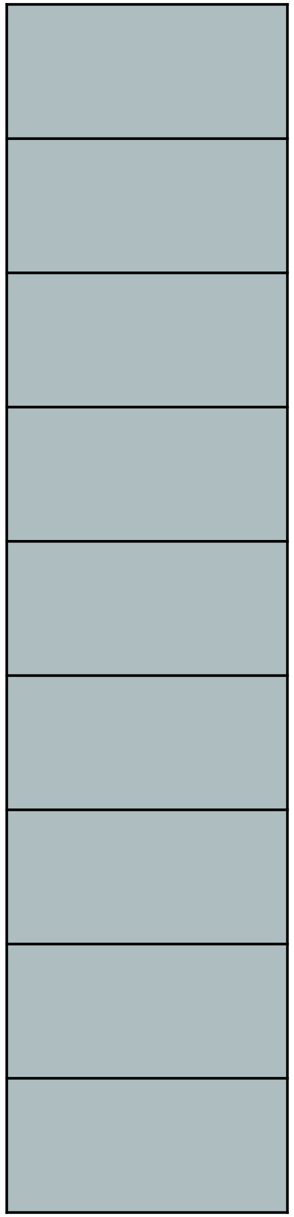
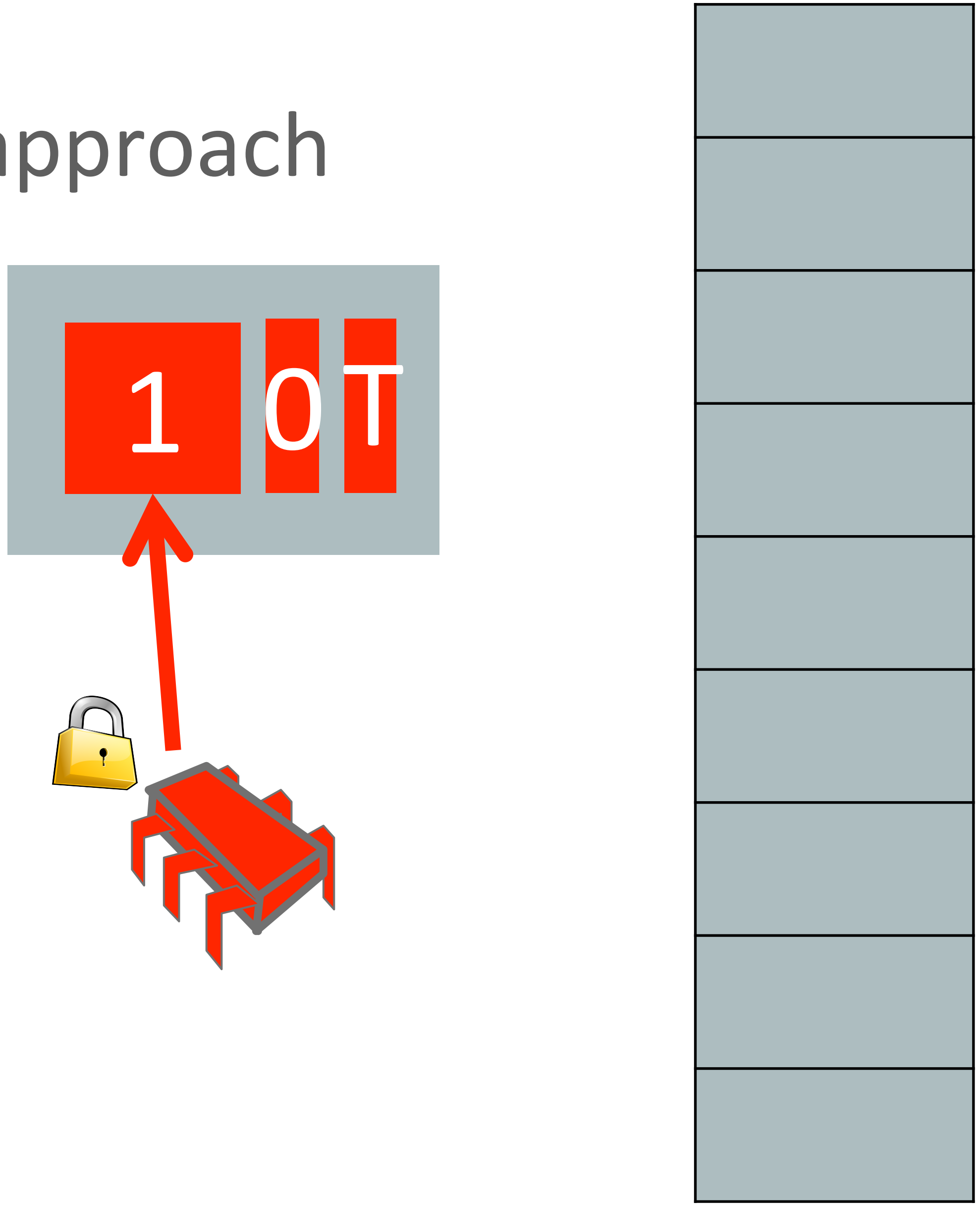


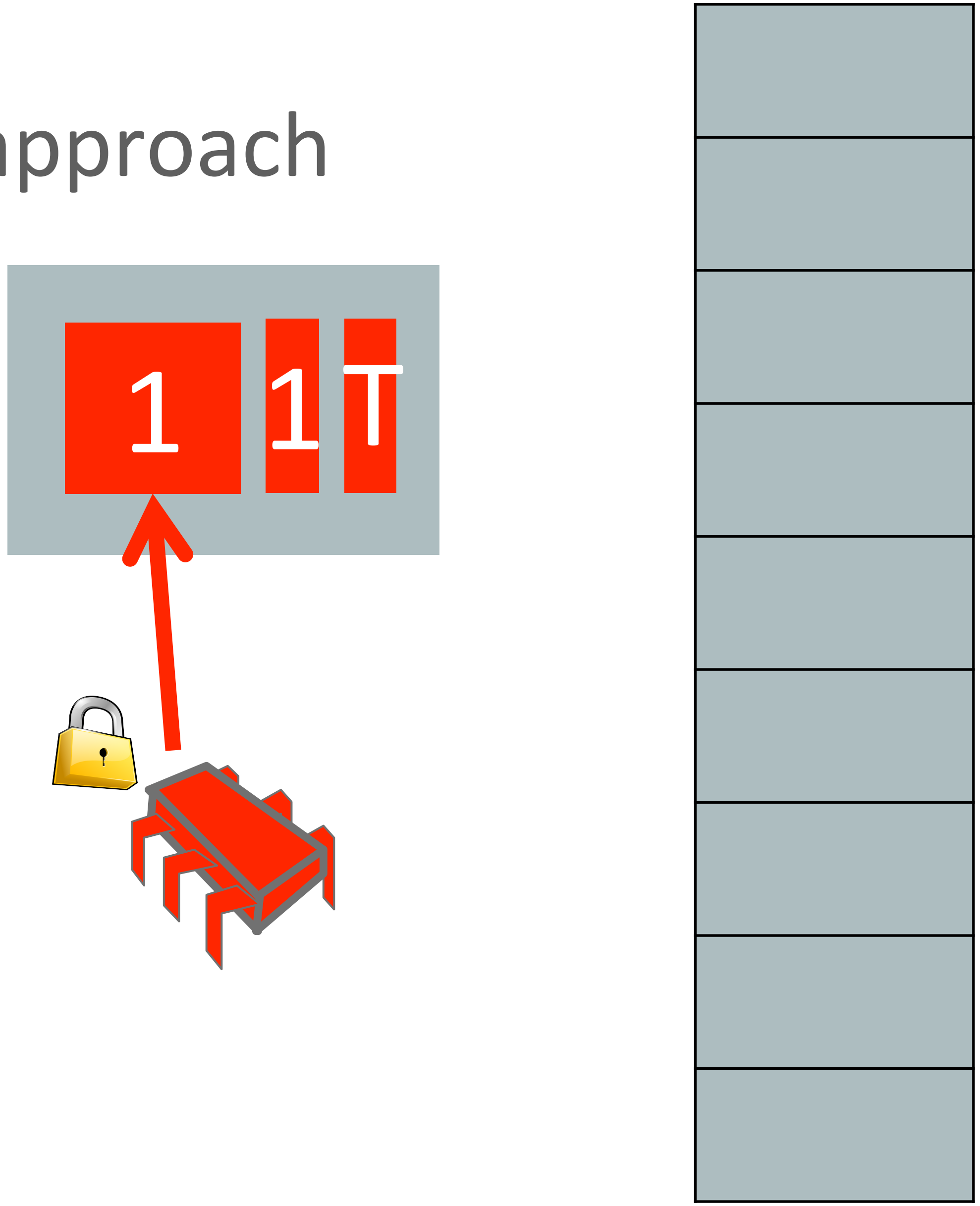




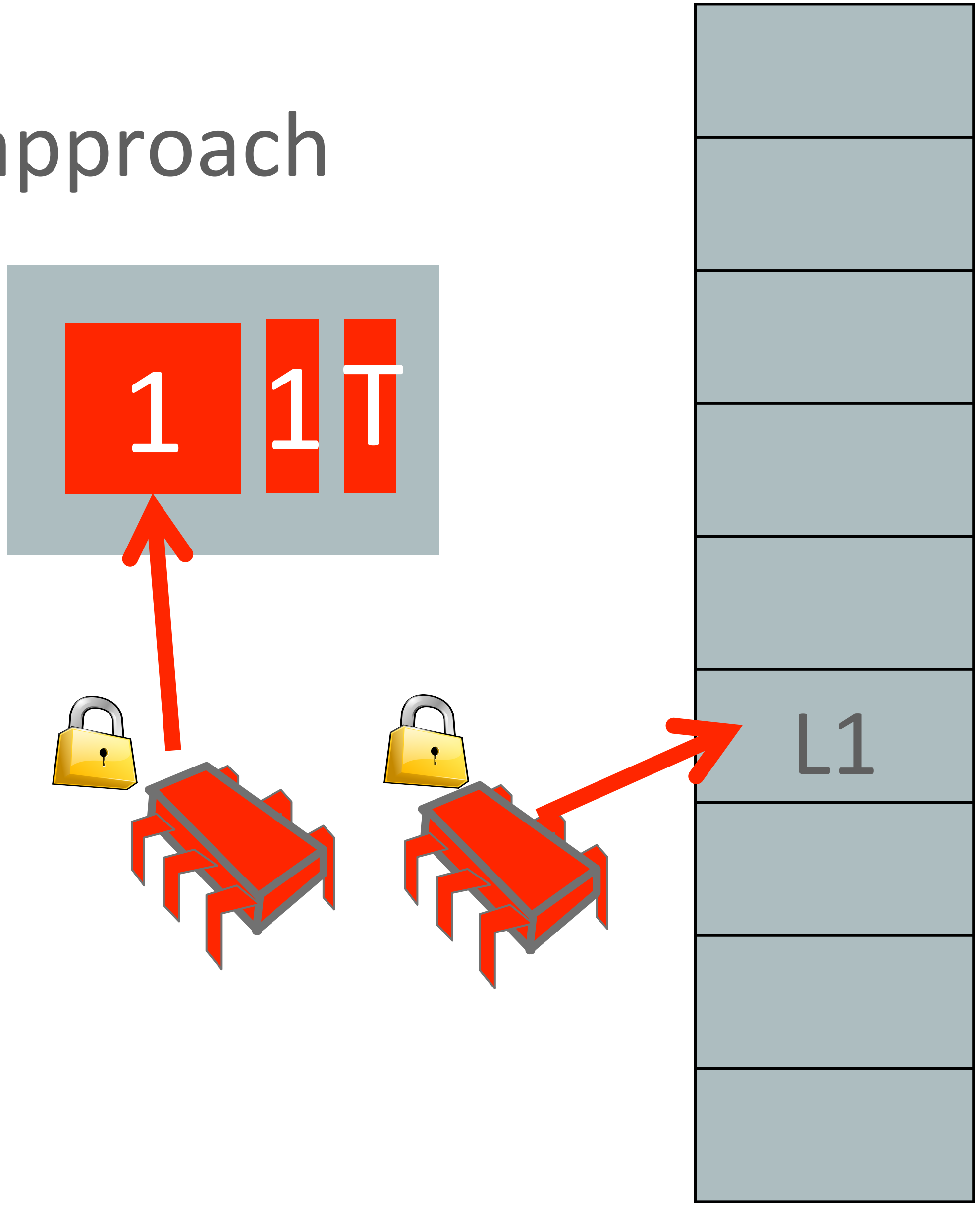
The BRAVO approach



The BRAVO approach



The BRAVO approach



Evaluation

- Easy to integrate with existing locks
- Compact
- Accelerates reads
- Handles writes gracefully

Evaluation: Easy to integrate

- Brandenburg-Anderson (BA) reader-writer lock
- POSIX Pthread reader-writer lock

- Linux kernel rwsem

Evaluation: Compact

Locks	Memory footprint
BA	40
BA + BRAVO	40 + 12 + 32KB (for a table)
Per-CPU	9216 (on a system with 72 CPUs)
Cohort-RW	896 (dual-socket)

Intel Xeon E5-2699 v3 CPU
2 sockets
72 logical CPUs in total

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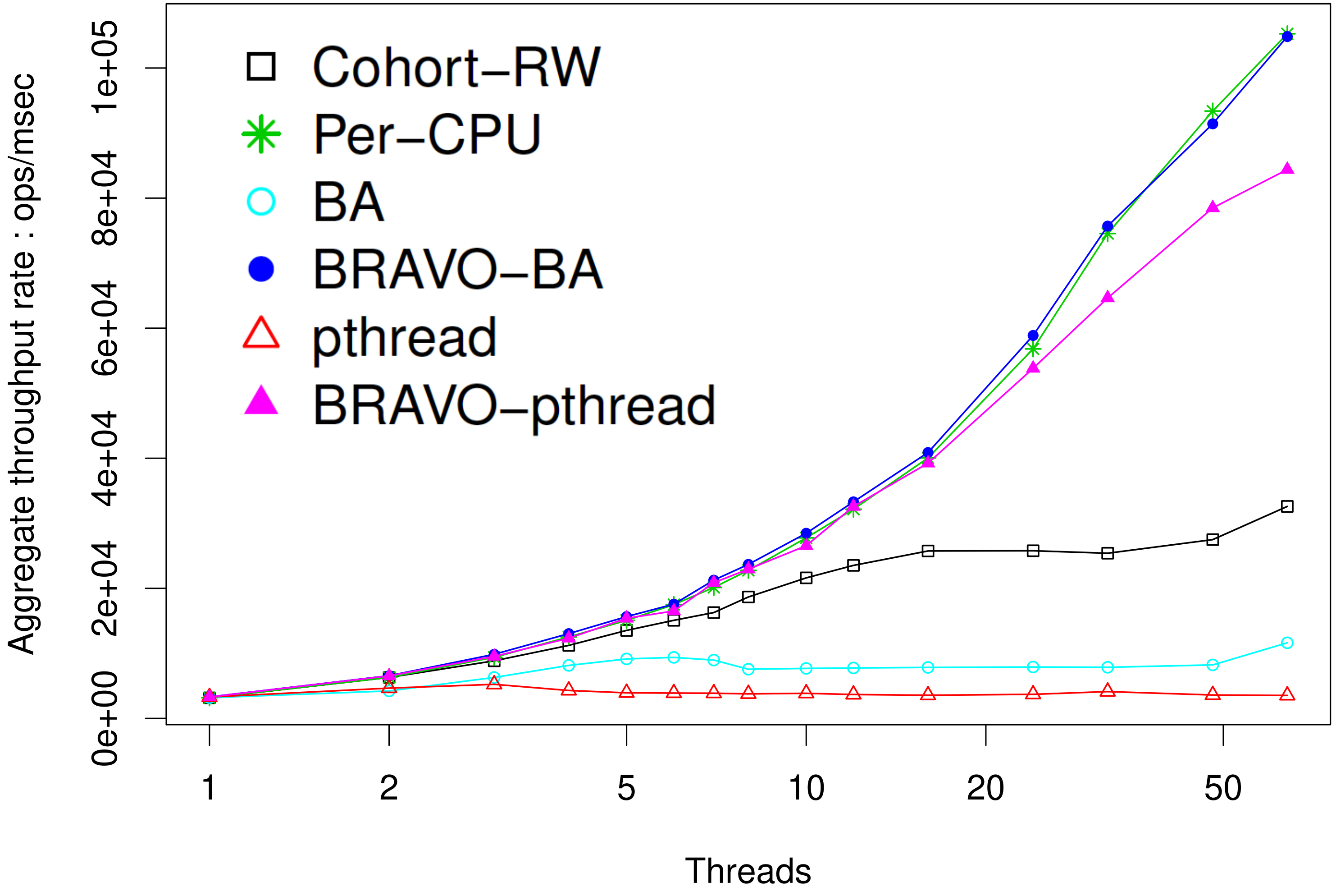
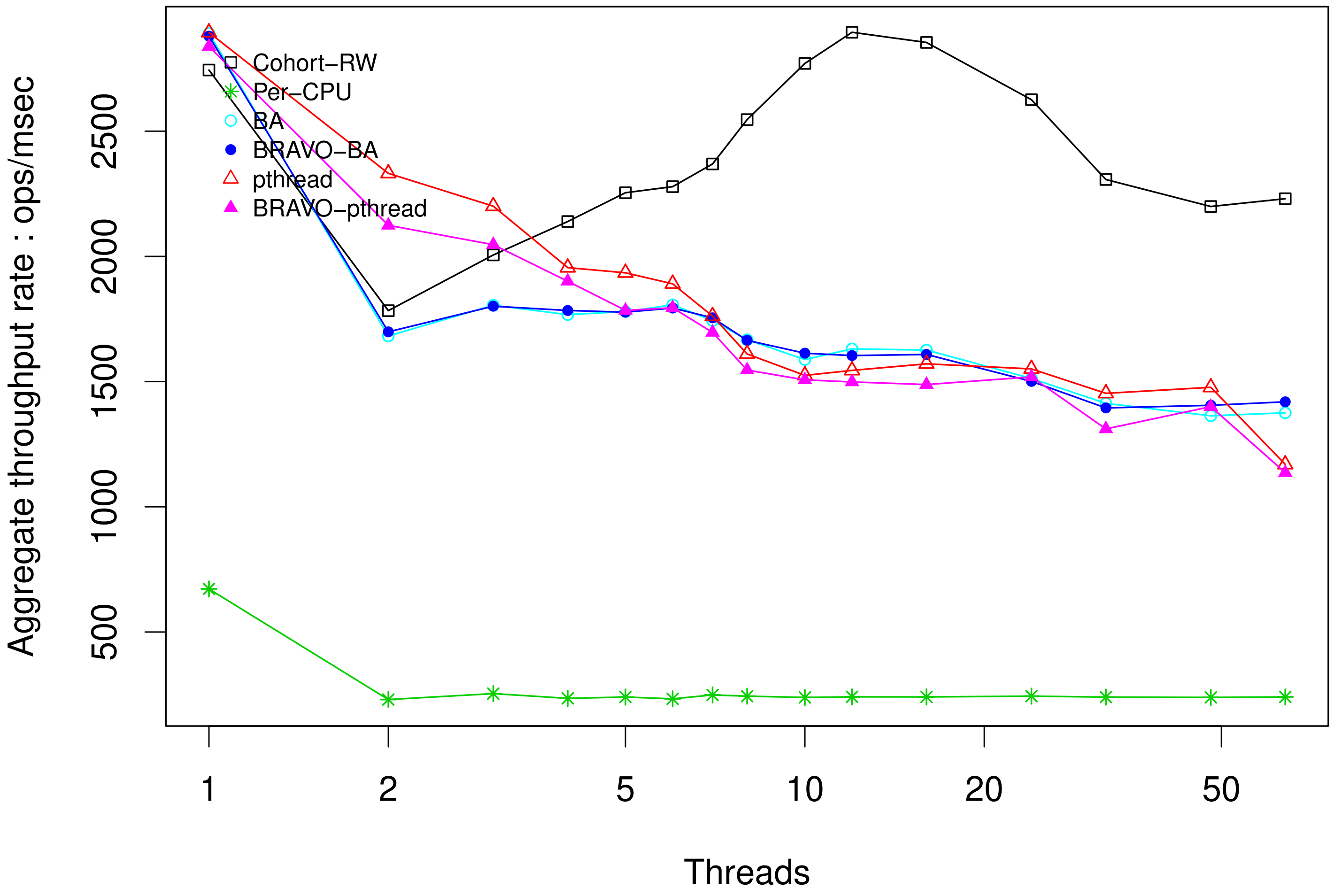
Evaluation: Accelerates reads

RWBench with 1 out of every 10000 are writes



Evaluation: Handles writes gracefully

RWBench with 9 out of every 10 are writes



Linux Kernel rwsem

- Counter + waiting queue protected by a spin lock
- Reader atomically increments the counter and checks its value

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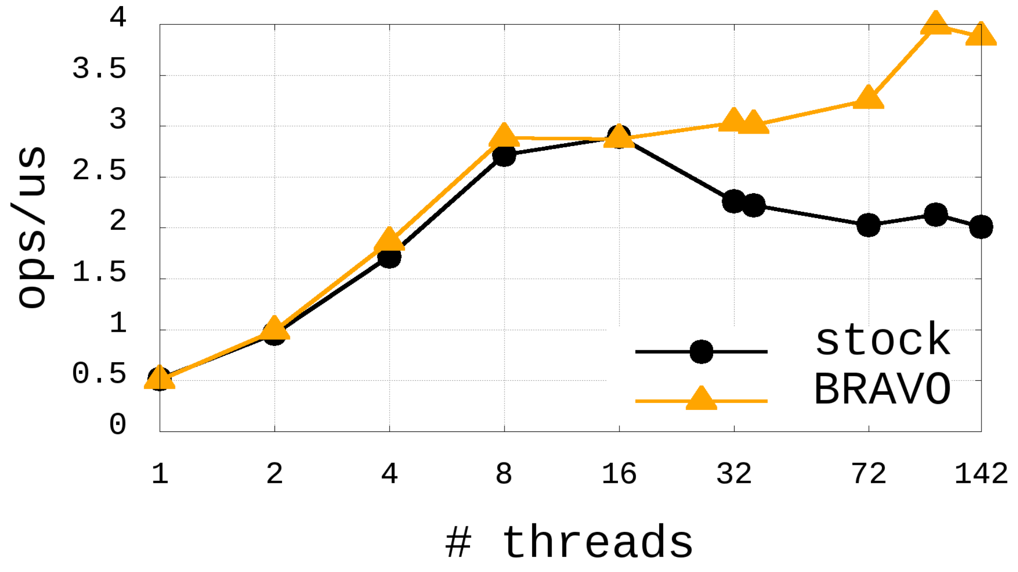
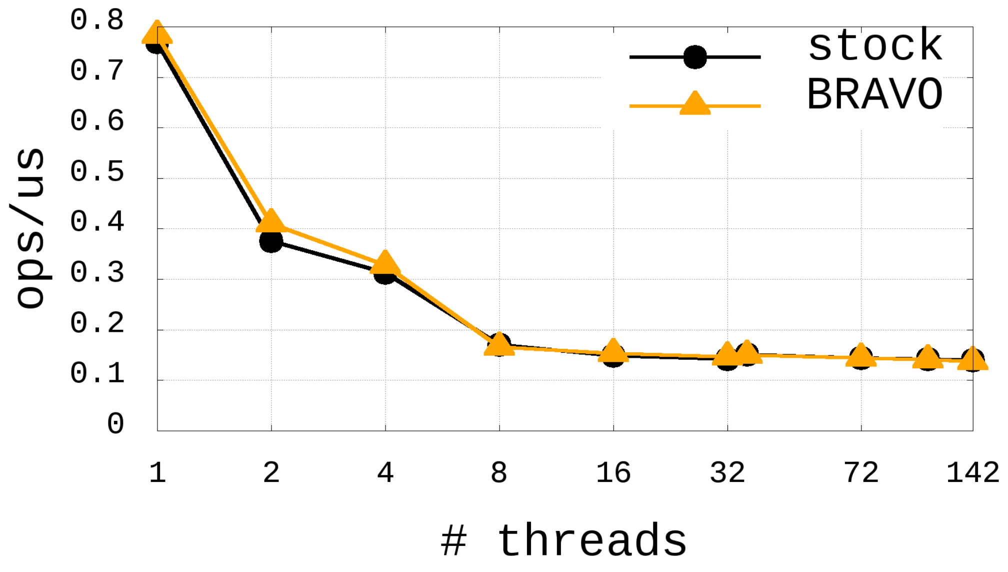
- Reader atomically increments the counter and checks its value
- Synchronization bottleneck in the kernel (mmap_sem)
- Stress-test with will-it-scale: page_fault and mmap

Evaluation with will-it-scale

Intel Xeon E7-8895 v3 CPU
4 sockets
144 logical CPUs in total



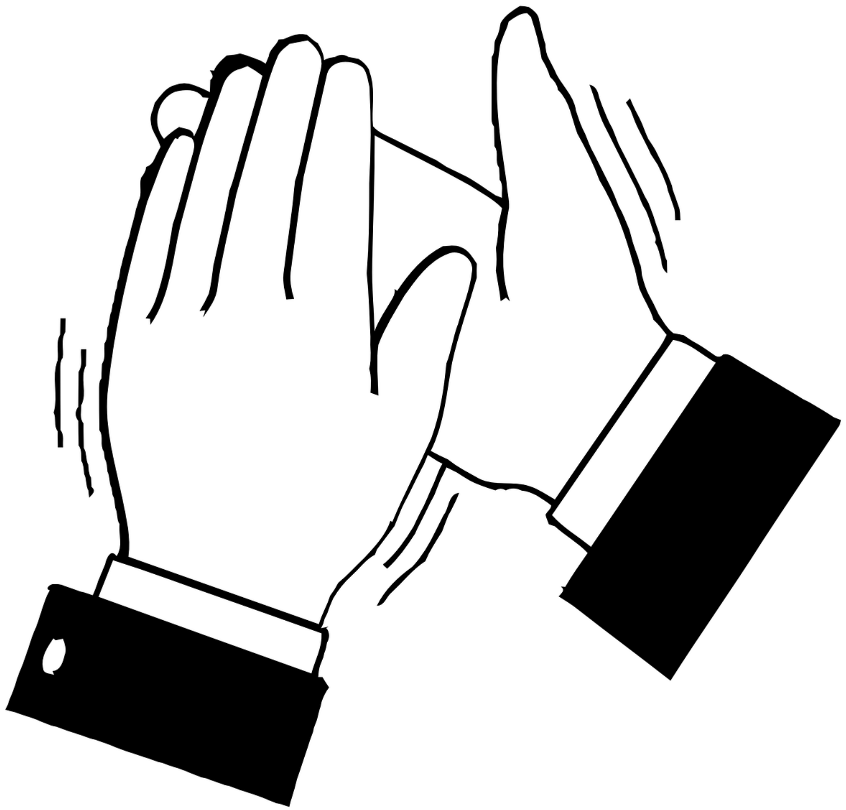
page_fault



mmap

BRAVO: wrap-up

- Builds into any existing lock
- Reads are accelerated
- Avoids write overhead
- Very compact
- Overall, takes the “reader indicator” dilemma away



Conclusion

- Kernel requirements impede adaptation of user-space locks
  - some considerations we did not talk about: real-time, paravirt
- Same techniques can still be used
  - trading (some) fairness for performance
  - eliminating contention bottlenecks
  - reducing #cache misses in lock handover
- Kernel locks remain hot

Thank you!

QUESTIONS?

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