PhD thesis defense, Université Pierre et Marie Curie

Regal/Whisper team, LIP6/INRIA

Towards More Scalable Mutual Exclusion for Multicore Architectures

Vers des mécanismes d'exclusion mutuelle plus efficaces pour les architectures multi-cœur

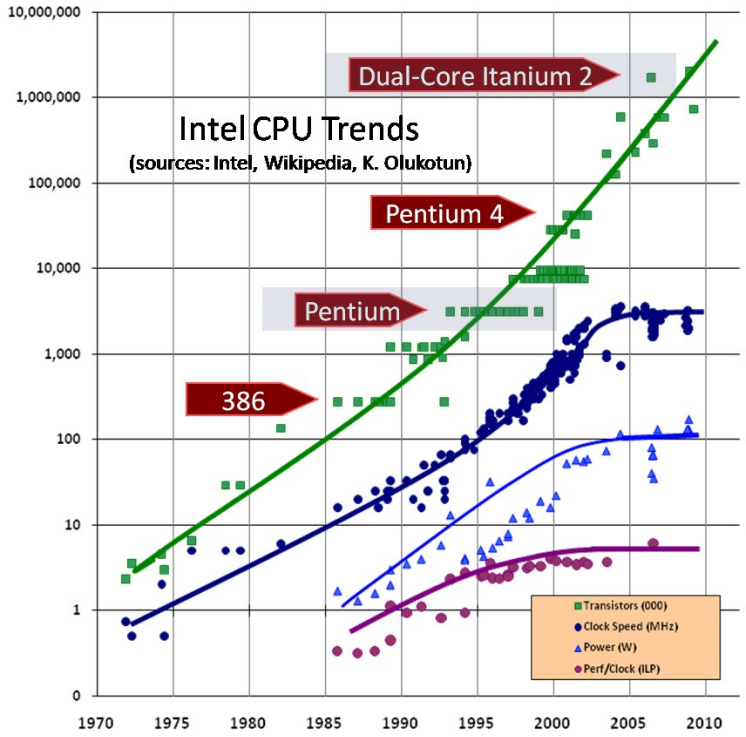
Jean-Pierre Lozi

Outline

- **Context: multicore architectures**
- State of the art: locks
- Contribution: Remote Core Locking
- Evaluation
- Perspectives and conclusion

Context: multicore architectures

- Decades of increasing CPU clock speeds
- Since early 2000's, problems with power consumption/dissipation
- Increasing numbers of cores to keep increasing processing power
  - Possible because number of transistors keeps increasing



→ # transistors

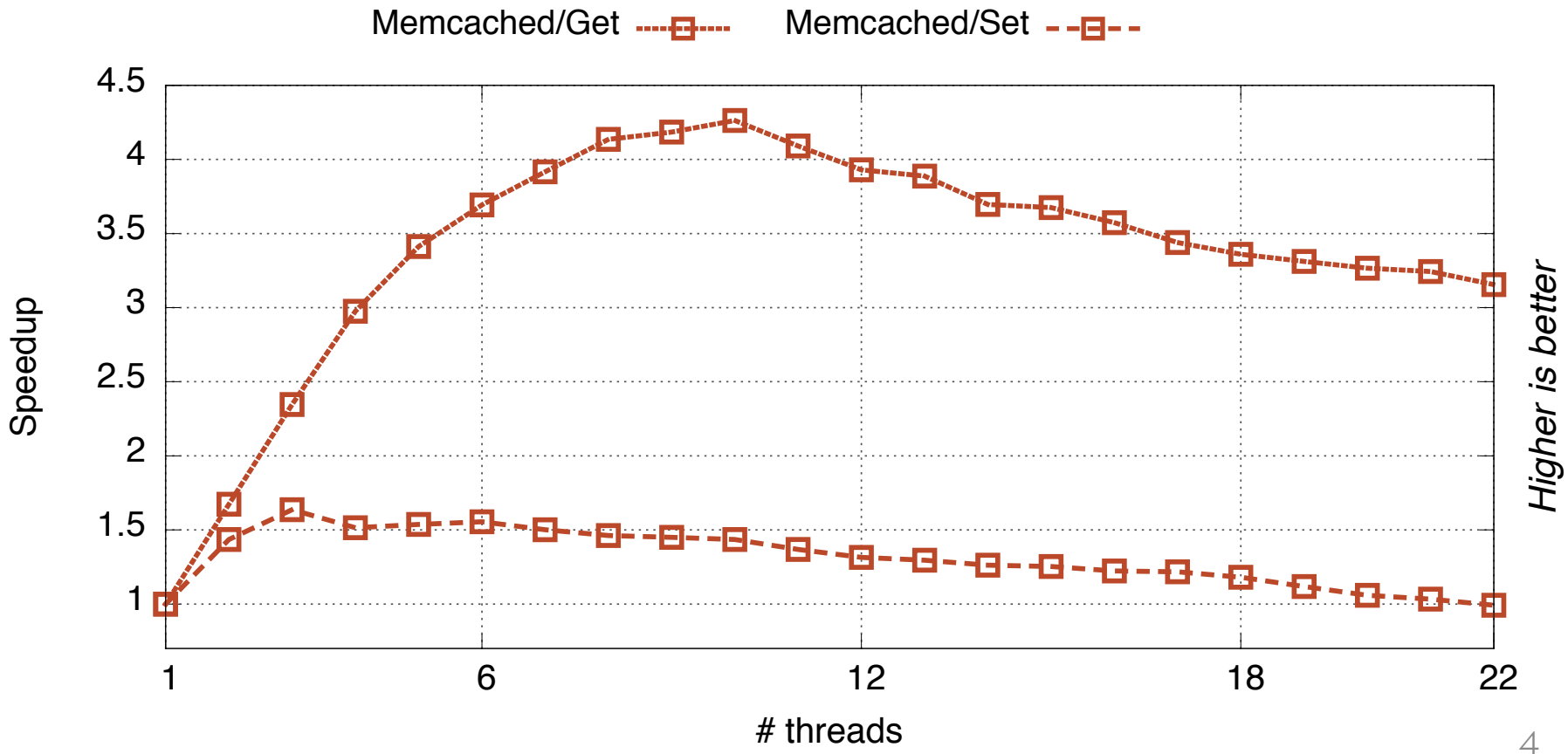
→ Clock speed

→ Power Consumption

→ Ratio power/speed

Problem with multicore: scalability

- Many legacy applications don't scale well on multicore architectures
- For instance, Memcached (Get/Set requests):



Experiments run on a 48-core, "magny-cours" x86 AMD machine

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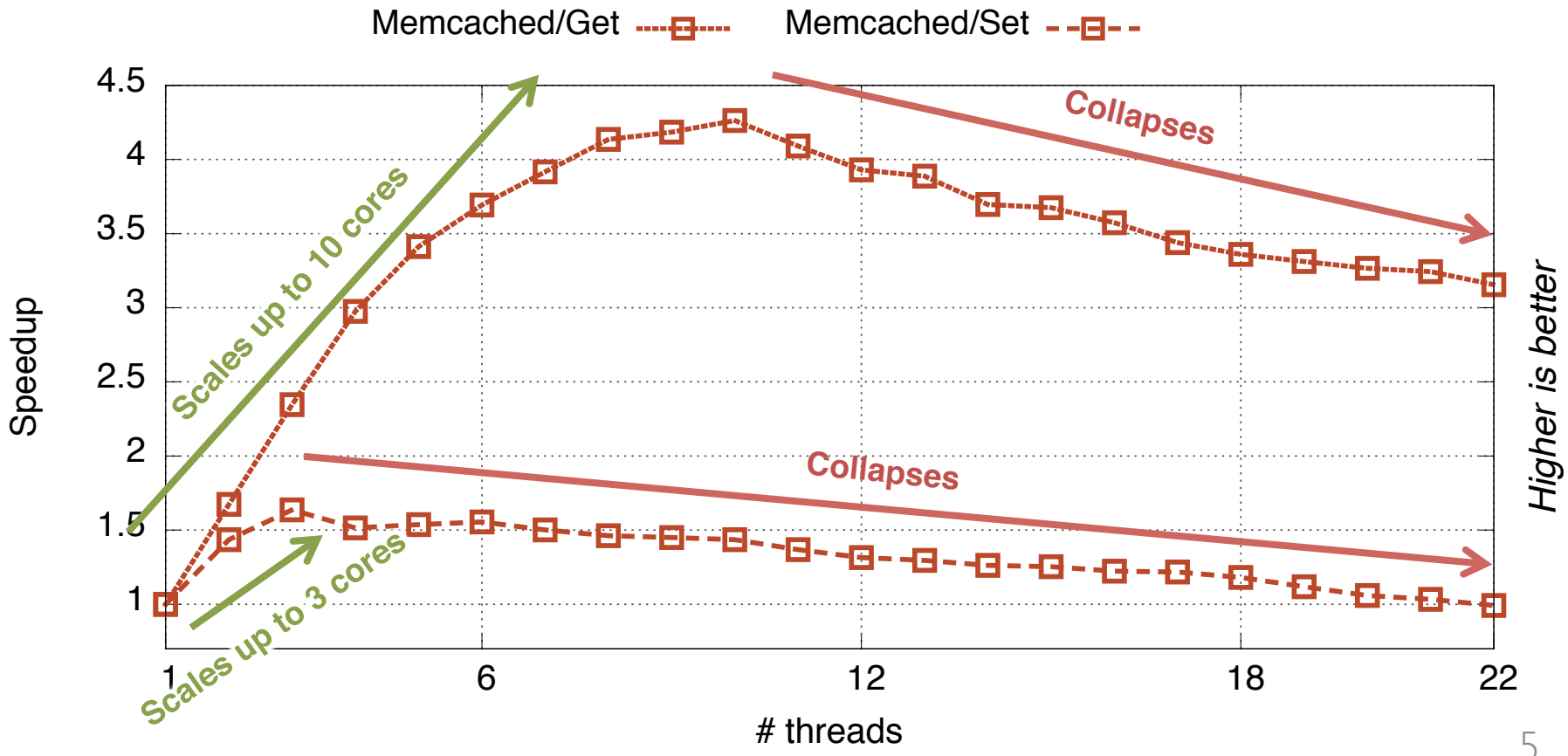
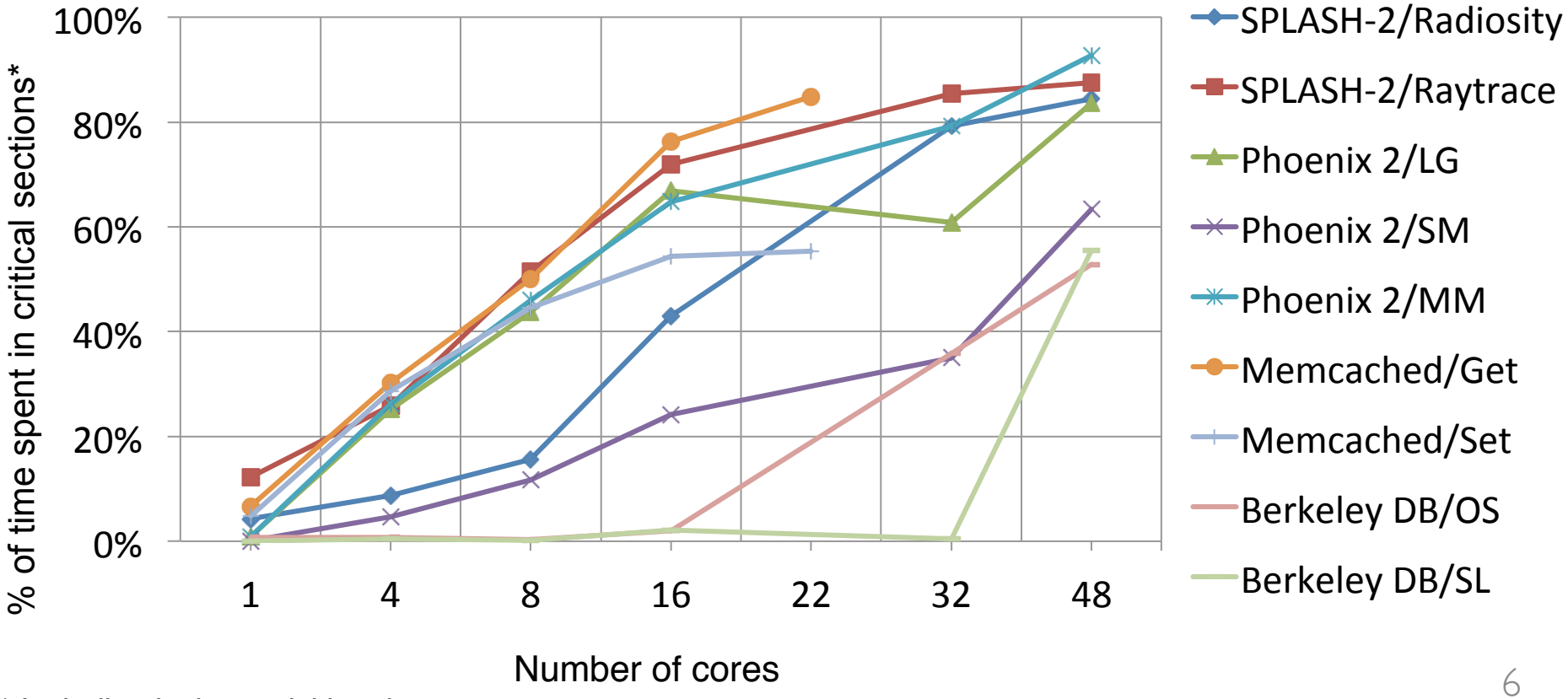


Experiments run on a 48-core, "magny-cours" x86 AMD machine

Why?

- Bottleneck = critical sections, protected by locks
- High contention ⇒ lock acquisition is costly
  - More cores ⇒ higher contention



* Including lock acquisition time

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  - Redesign applications (fine-grained locking)
    - Costly (millions of lines of legacy code)
  - Design better locks

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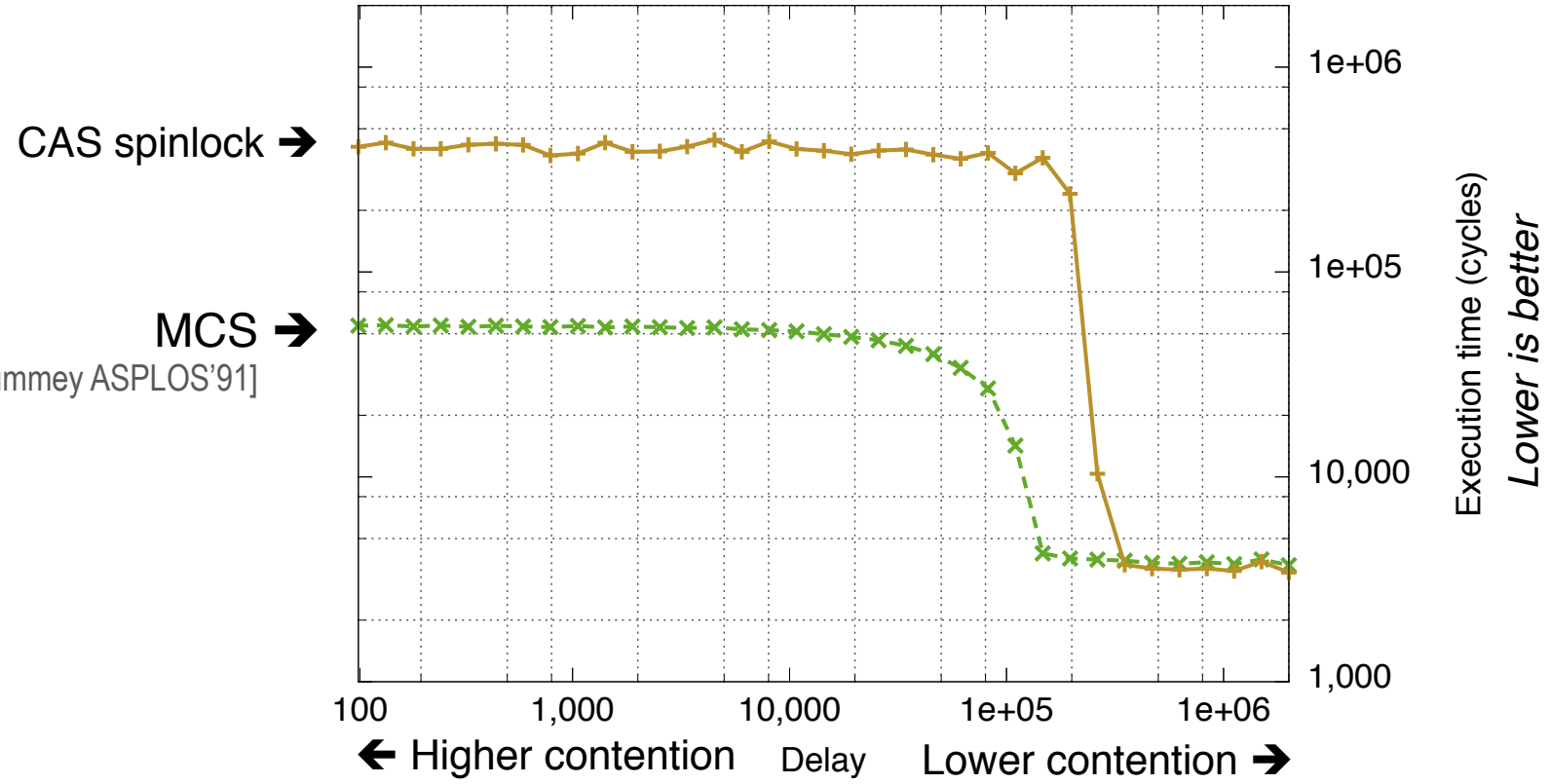
Designing better locks

- No need to redesign the application
- Better resistance to contention
- Custom microbenchmark to compare locks:



Critical sections access 5 cache lines each

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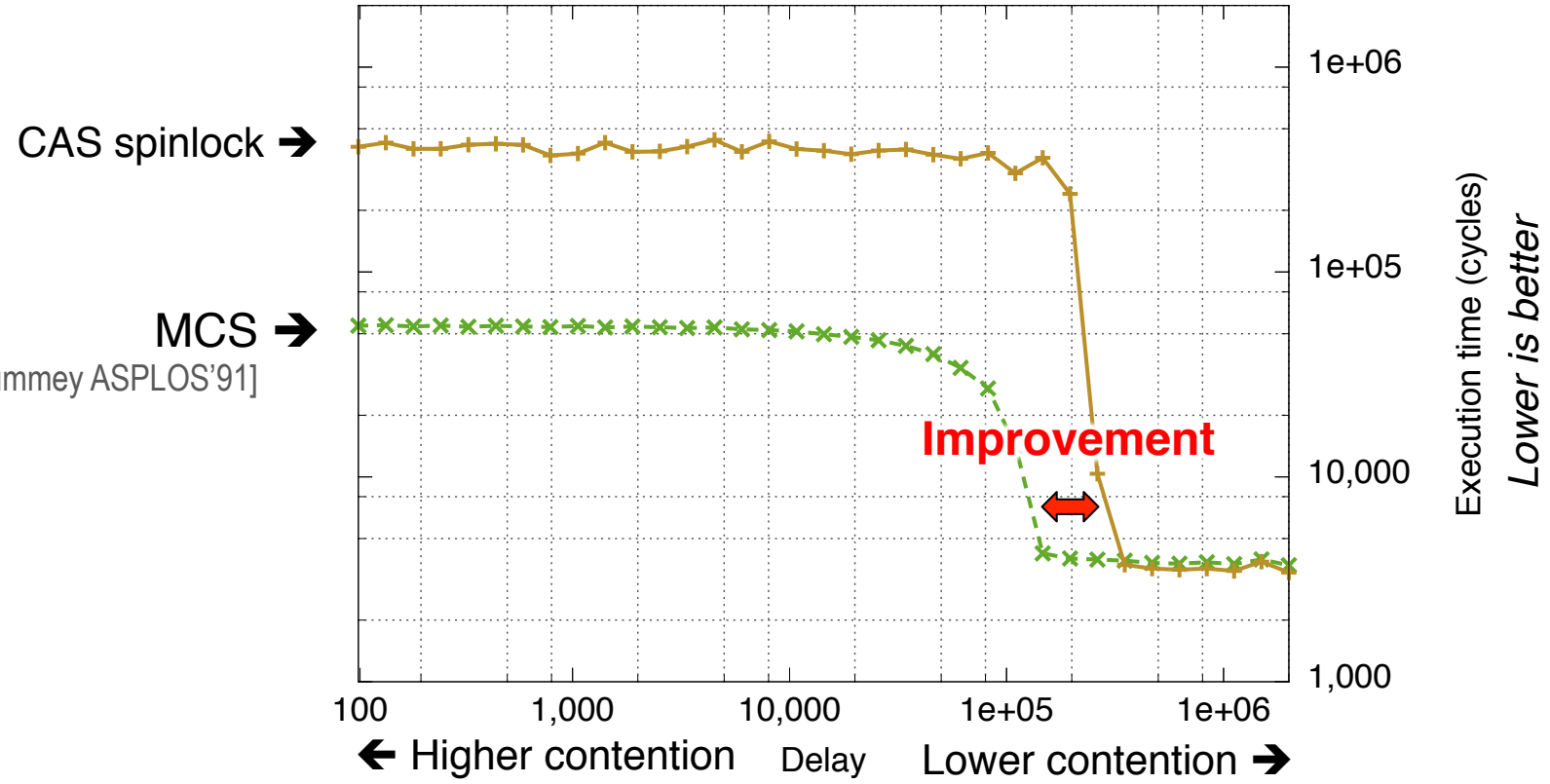

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State of the art

- Spinlocks
- Blocking locks
- Queue locks (MCS, CLH)
  [Mellor-Crummey ASPLOS'91, Craig TR'93, Hagersten IPPS'94]
- Flat combining
  [Hendler SPAA'10]

Spinlocks

- Spinlocks
  - Busy-wait, trying to set a lock variable with an atomic instruction
  - Contention when all threads try to set that variable concurrently!

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function lock(boolean *lock)
    while !compare_and_swap(lock, false, true) do
        ;


function unlock(boolean *lock)
    *lock = false;
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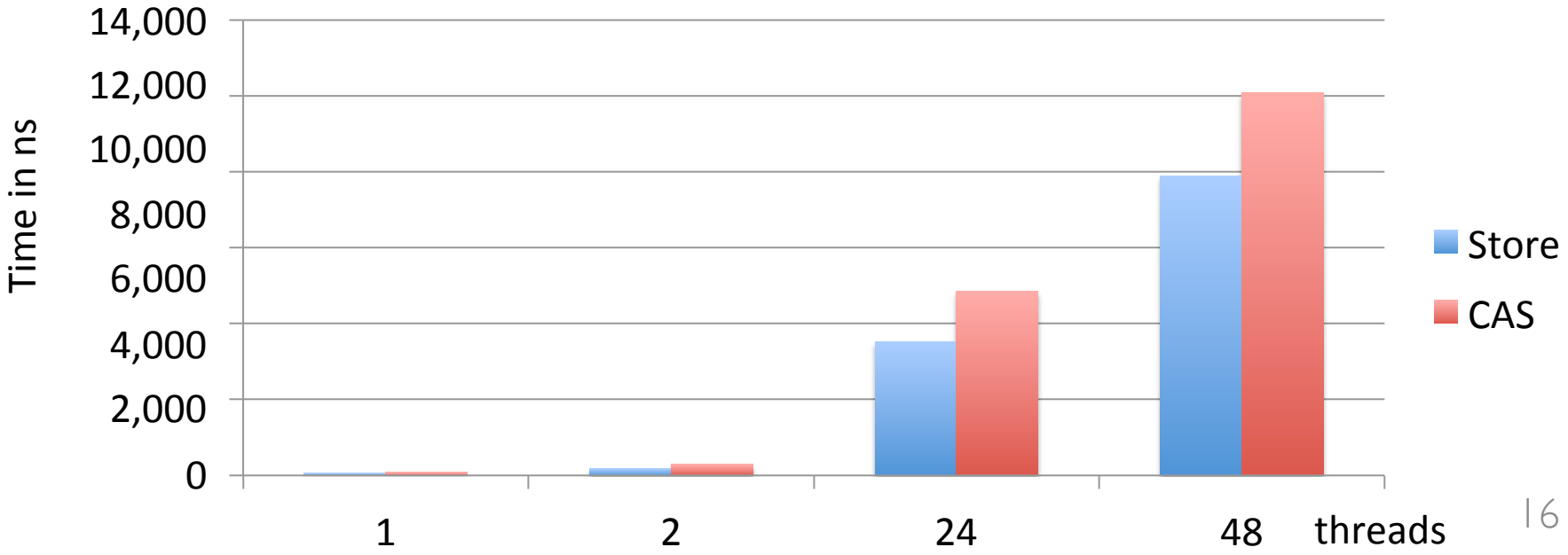
Spinlocks

- Spinlocks
  - Busy-wait, trying to set a lock variable with an atomic instruction
  - Contention when all threads try to set that variable concurrently!
- Cost of all threads concurrently writing to a single variable:
  - Up to 125 times slower when all hardware threads used!



Blocking locks

- Try to acquire lock; in case of failure, sleep
- Does not waste CPU resources
- Context switches needed between each acquisition: not very reactive

```
function lock(boolean *lock)
    while !compare_and_swap(lock, false, true) do
        yield();


function unlock(boolean *lock)
    *lock = false;
```

Blocking locks

- Try to acquire lock; in case of failure, sleep
- Does not waste CPU resources
- Context switches needed between each acquisition: not very reactive
- Very frequently used because works with only one core
  - The "legacy" lock
  - POSIX locks are blocking locks

Queue locks

- Example: MCS [Mellor-Crummey ASPLOS'91]
- Idea: threads enqueue themselves in a list
  - One synchronization variable per thread instead of global

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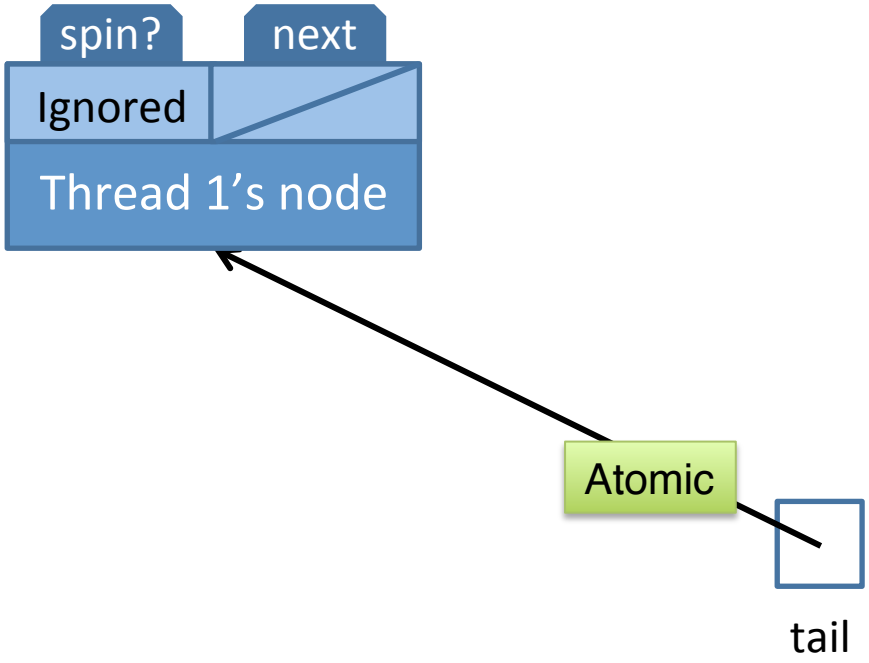

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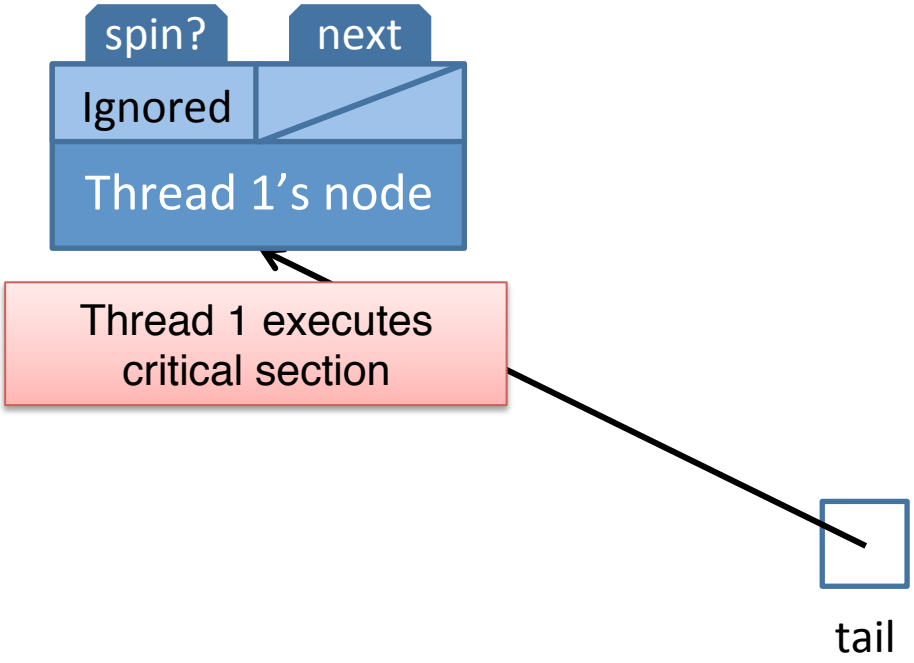

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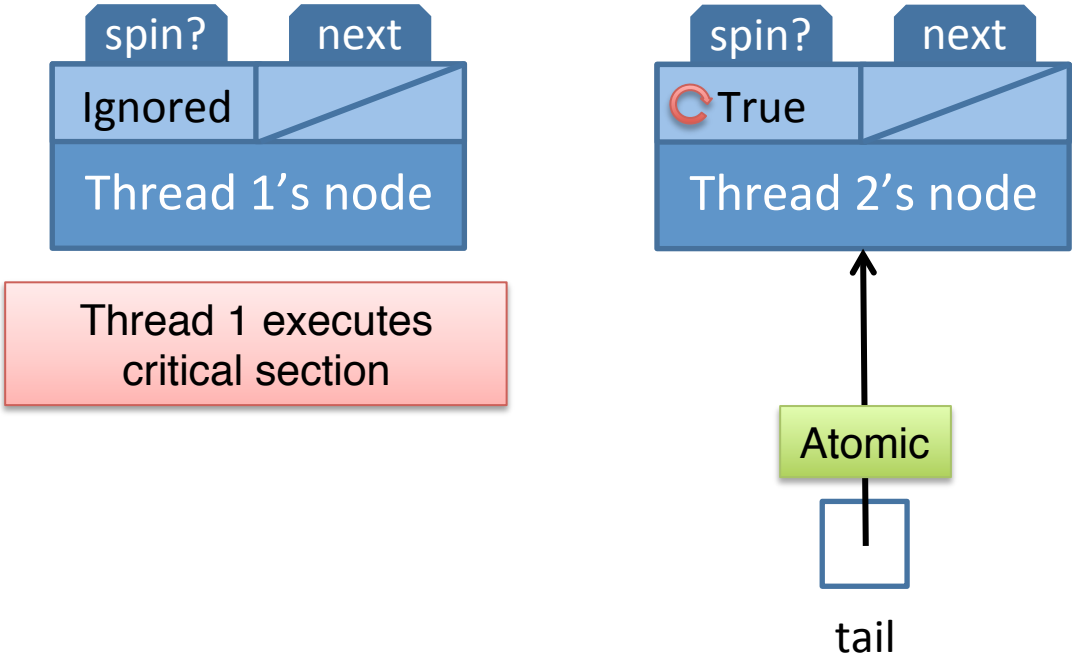

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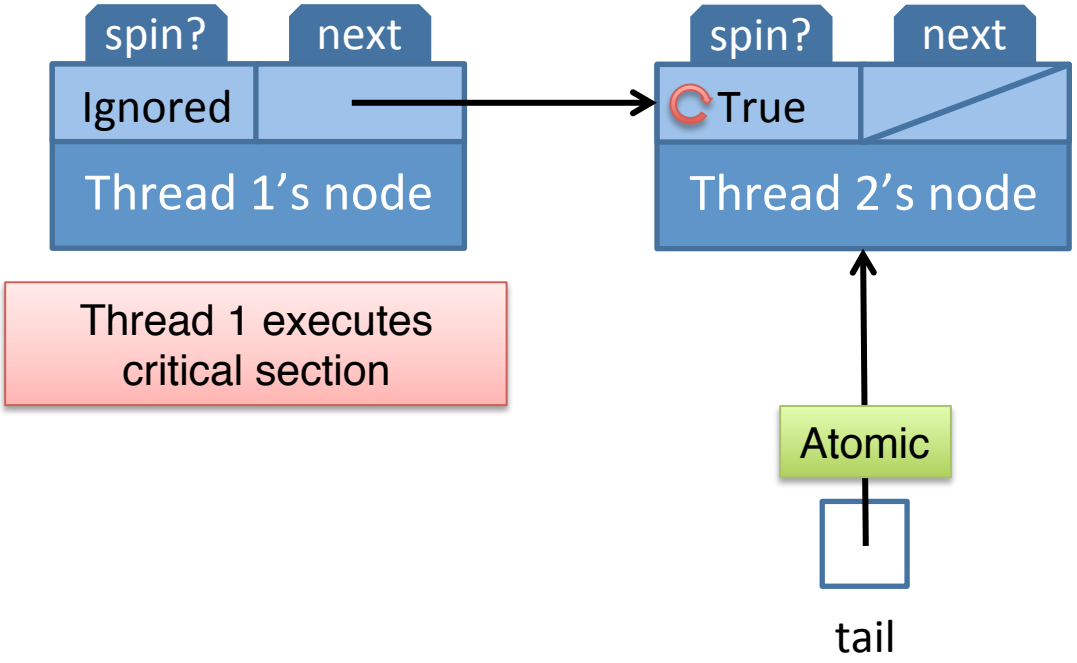

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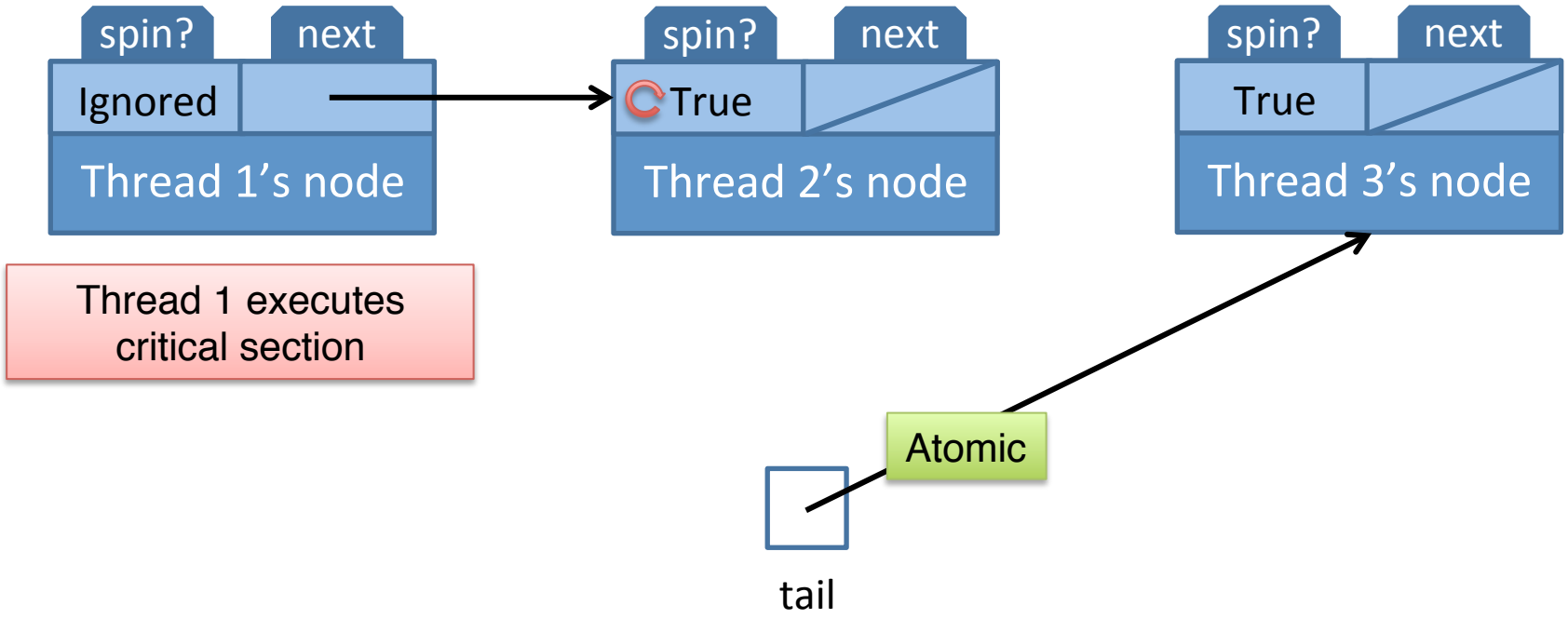

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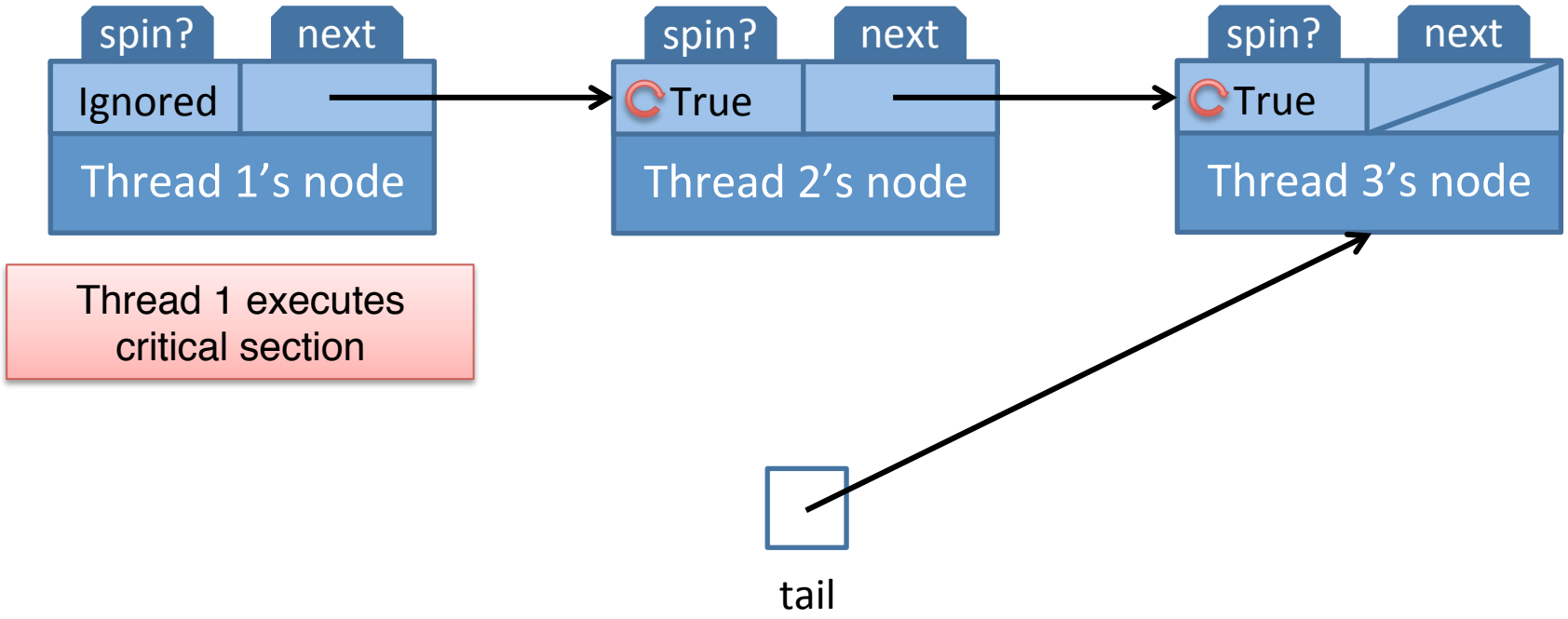

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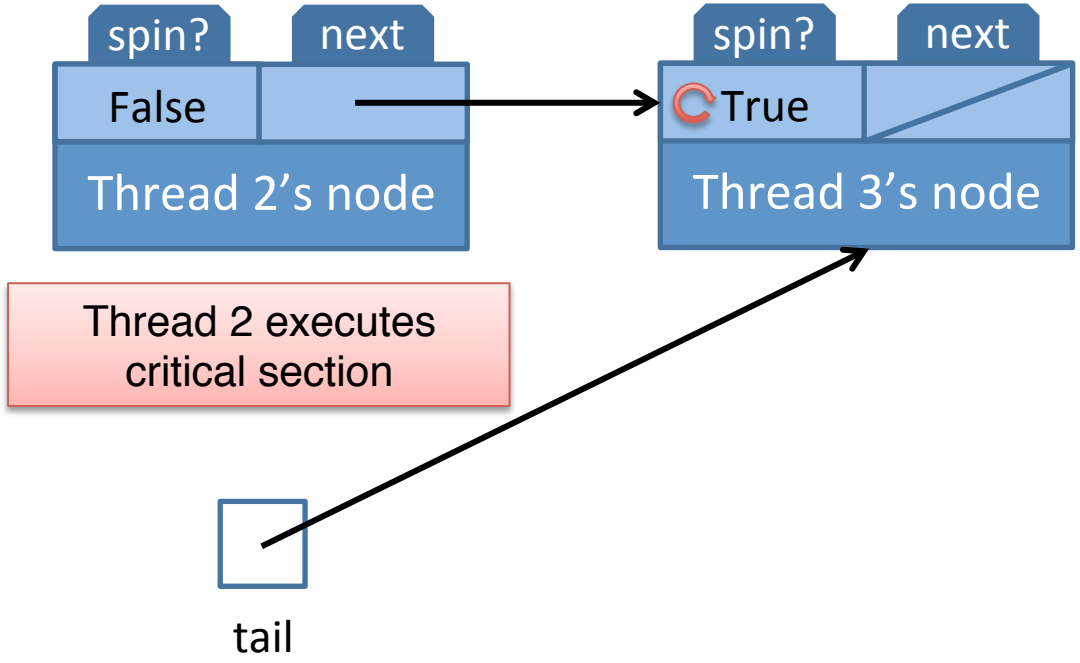

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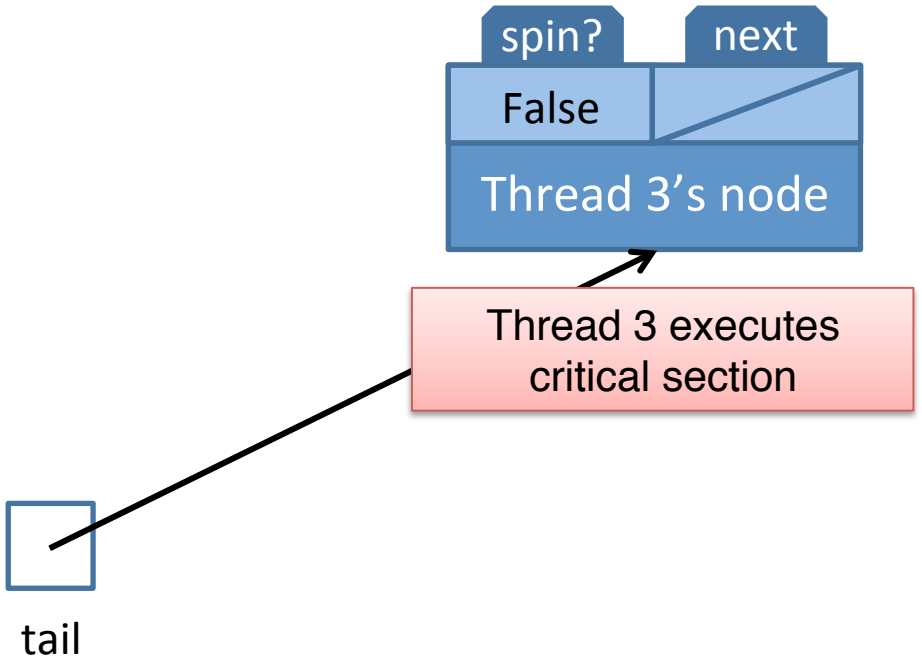

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Flat Combining [Hendler SPAA'10]

- Threads enqueue critical sections (functions) in list
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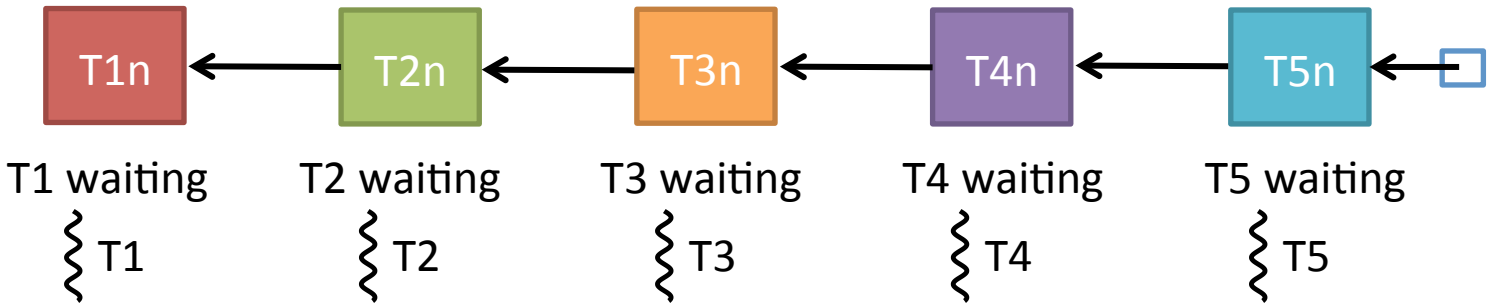

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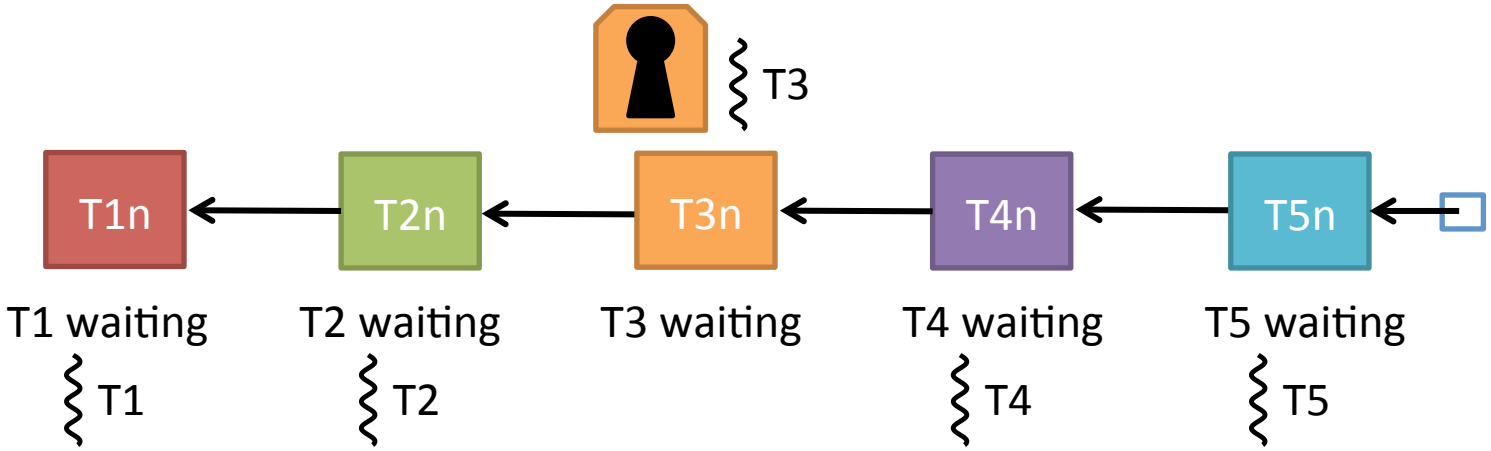

T3 acquires the global lock

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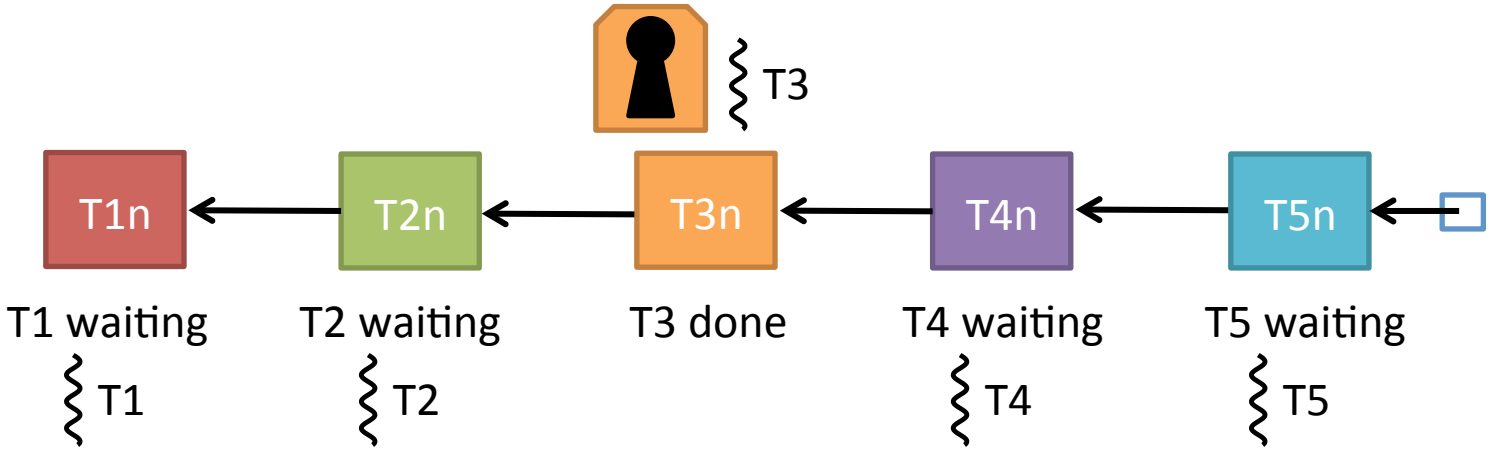

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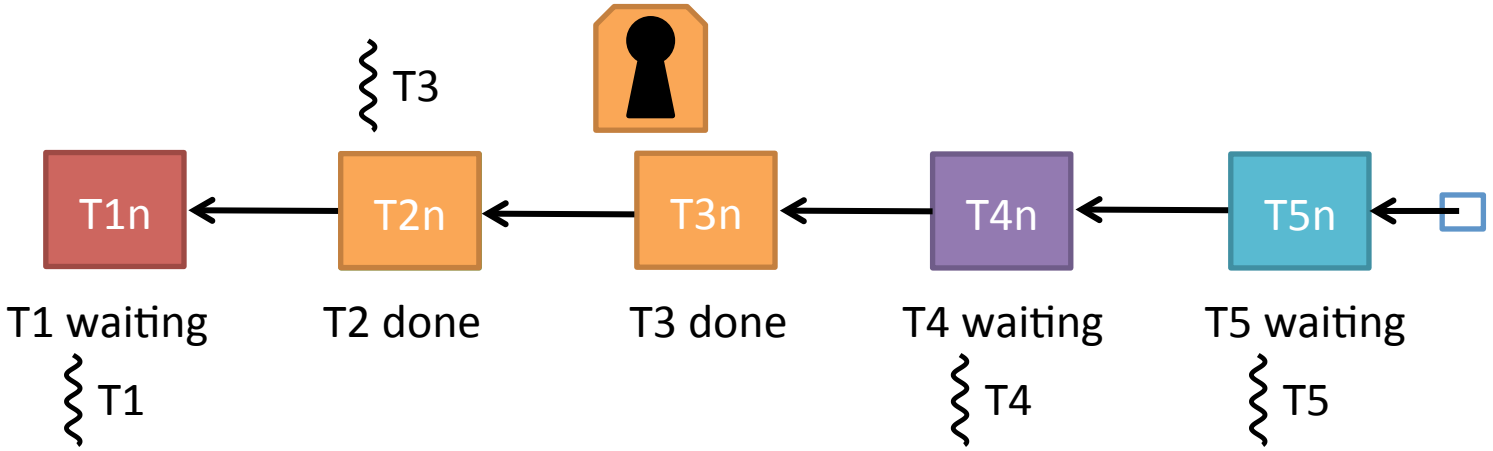

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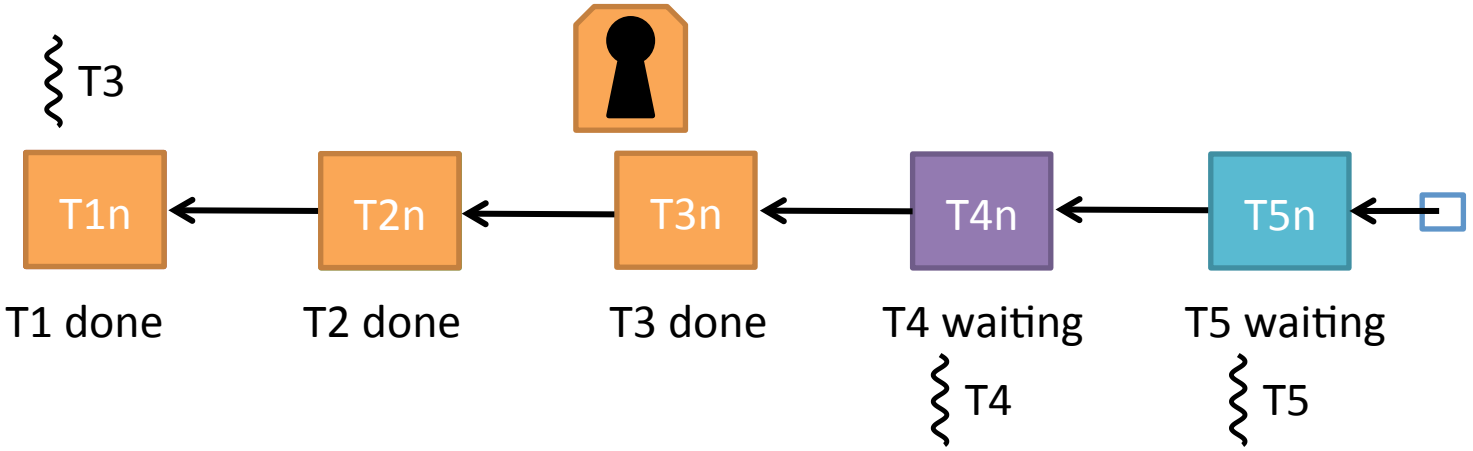

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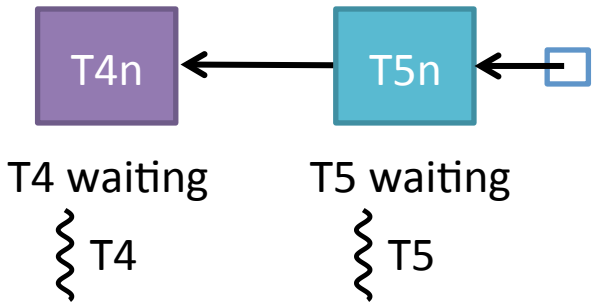
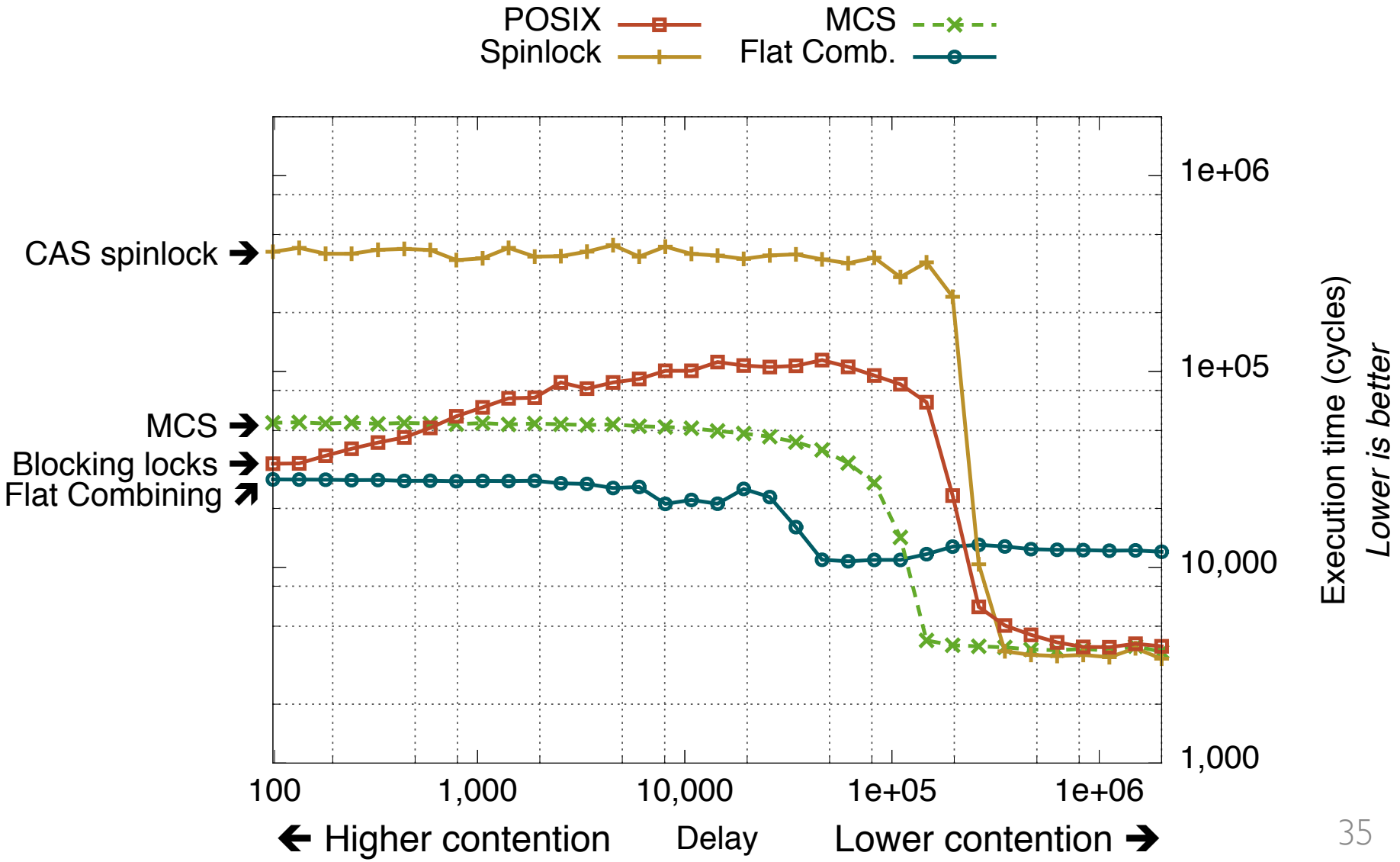


Lock performance assessment



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How?

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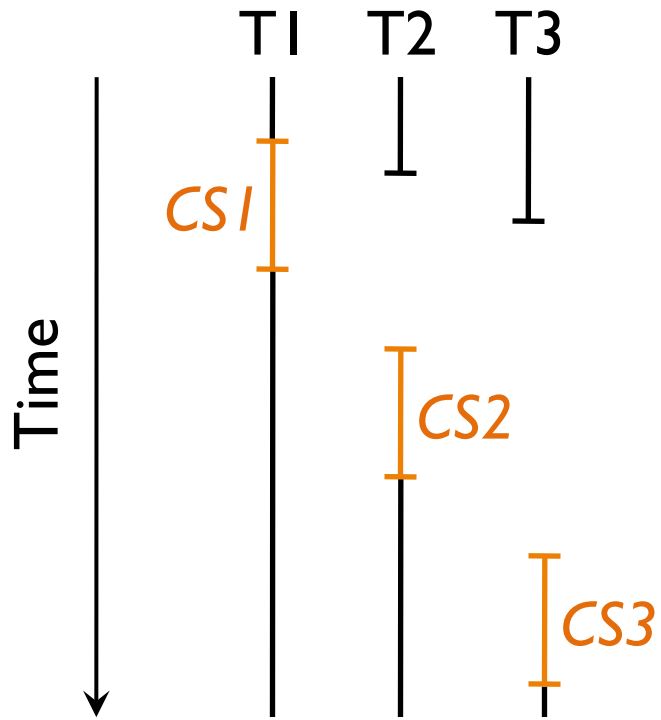

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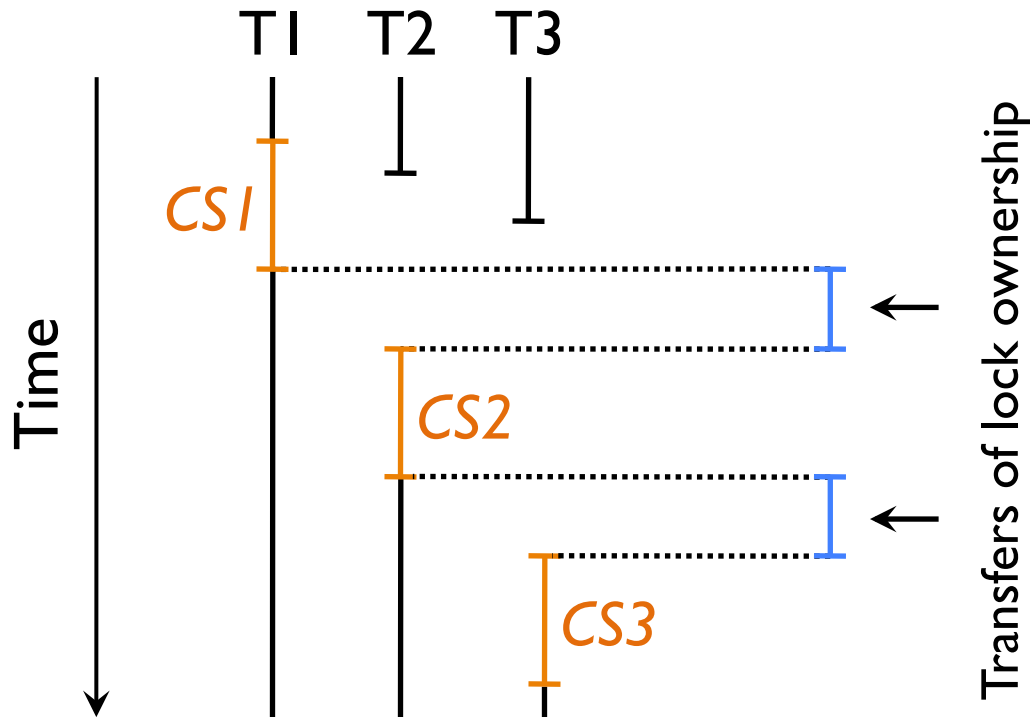

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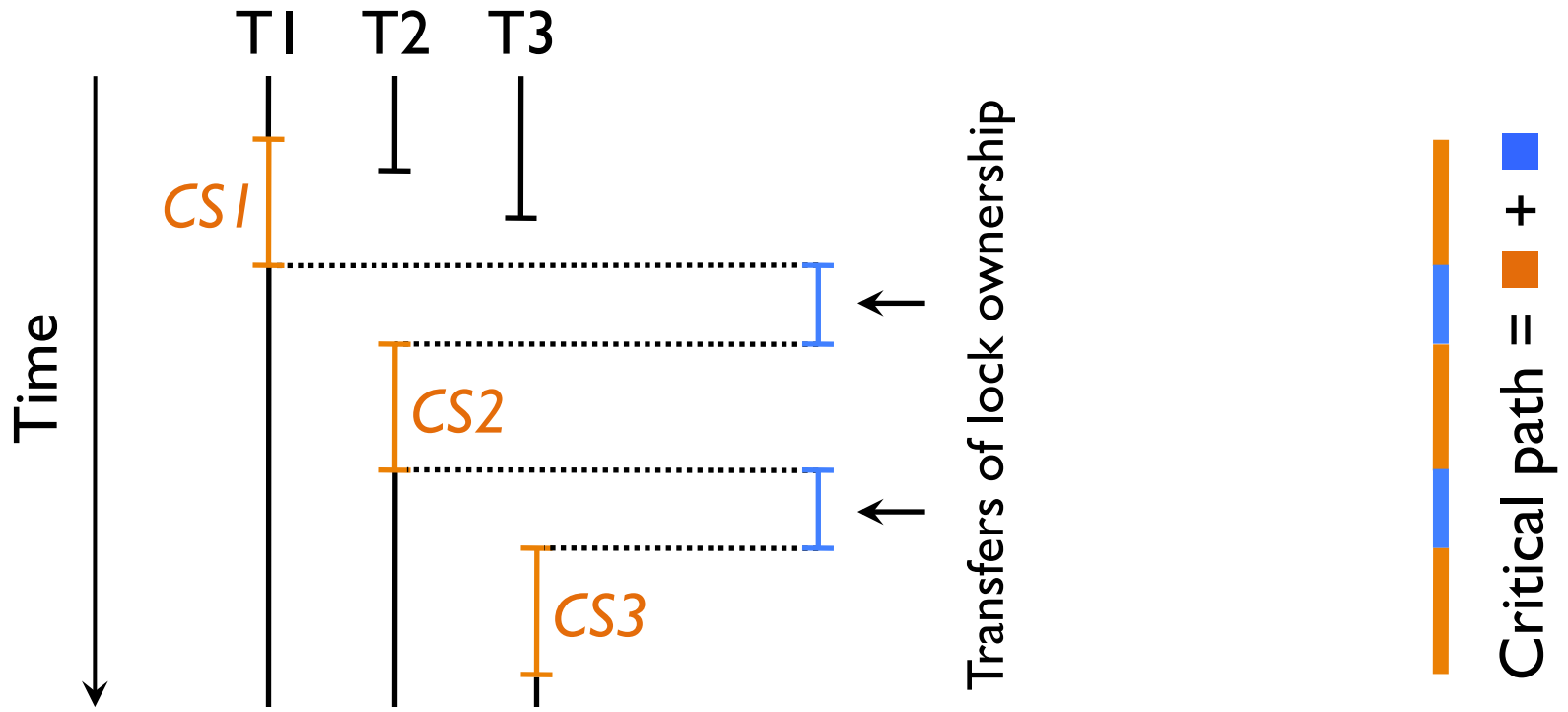

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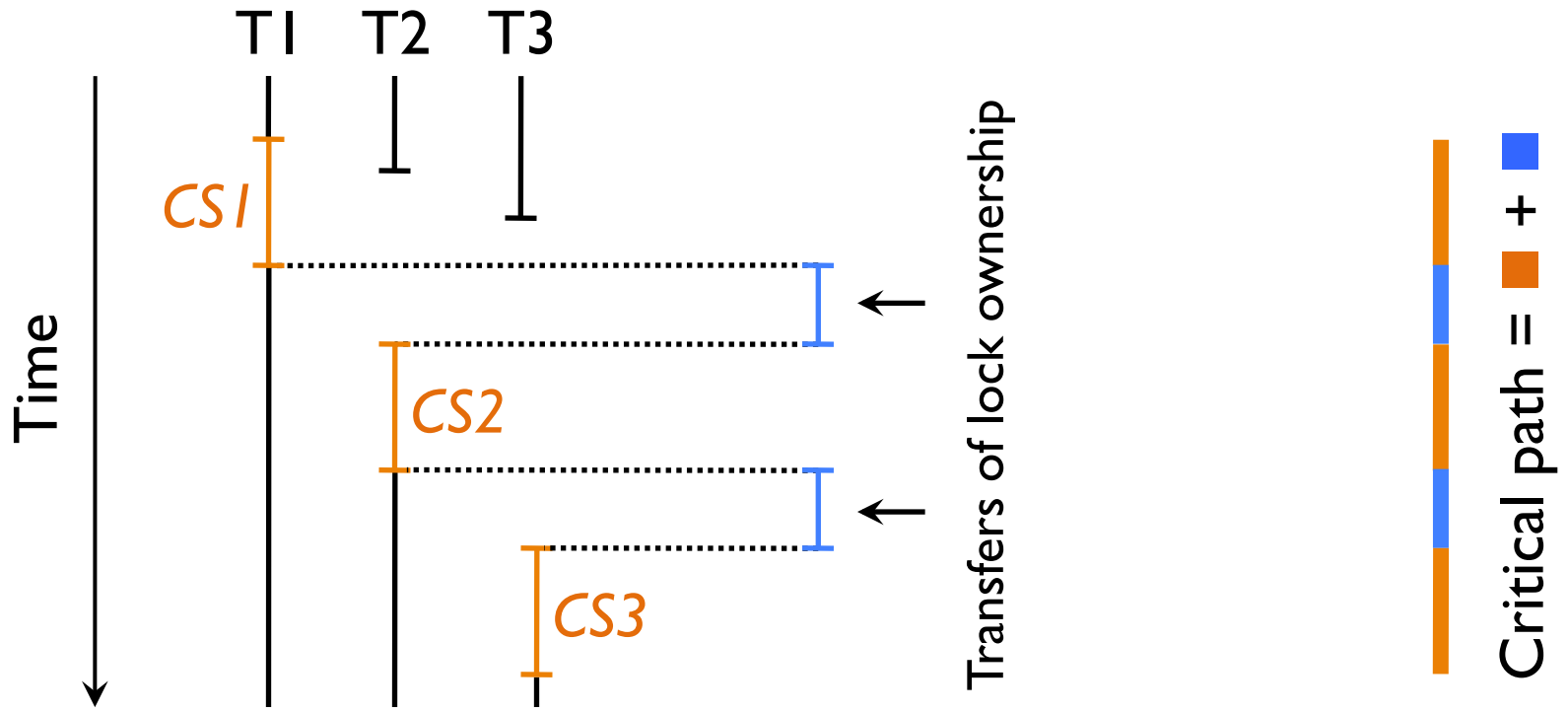
How? By shortening the critical path as much as possible



Contribution: Remote Core Locking

What makes the critical path longer than needed?

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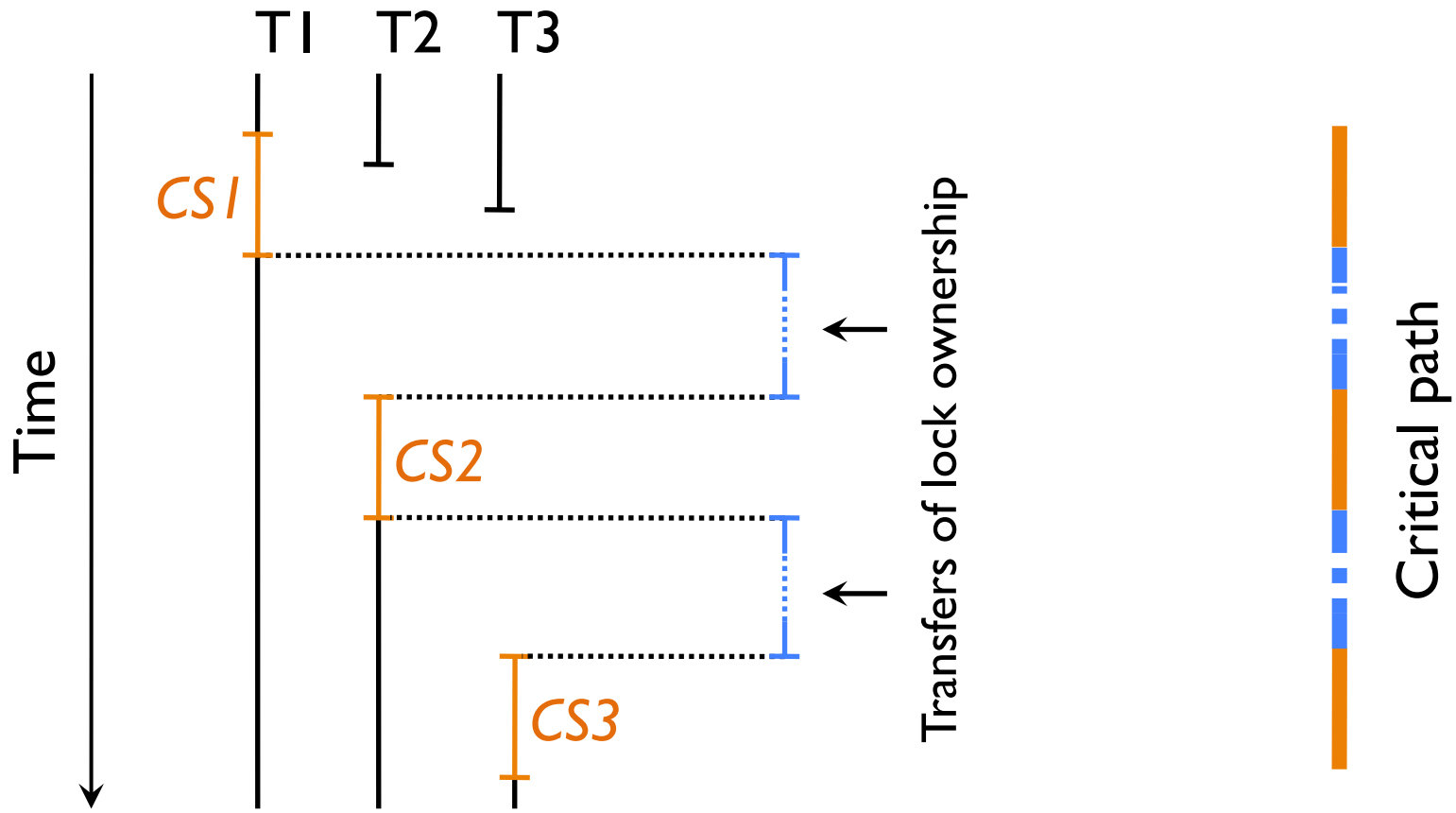
What lengthens the critical path?

1) Long transfers of lock ownership



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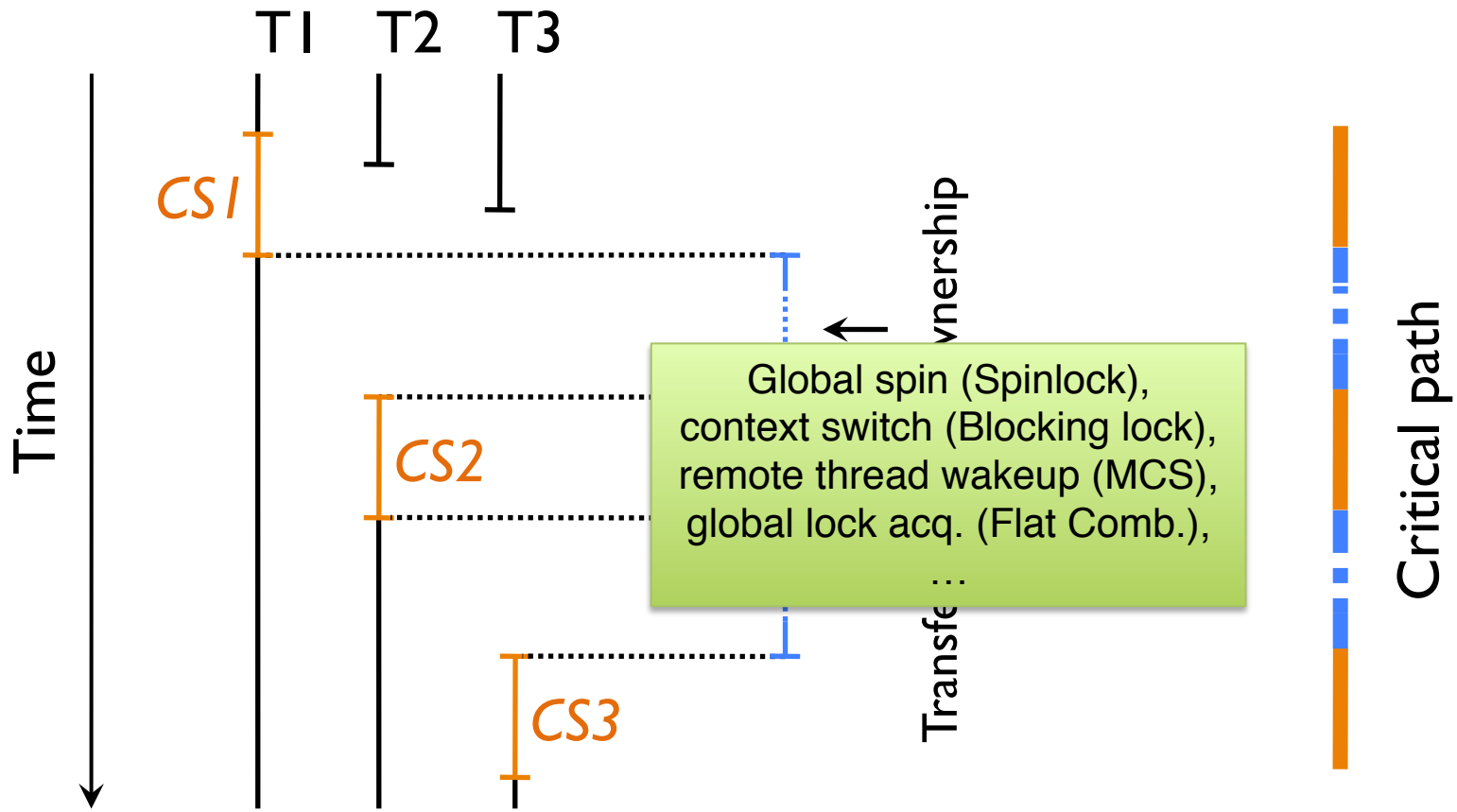

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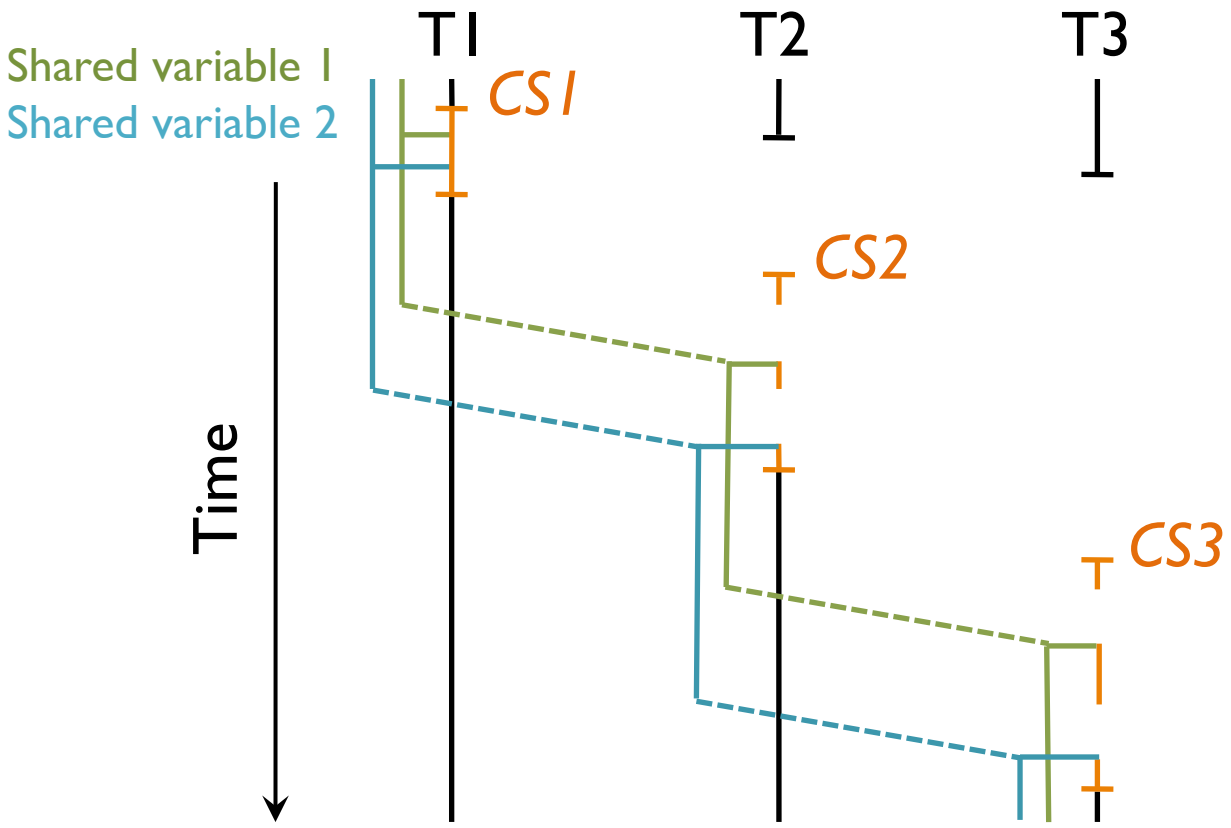

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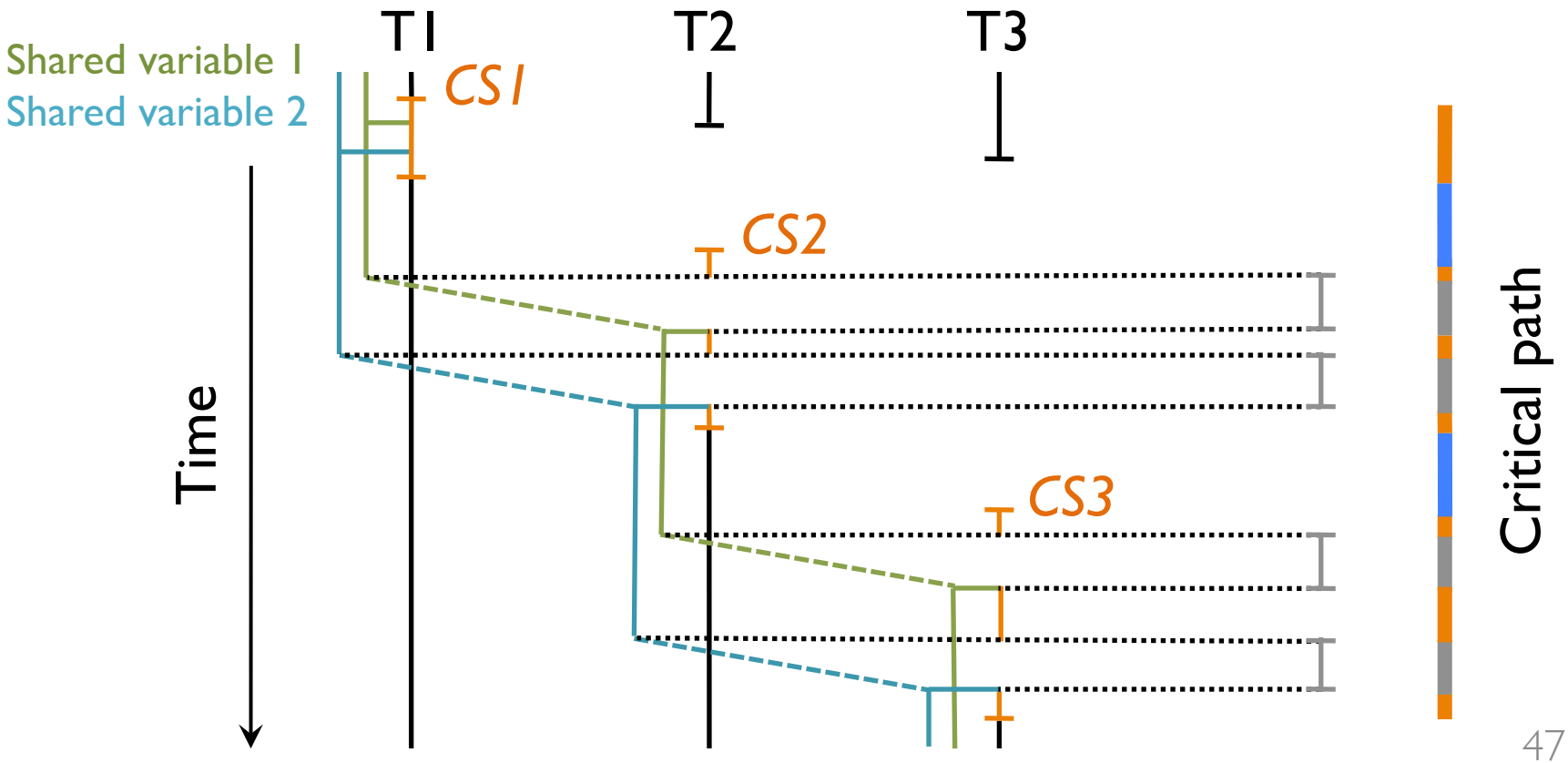

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Solution: *Remote Core Locking*

Dedicate a core for executing critical sections

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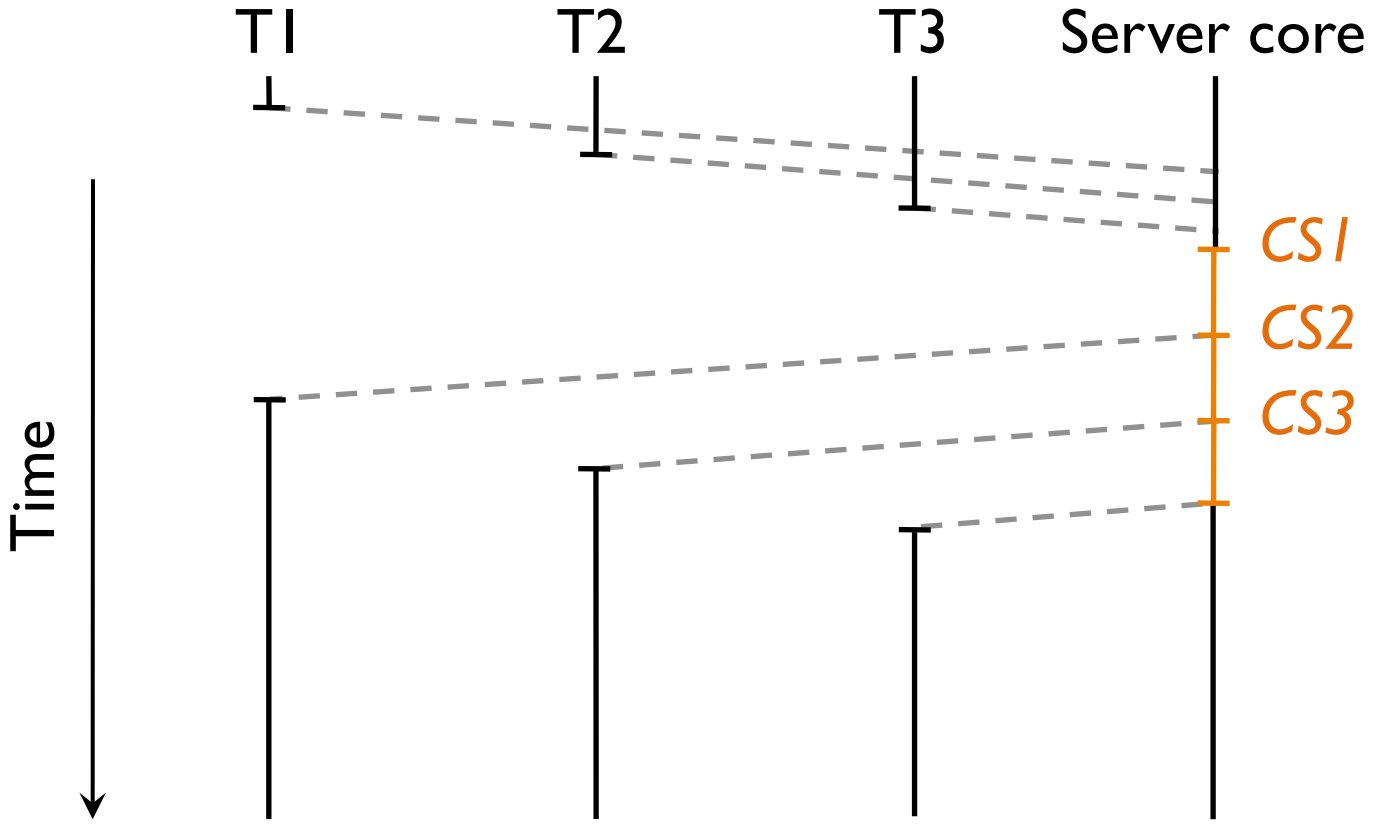

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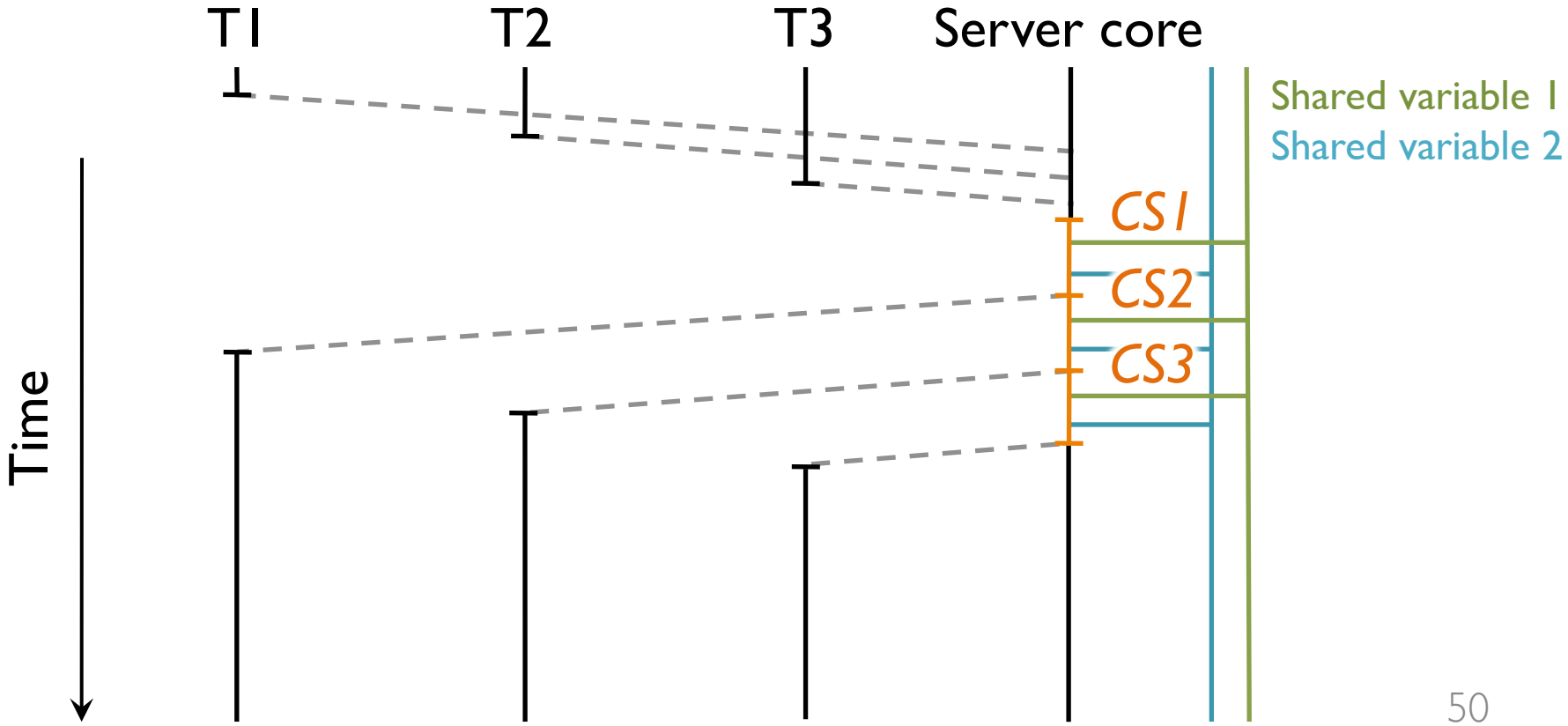

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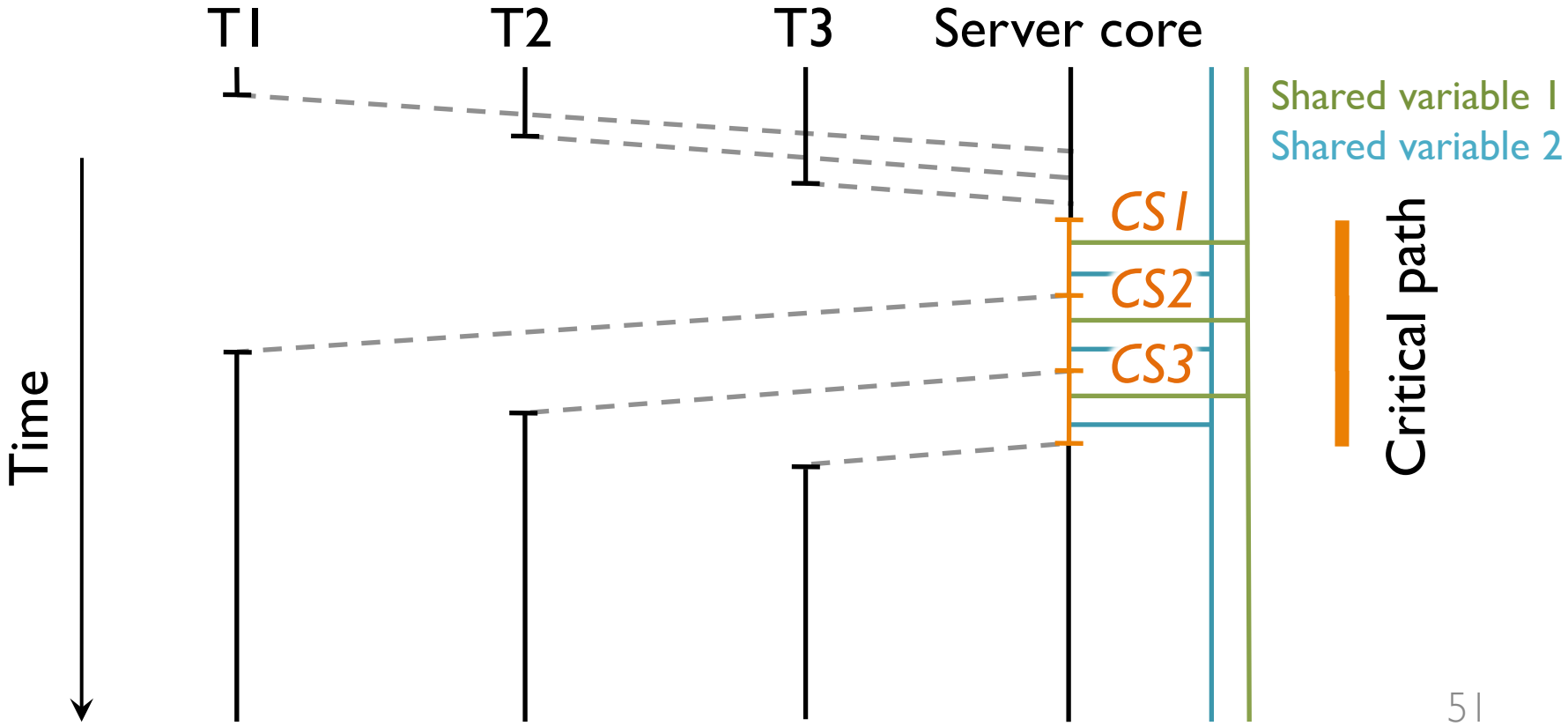
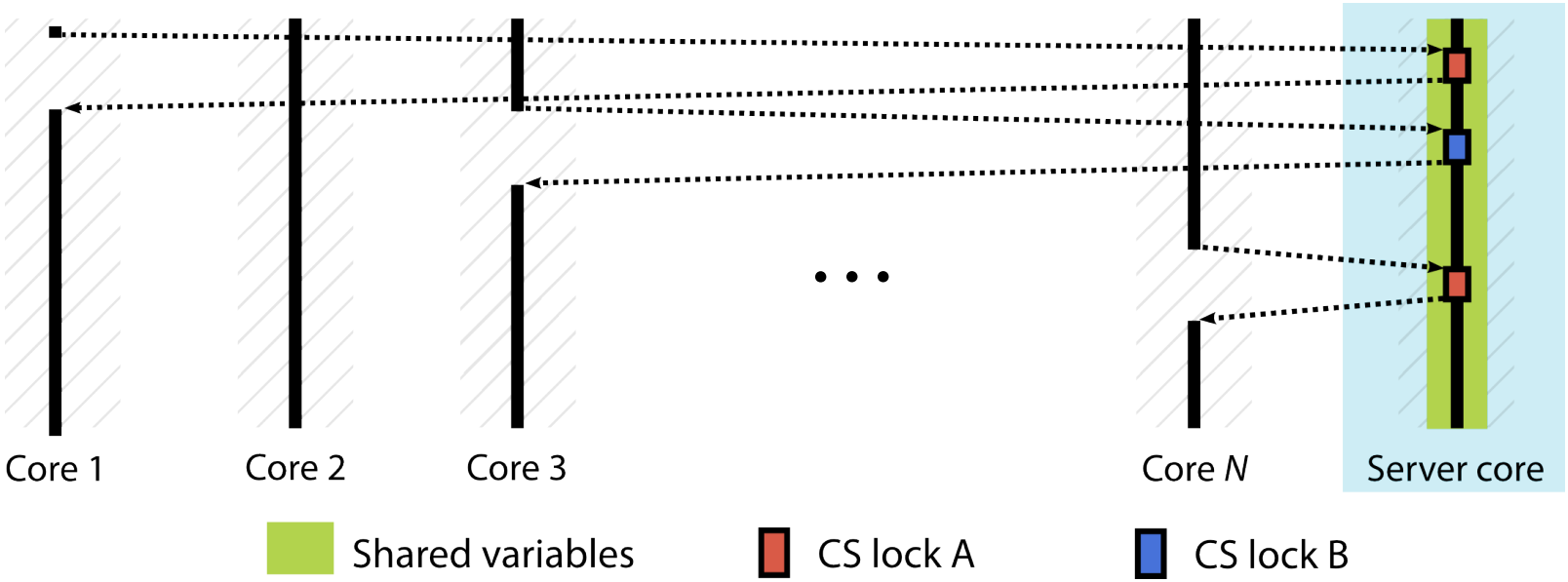


False serialization

- Problem: what to do when using several locks?
  - False serialization, bad for performance
- If too much contention: simply add more servers
  - Not a problem, because RCL only targets contended locks
  - Typically only a handful of them



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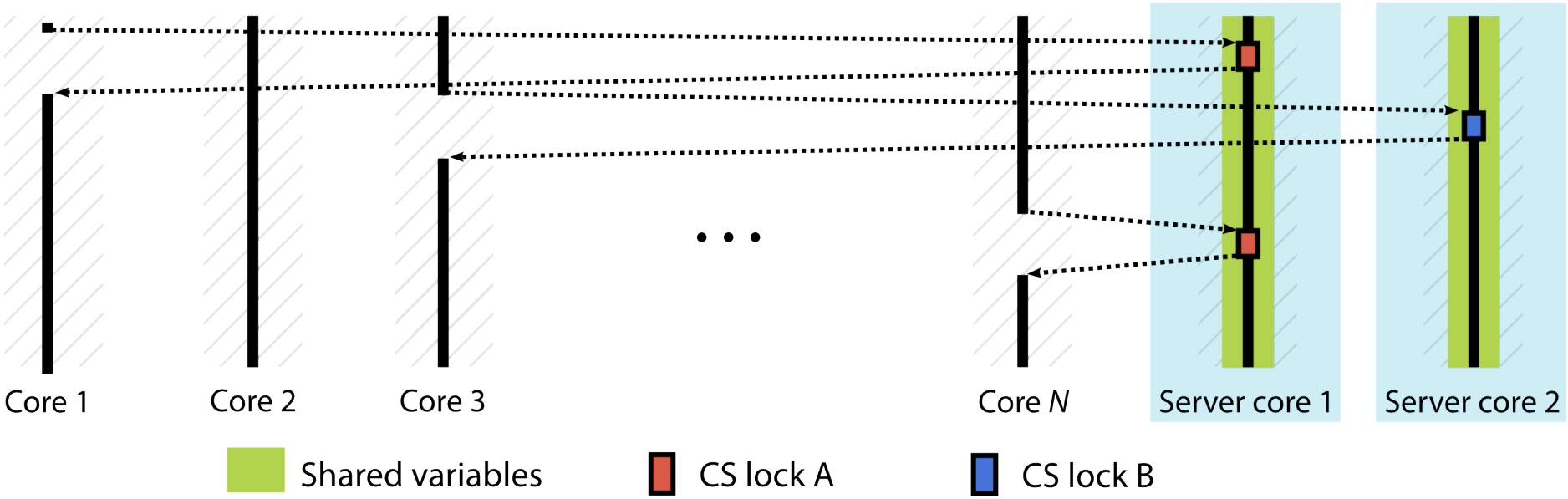
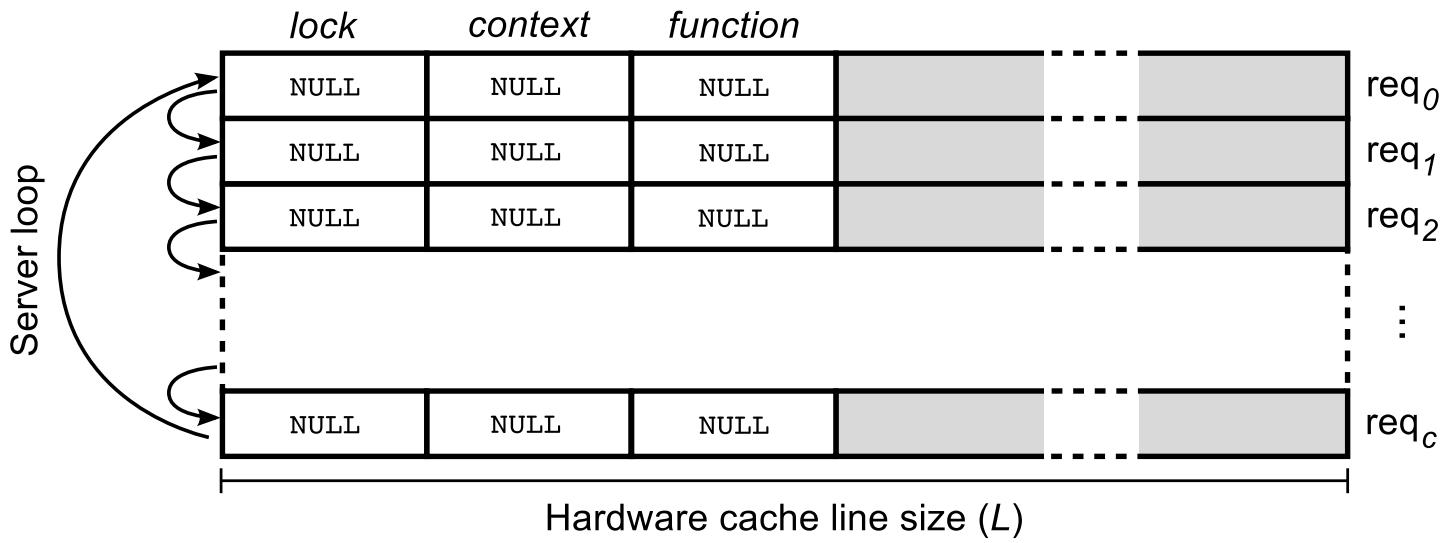


Implementation: general idea

- Communication based on cache line-sized mailboxes
- Three fields: lock, context, function



- Client fills the field and waits for the function to be reset
- Server loops across the fields (fair)

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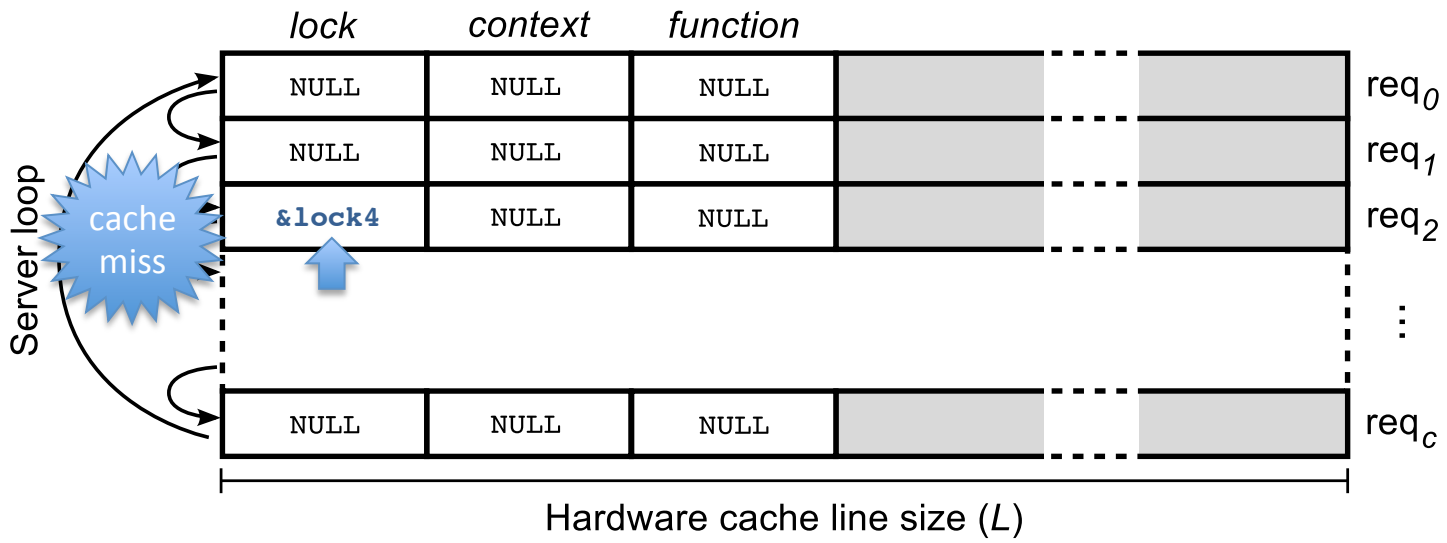

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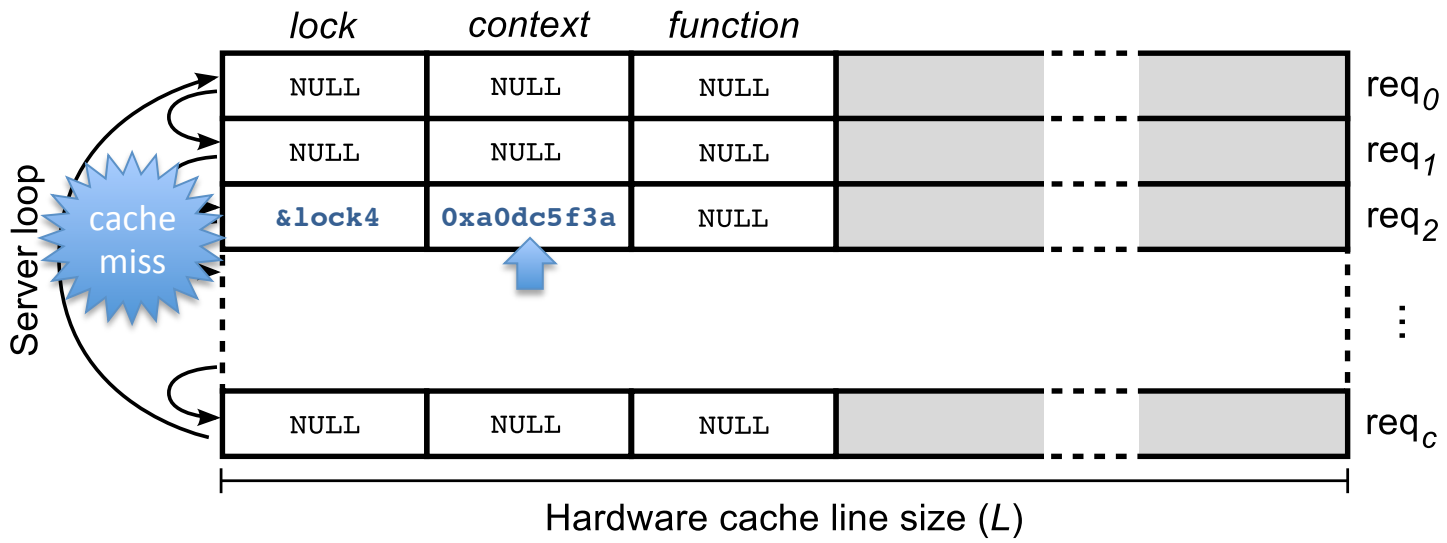

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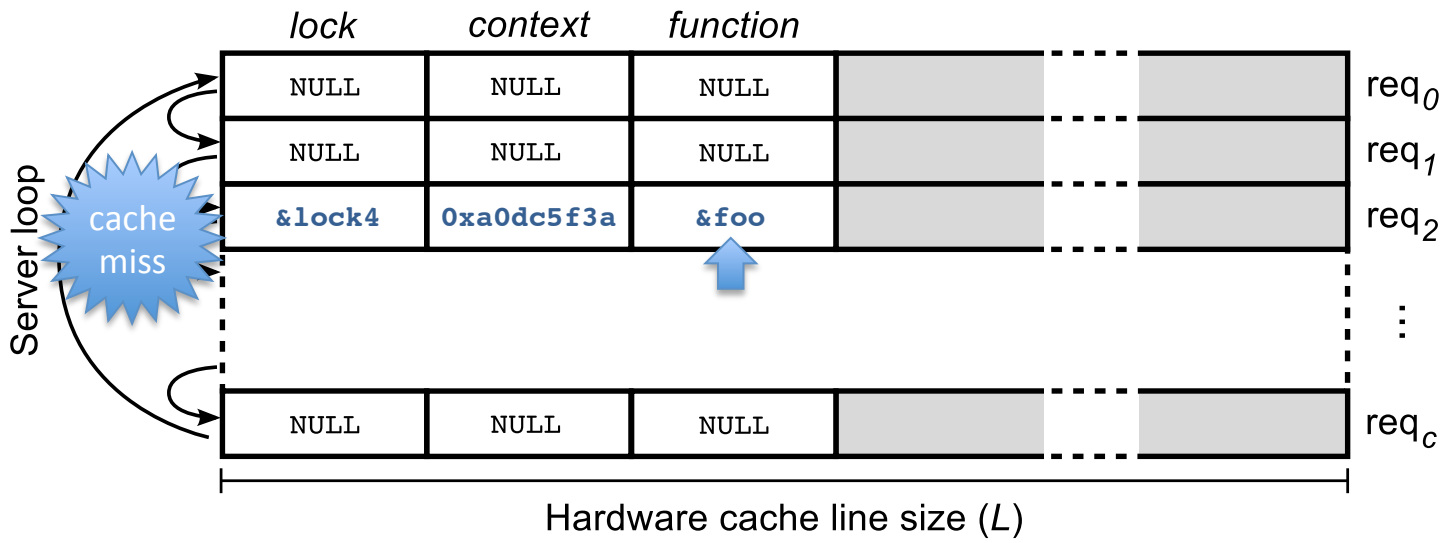

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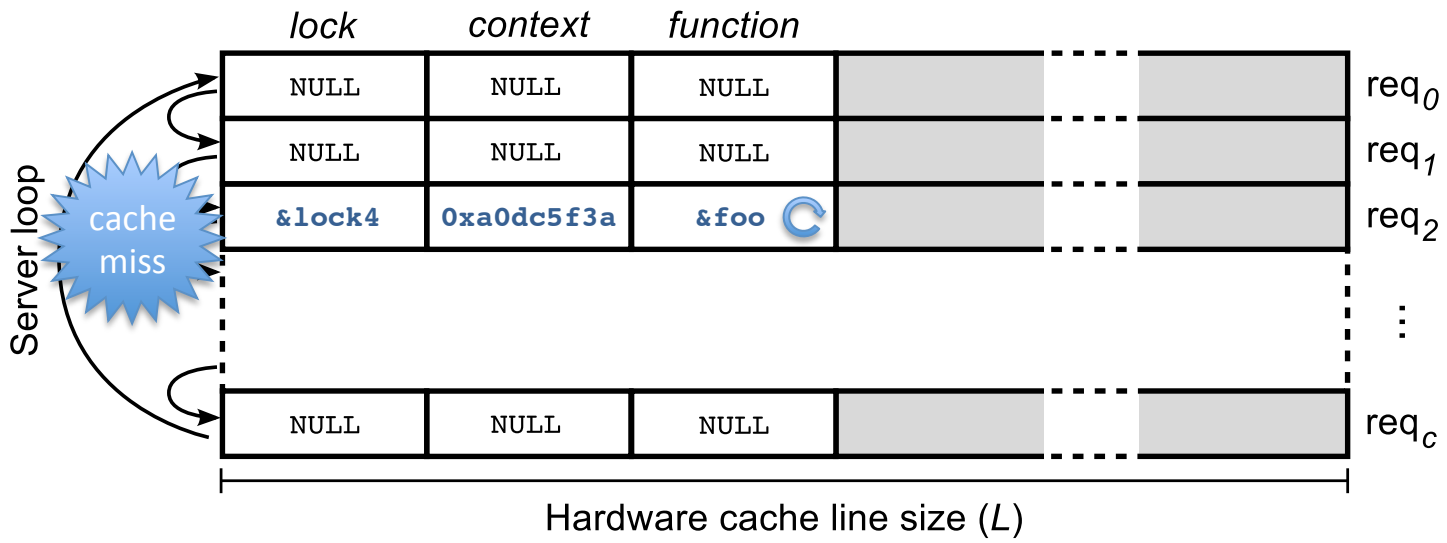

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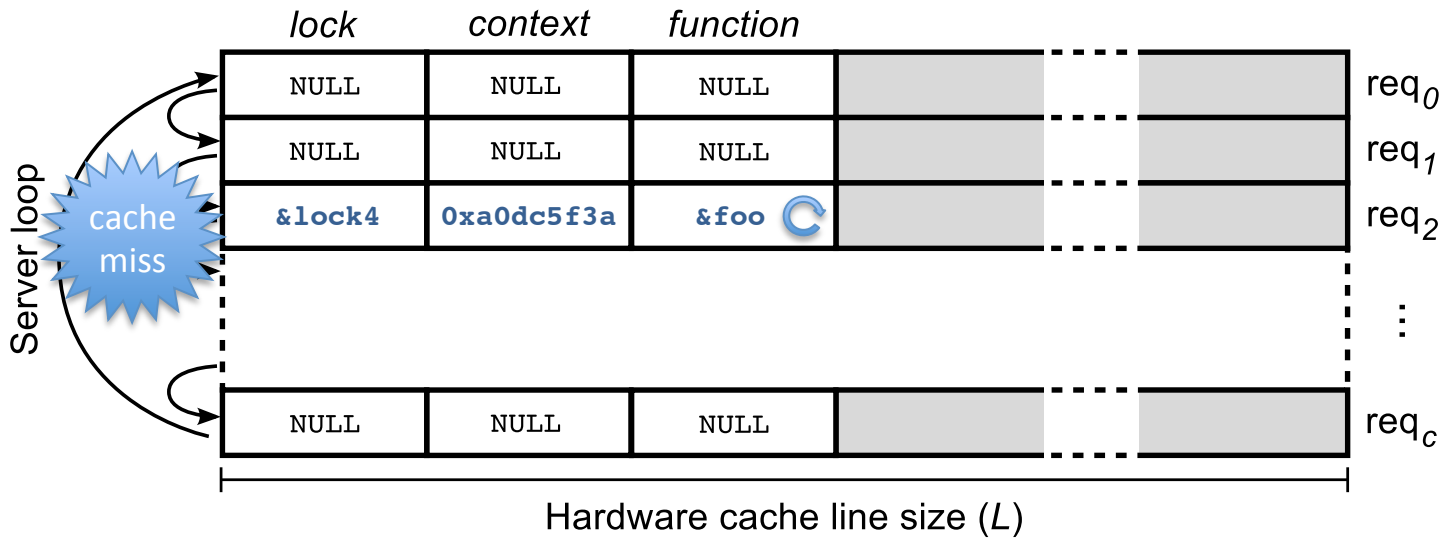

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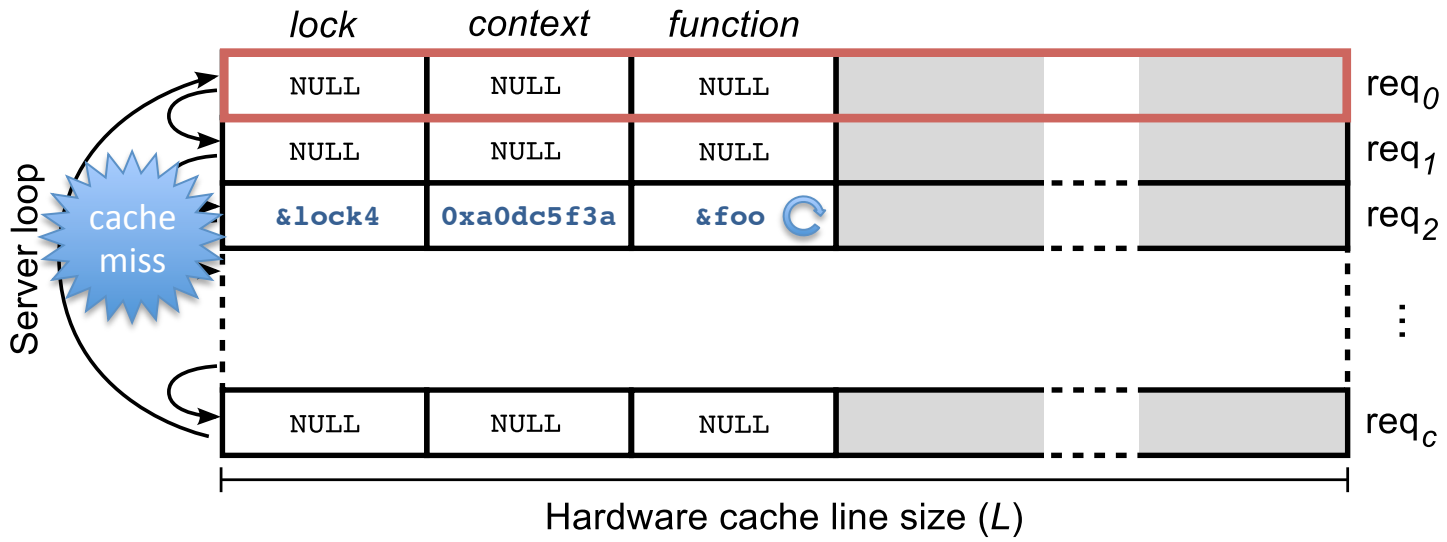

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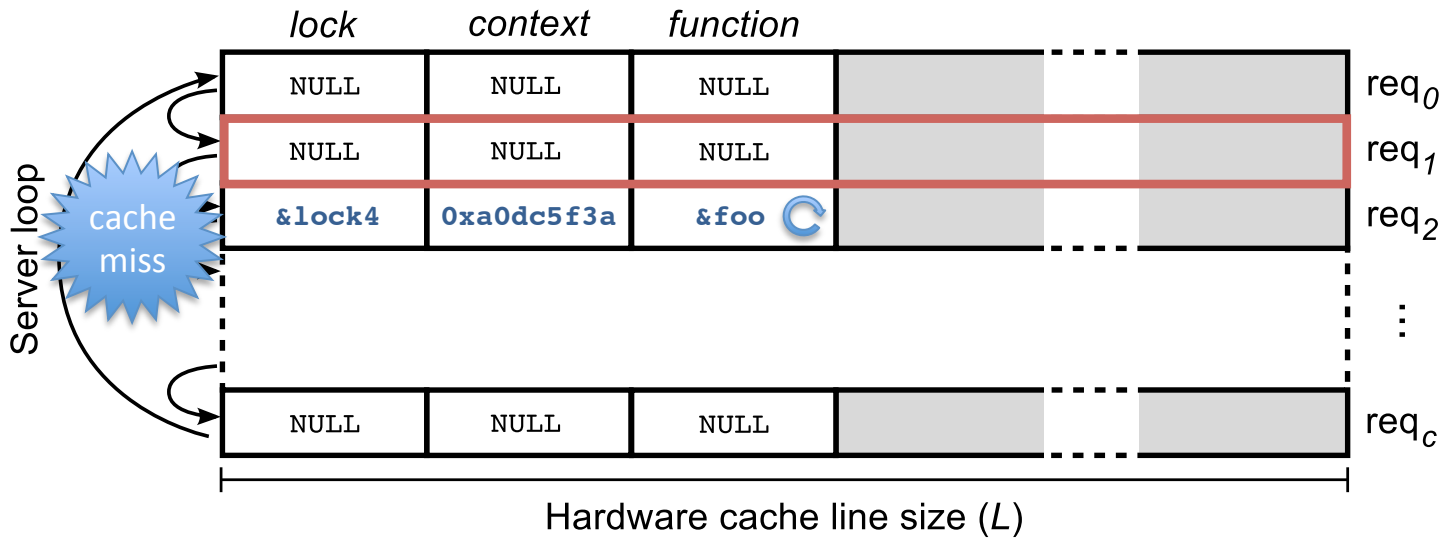

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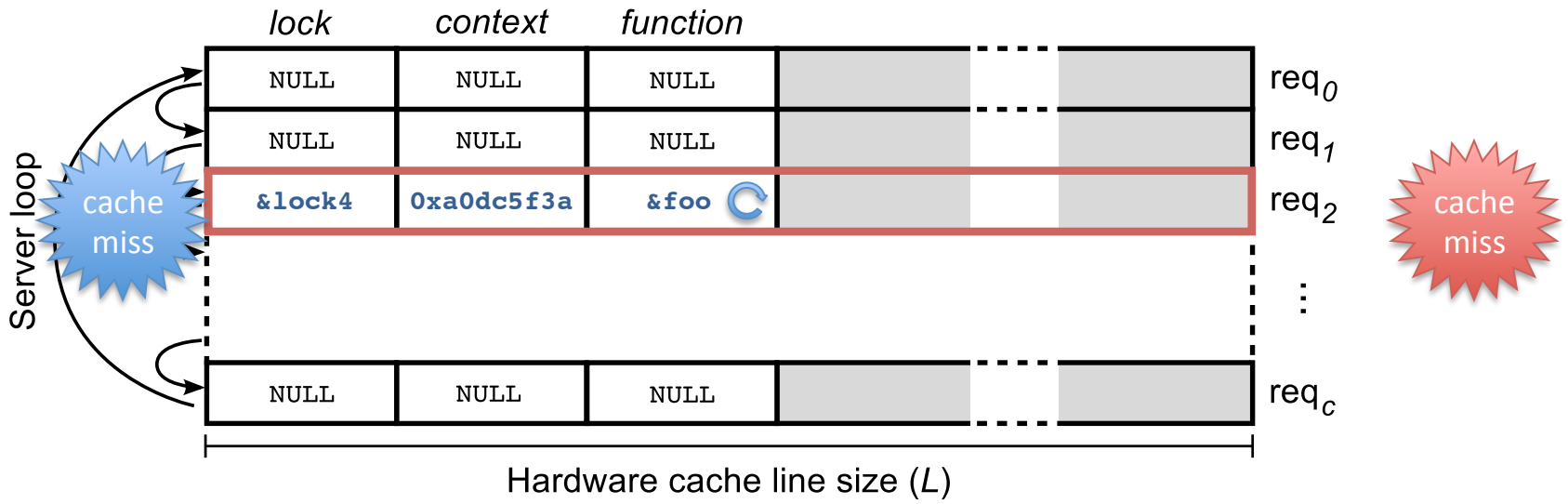

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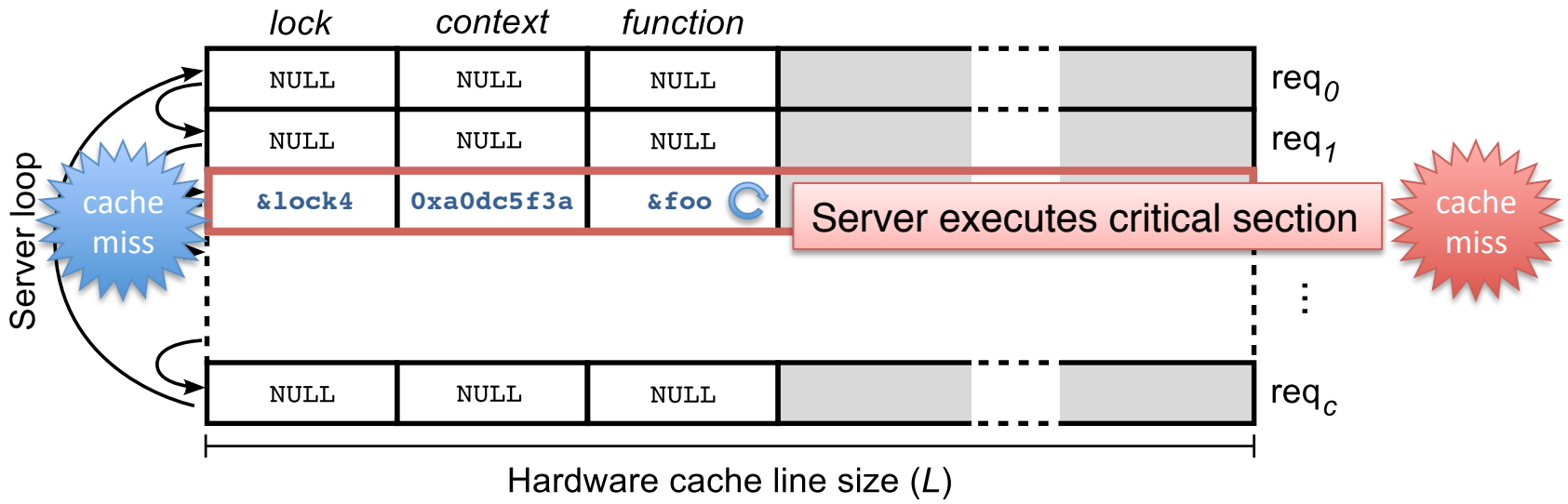

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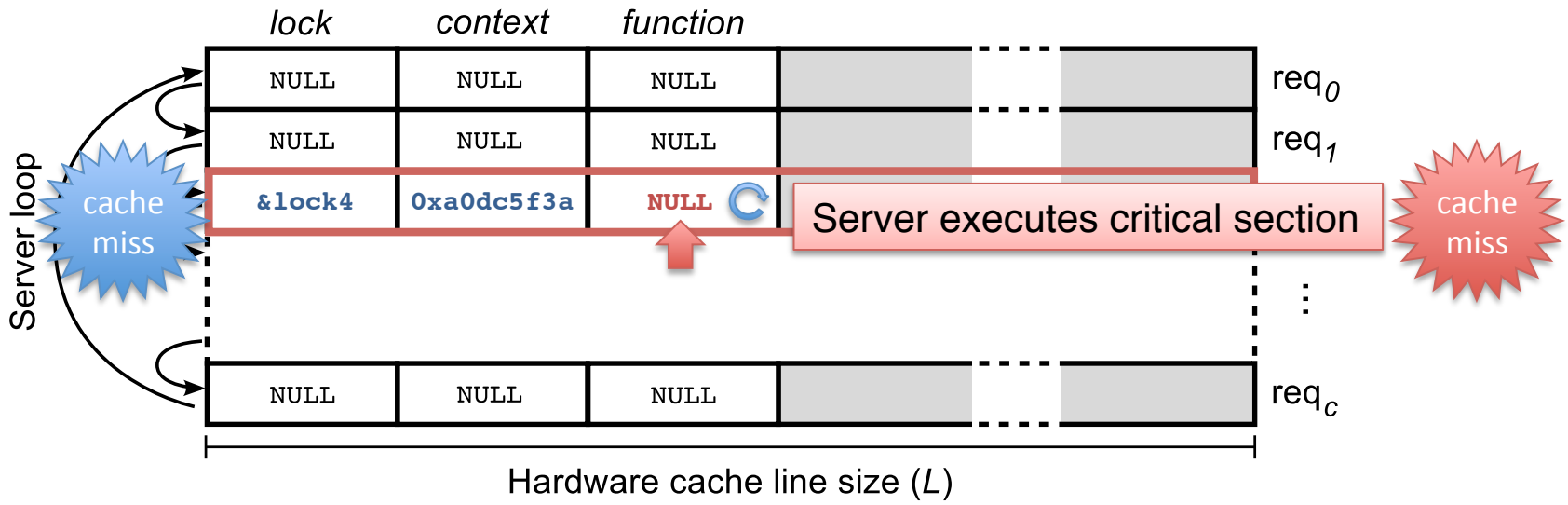

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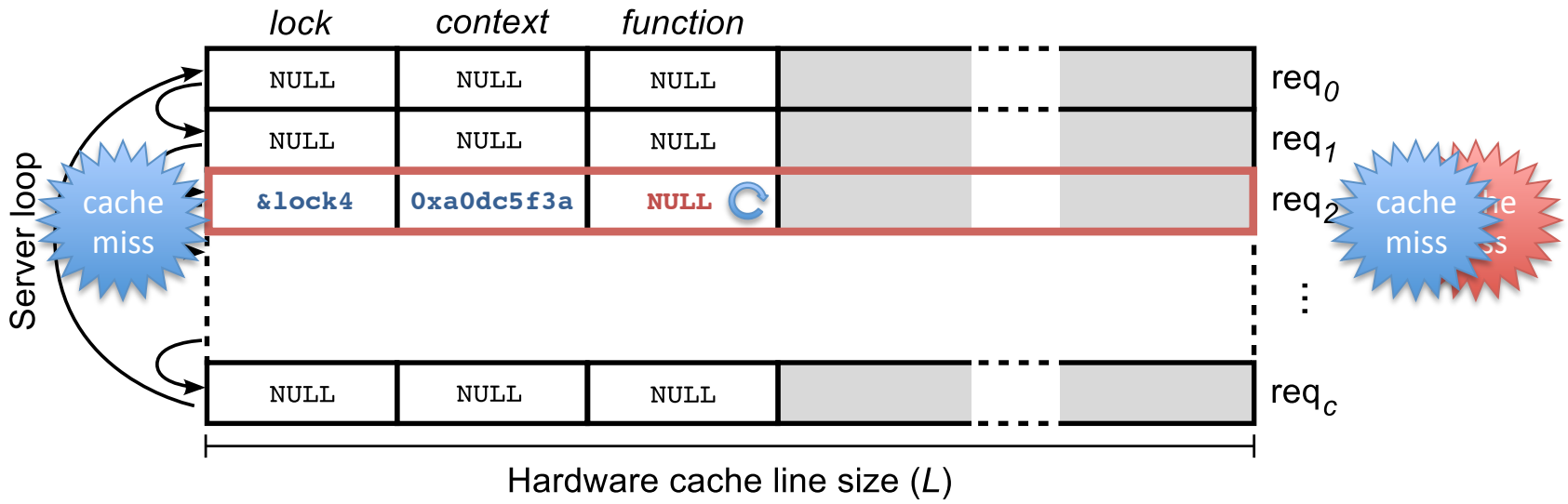

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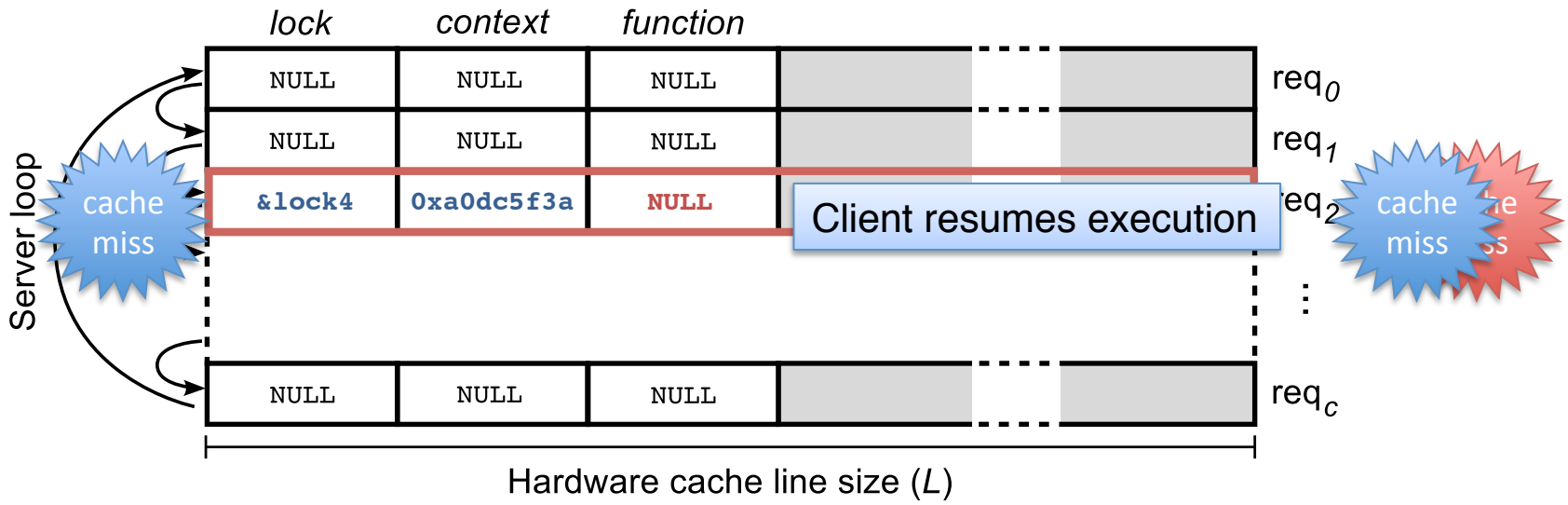

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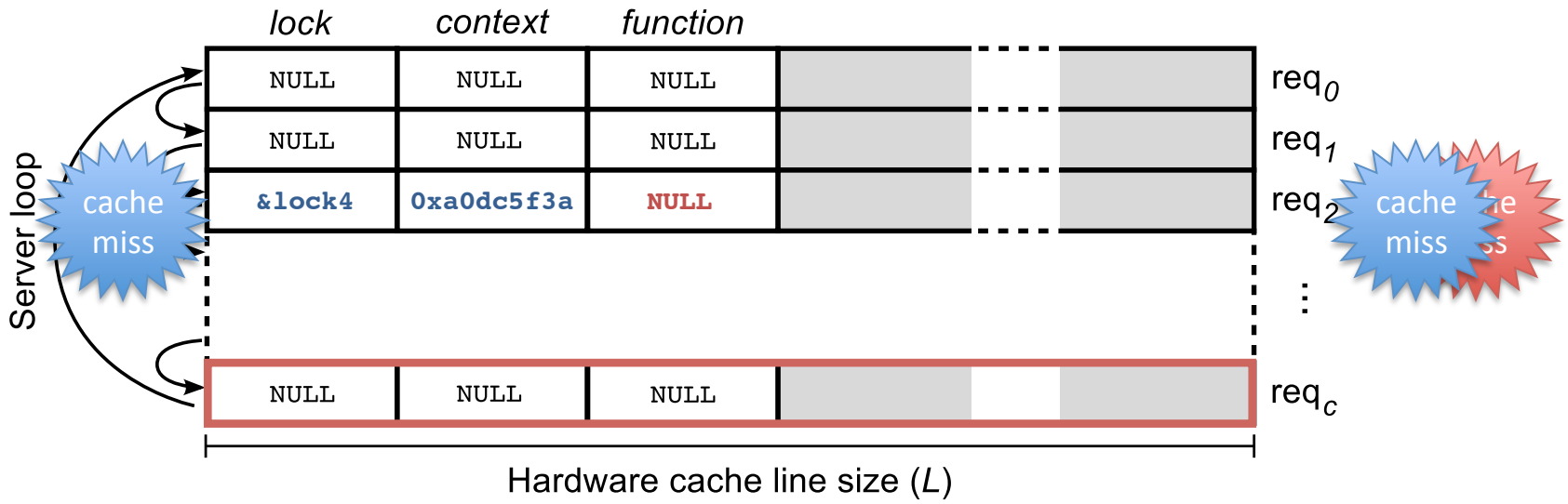

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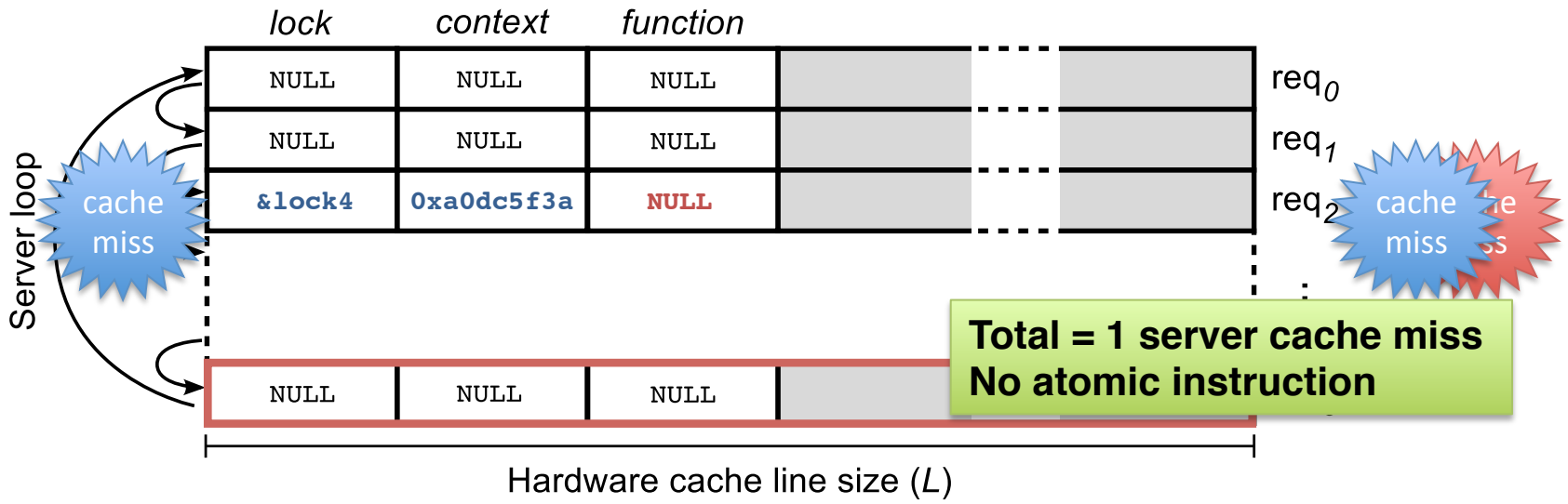

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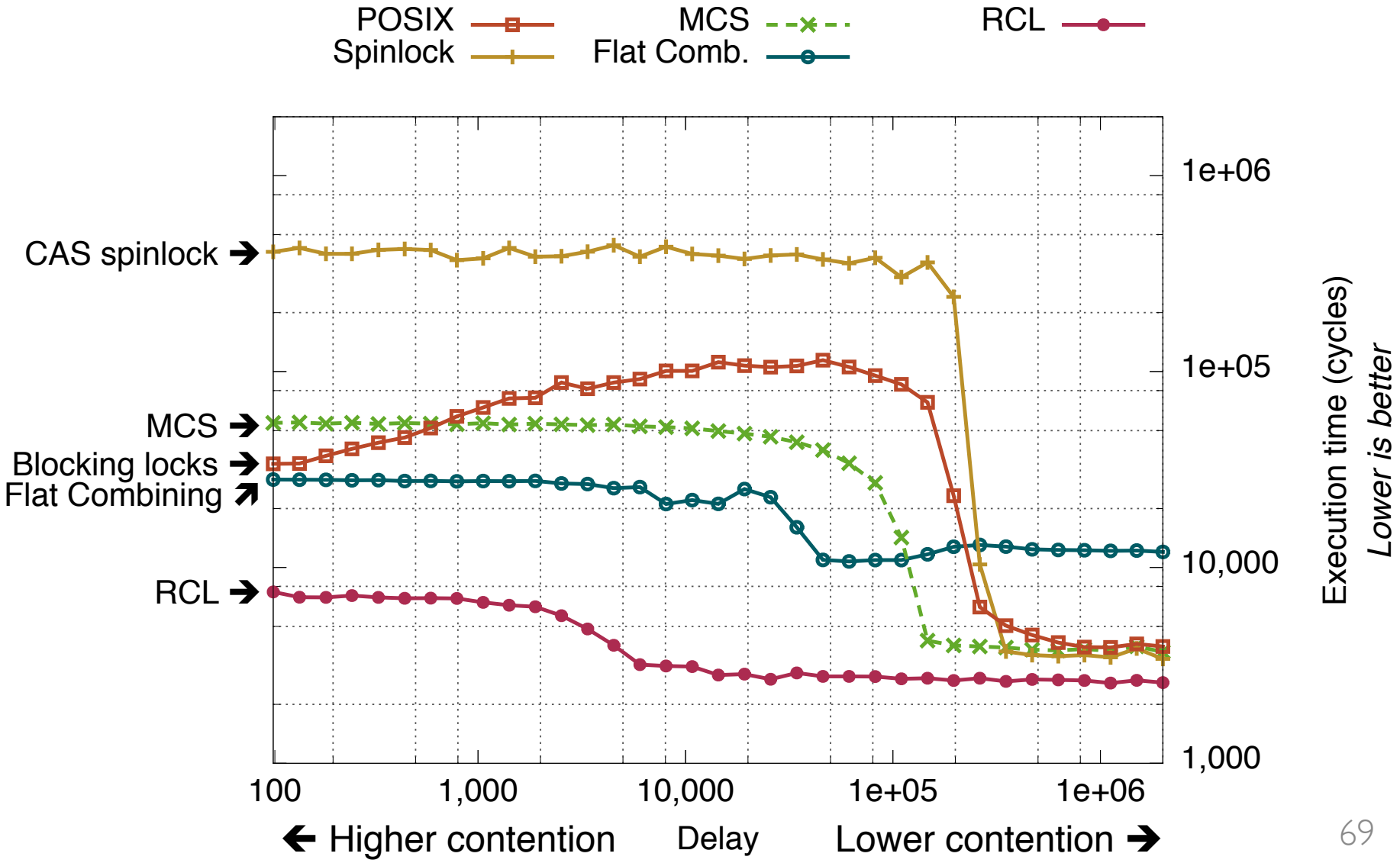
RCL Performance



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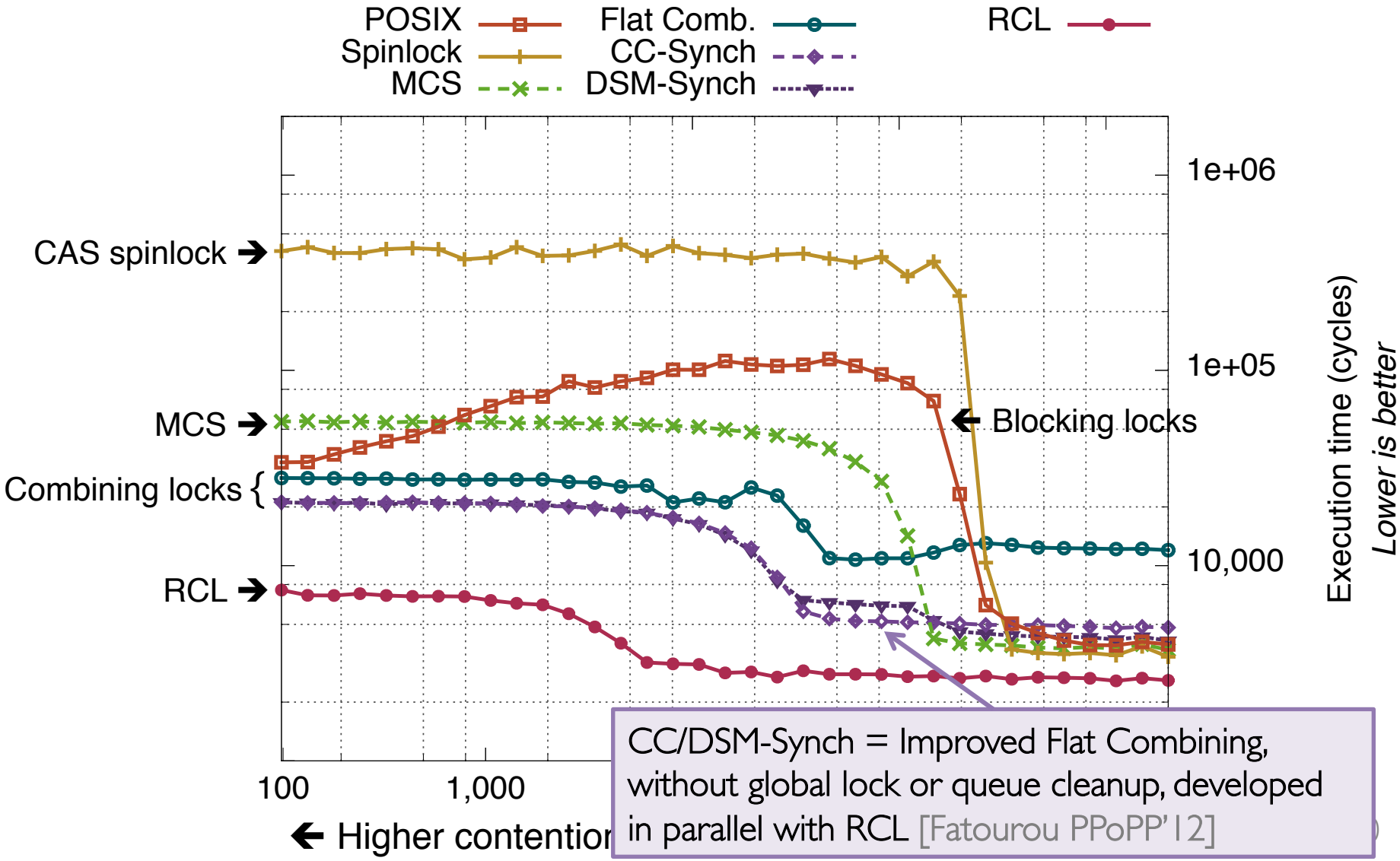


Using RCL in legacy applications

Three components :

- RCL runtime
  - Library that makes it possible to write RCL applications
- Profiler
  - To find out which applications / locks can potentially benefit from RCL
- Reengineering
  - To transform code for traditional locks into code that can use RCL

Using RCL in legacy applications

RCL Runtime:

- Handles blocking in critical sections (I/O, page faults…)
  - Pool of servicing threads on server
  - Able to service other (independent) critical sections when blocked
- Makes it possible to use condition variables (cond/wait)
  - Used by ~50% of applications that use POSIX locks in Debian 6.0.3
  - Not possible with combining locks

Using RCL in legacy applications

Profiler:

- Detects which applications / locks benefit from RCL
- Uses two metrics:
  - % of time spent in critical sections (measures contention)
  - Avg. # of cache misses in critical sections (measures data locality)

Using RCL in legacy applications (2)

Reengineering:

- Critical sections must be encapsulated into functions
  - Local variables sent as parameters (context)

Using RCL in legacy applications (2)

Reengineering:

```
void func(void) {
  int a, b, x;
  …
  a = …;
  …
  pthread_mutex_lock();
  a = f(a);
  f(b);
  pthread_mutex_unlock();
  …
}
```

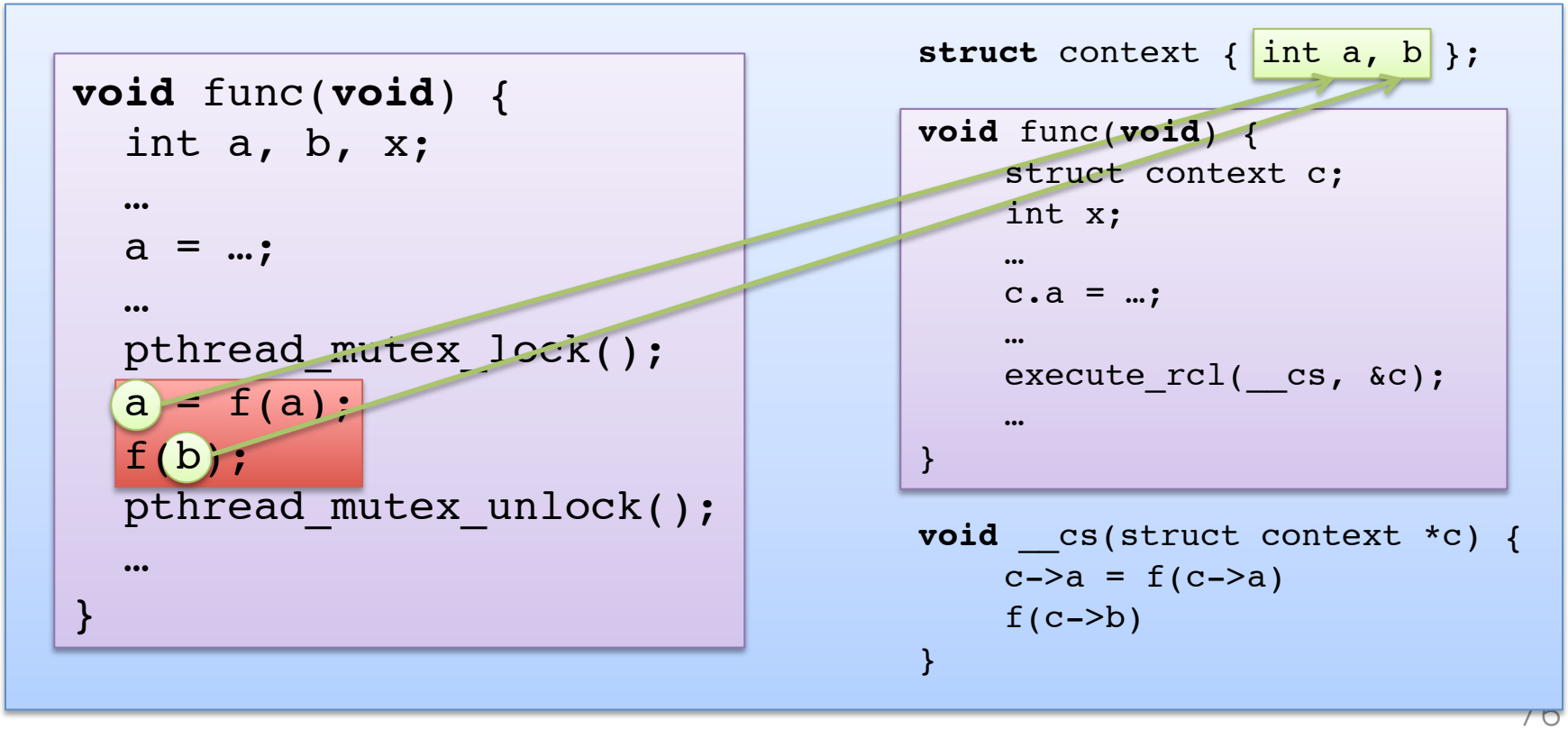
```
struct context { int a, b };

void func(void) {
     struct context c;
     int x;
     …
     c.a = …;
     …
     execute_rcl(__cs, &c);
     …
}

void __cs(struct context *c) {
     c->a = f(c->a)
     f(c->b)
}
```

Using RCL in legacy applications (2)

Reengineering:



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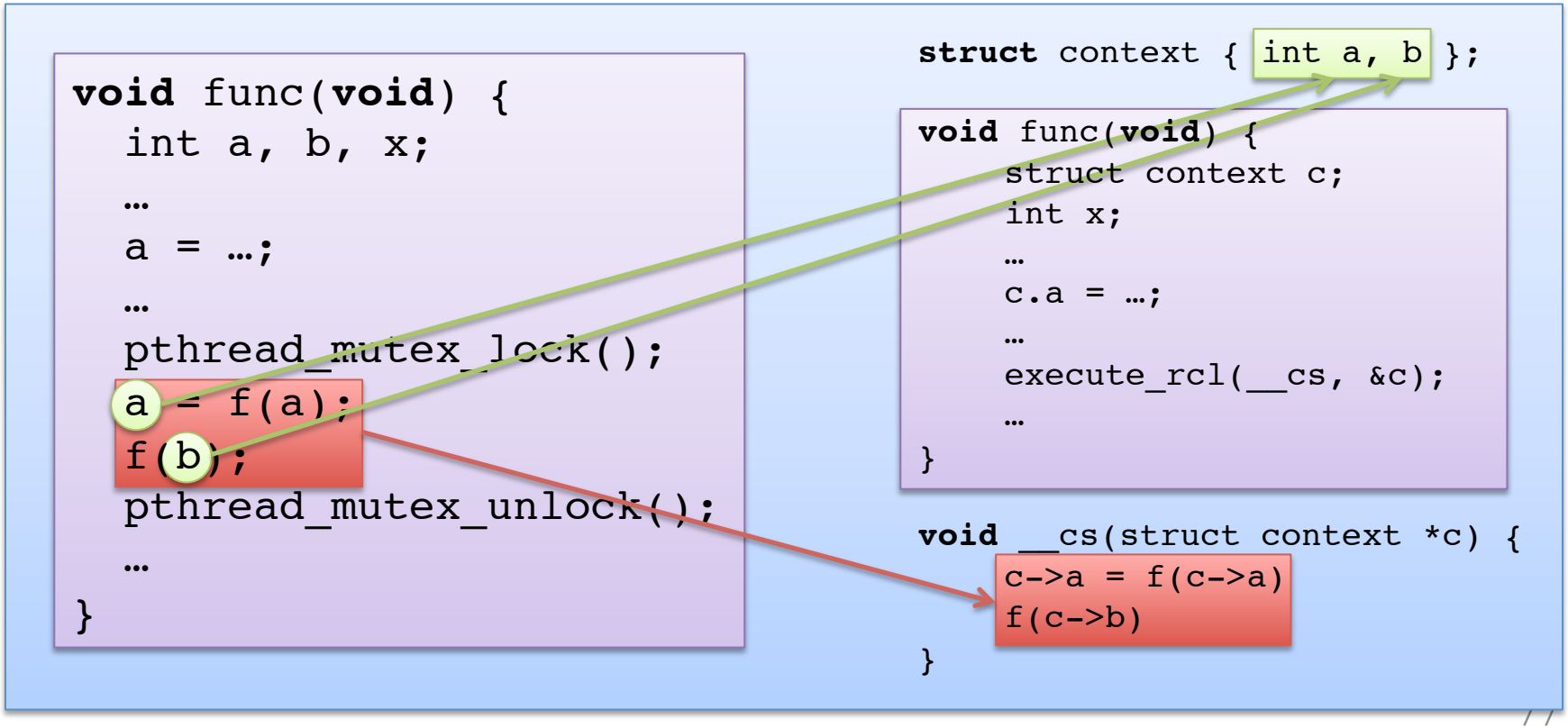

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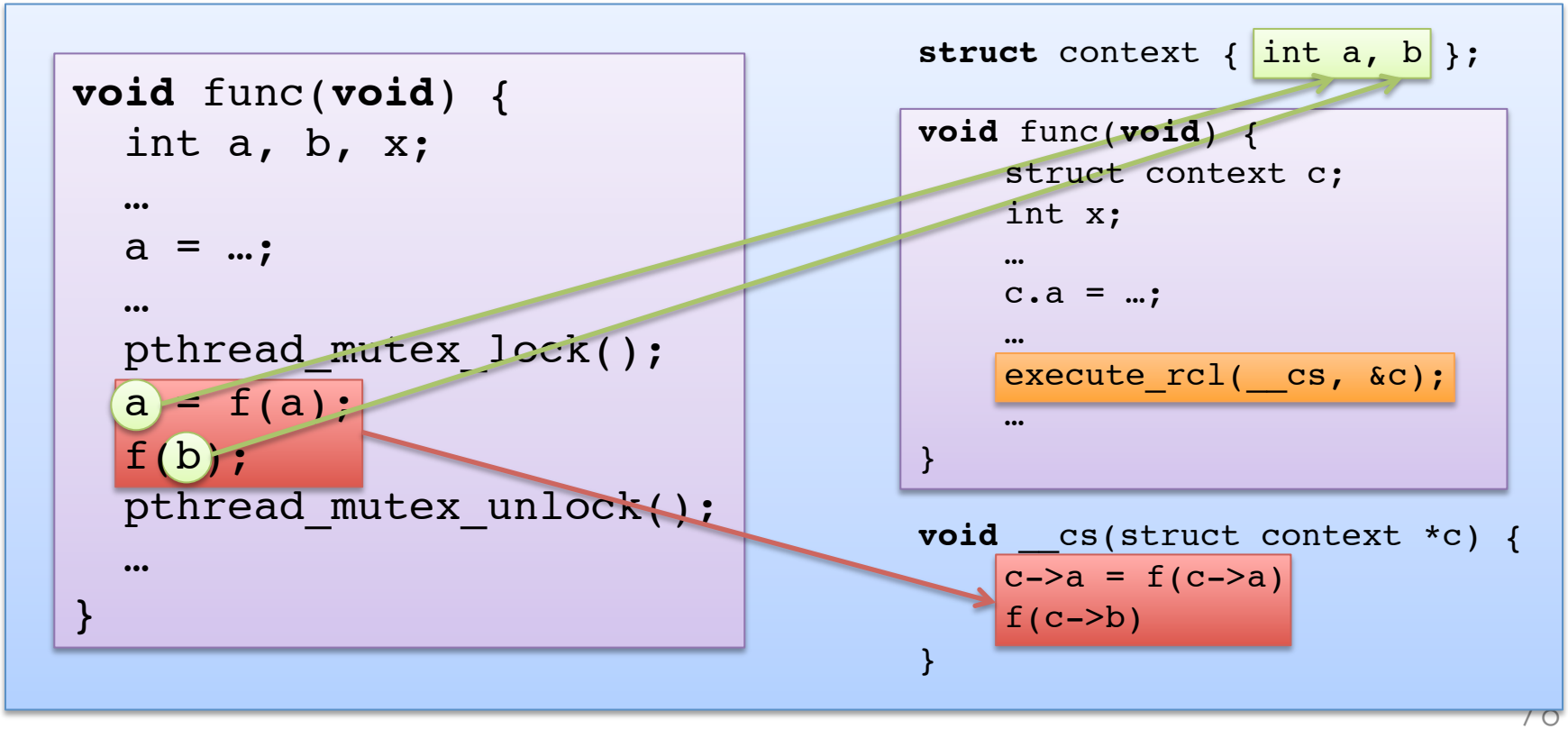


Using RCL in legacy applications (2)

Reengineering:

- Critical sections must be encapsulated into functions
  - Local variables sent as parameters (context)
- Tool to reengineer applications automatically
  - Possible to pick which locks use RCL
  - To avoid false serialization:
    possible to pick which server(s) handle which lock(s).

Outline

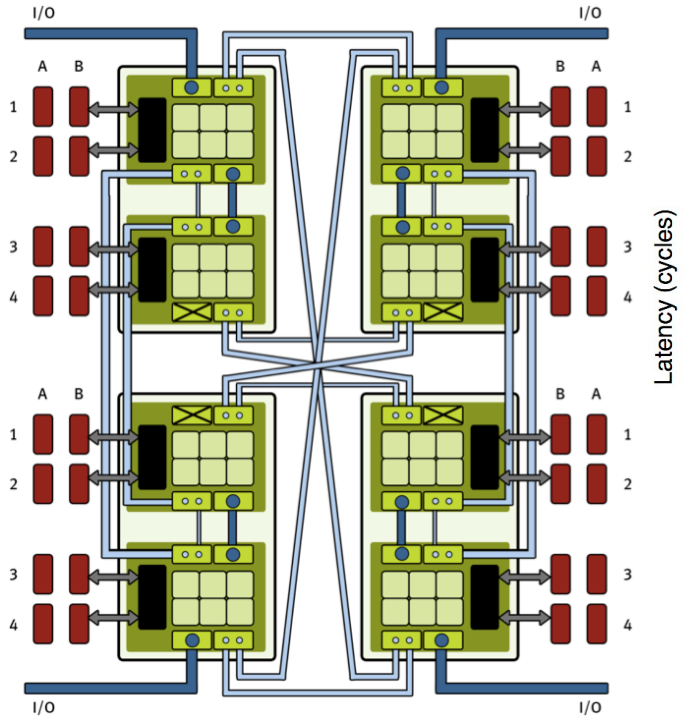
- Context: multicore architectures
- State of the art: locks
- Contribution: Remote Core Locking
- **Evaluation in legacy applications**
  - **Methodology**
  - Main results
  - Scalability
  - More software threads than hardware threads
- Perspectives and conclusion

Methodology

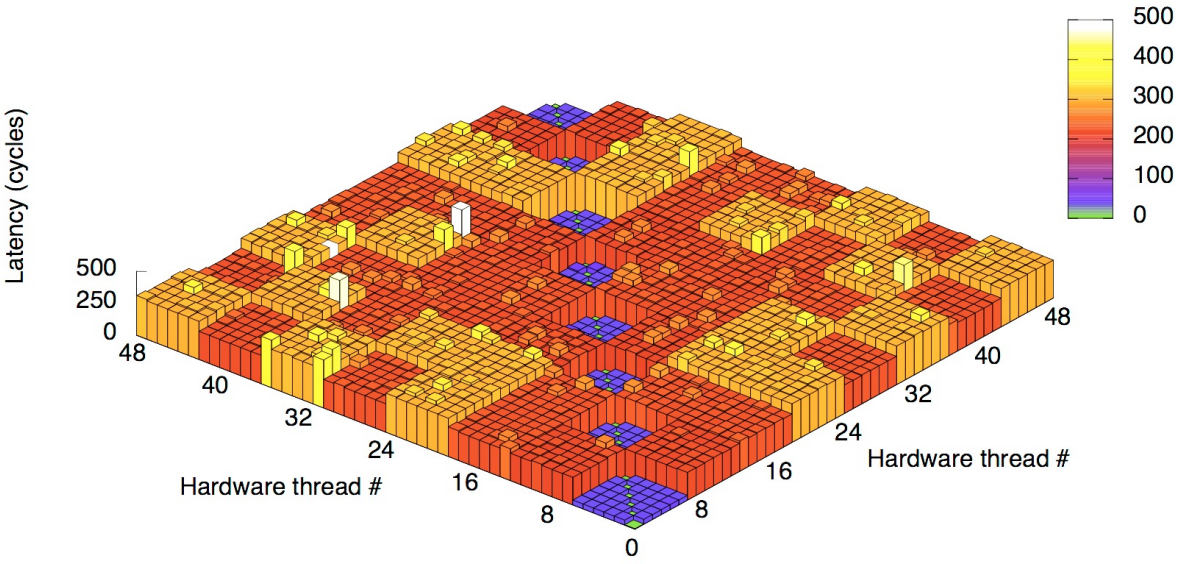
- Evaluation on two different machines
  - Different architectures and OSes
- Different application types
  - Parallel computing
    - Scientific computations (SPLASH-2), MapReduce (Phoenix 2)
  - Server applications (Memcached, Berkeley DB)
- Different configurations
  - One software thread per hardware thread
  - More software threads than hardware threads (Berkeley DB)

Magnycours-48

- Four Opteron 6172, two dies per CPU, six cores per die
  - No hardware multithreading: 48 hardware threads
- Non-complete interconnect graph
  - Asymmetrical access times

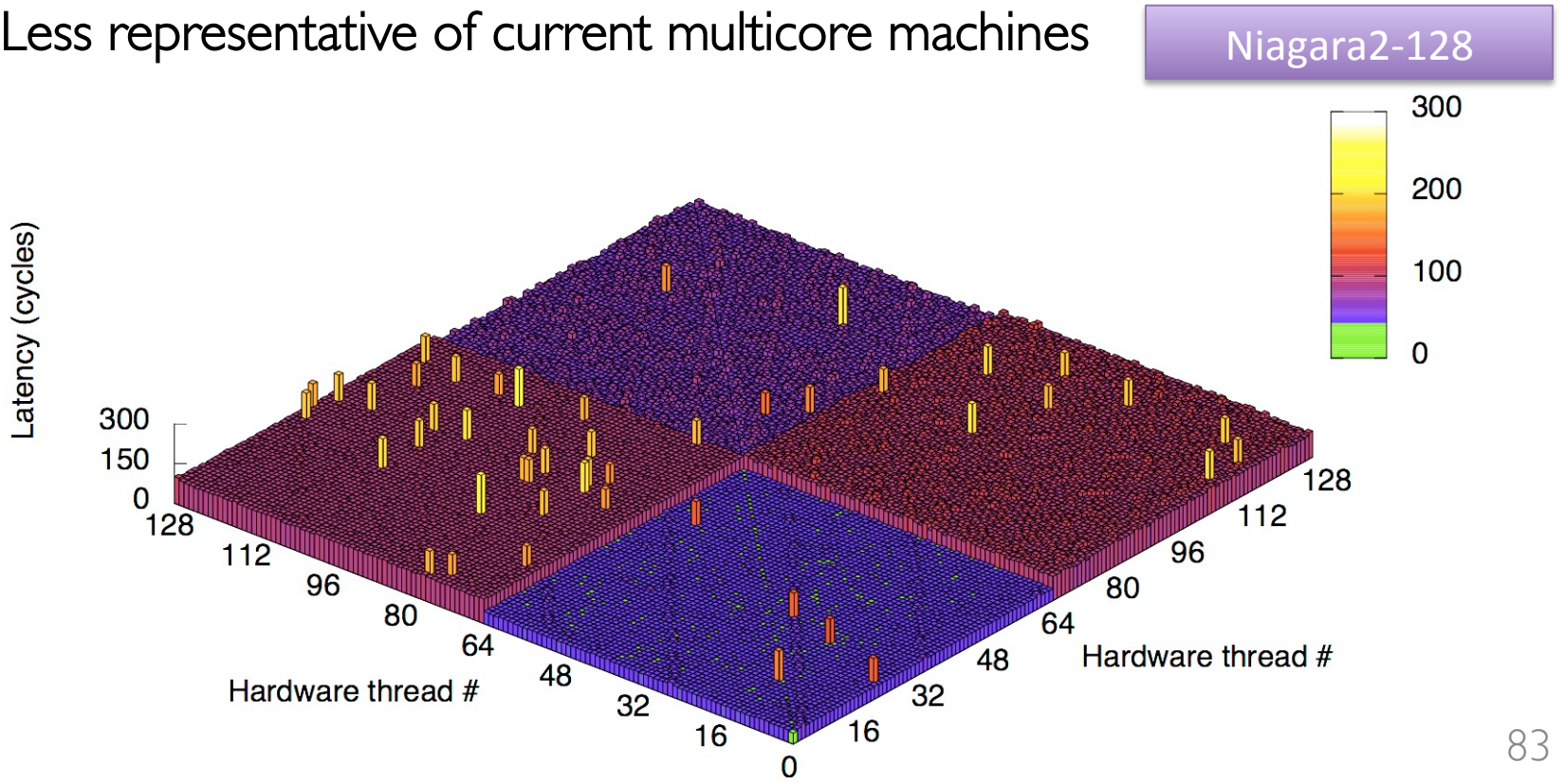


Magnycours-48



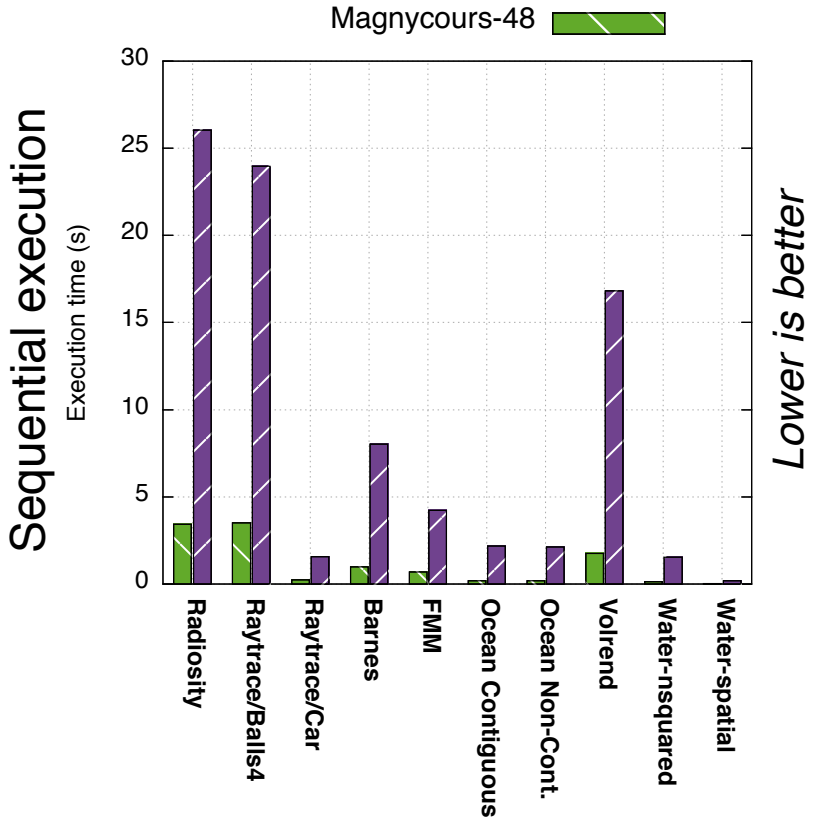
Niagara2-128

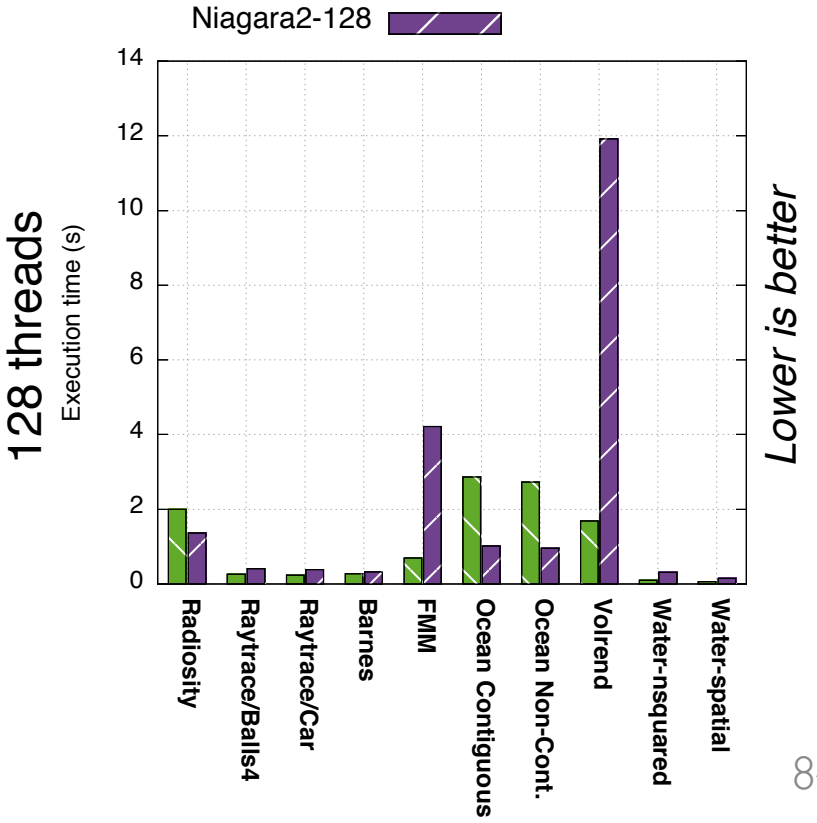
- Two UltraSPARC-T2+ CPUs, each with 8 cores
- Simultaneous hyperthreading: 8 hardware threads per core (!)
  - 128 hardware threads
- Less representative of current multicore machines



Differences

- Magnycours-48 has much faster sequential speed
- Niagara2-128 has faster communication speed / sequential speed
- On SPLASH-2, parallel scientific applications:





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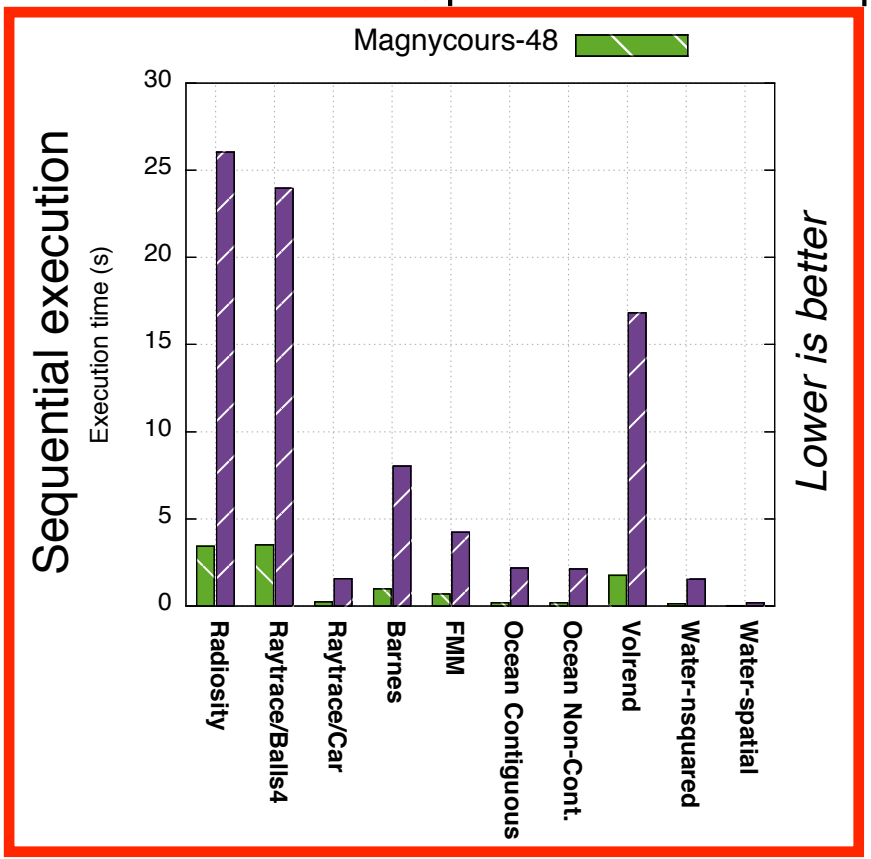

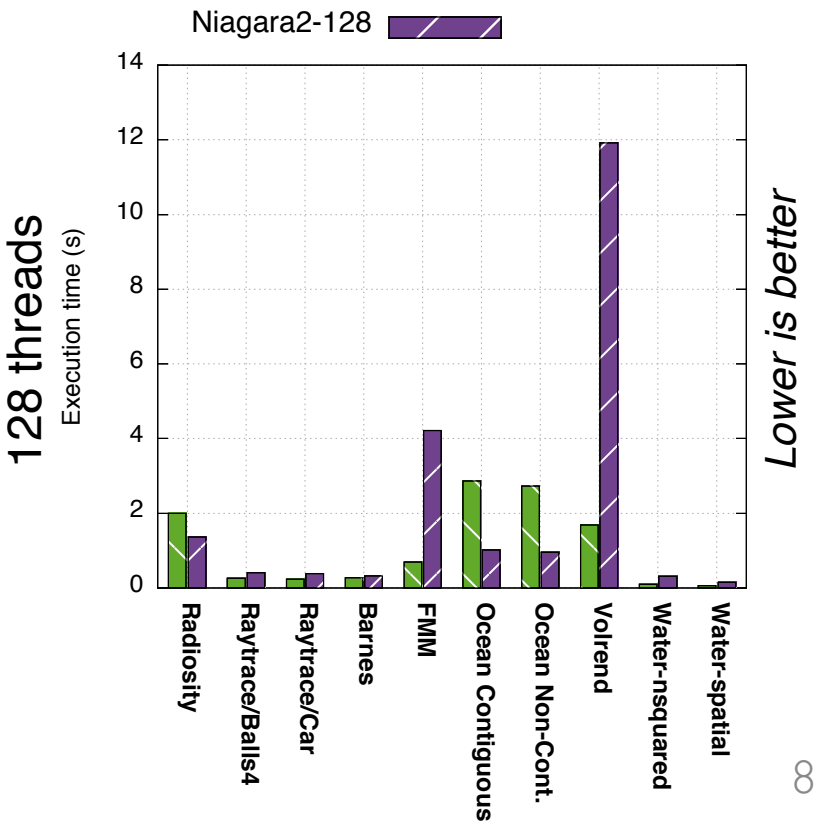

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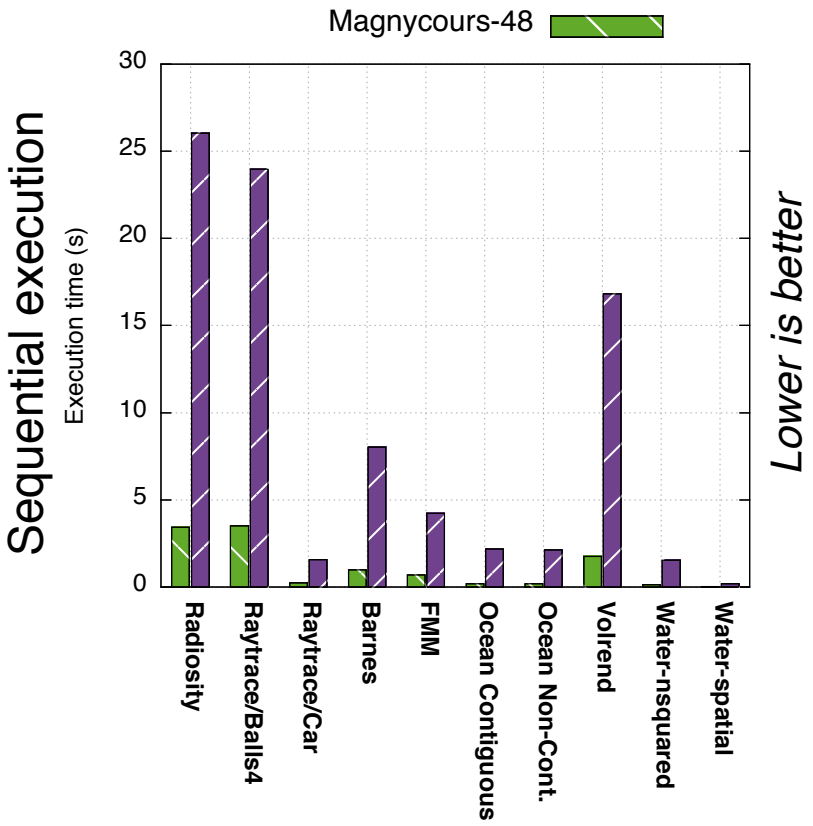

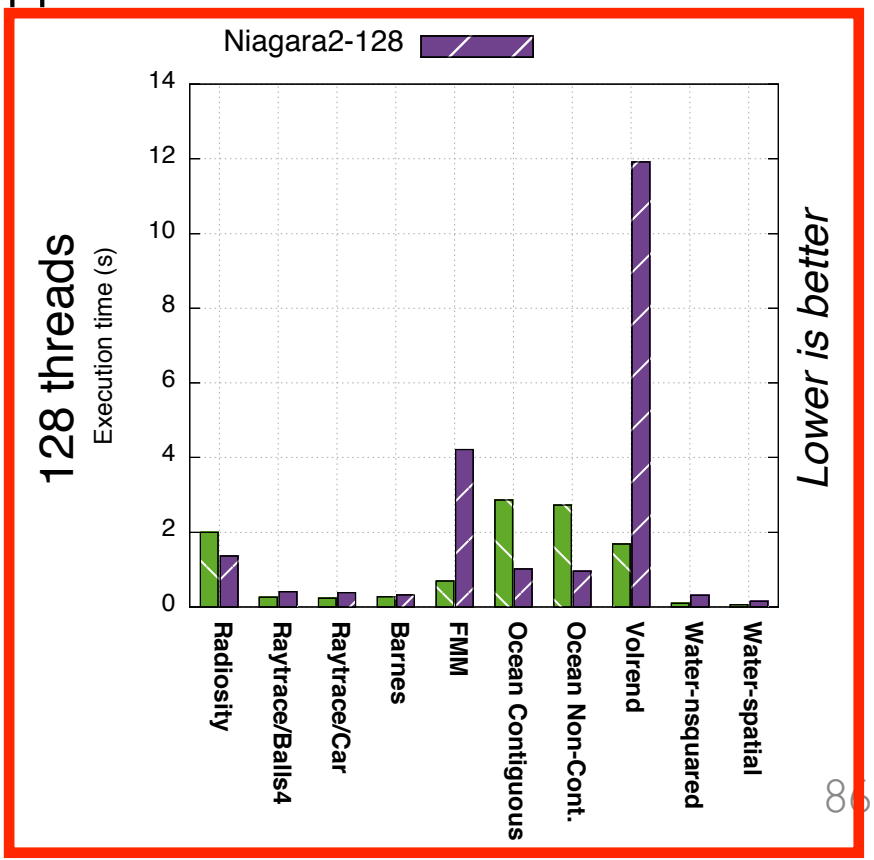

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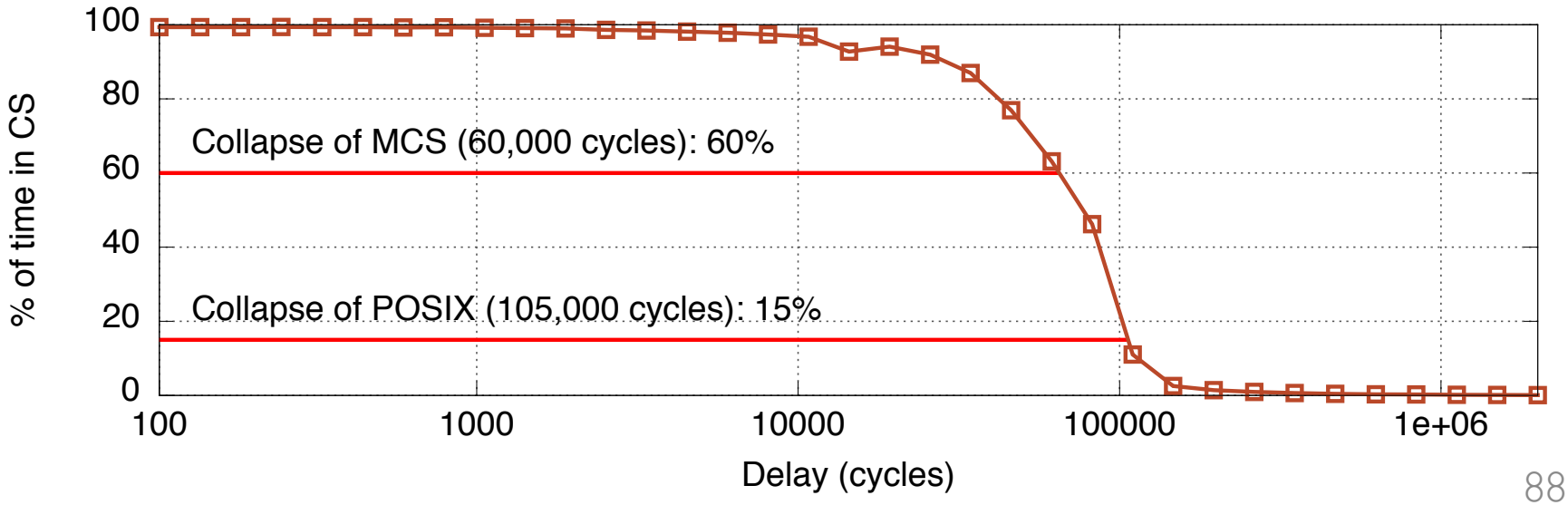
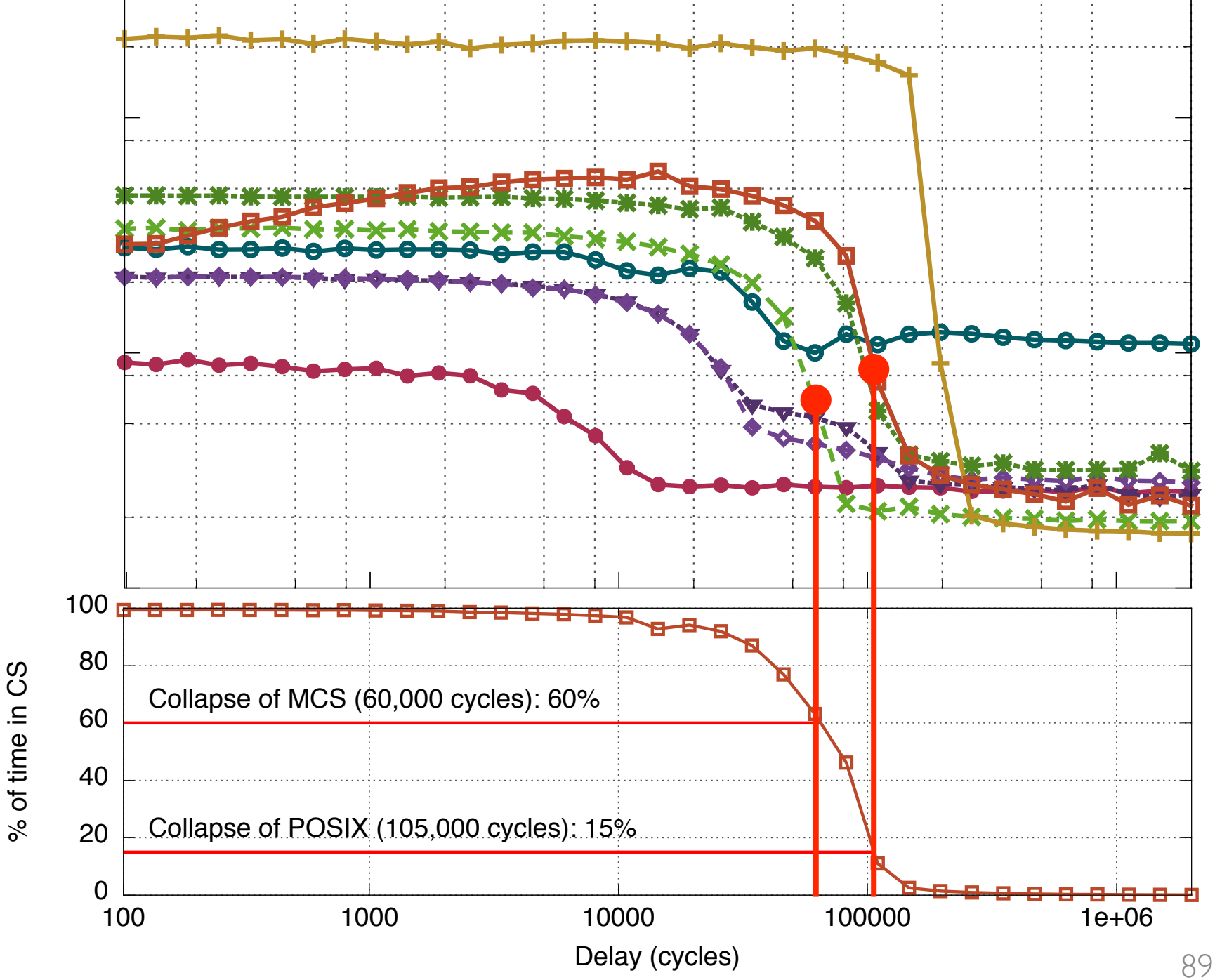
Main results

Magnycours-48

Profiling:

- Custom profiler to find good candidates
- Metric: time spent in critical sections
- Running the profiler on the microbenchmark shows that:
  - If time spent in CS > 15%, RCL is more efficient than POSIX locks
  - If time spent in CS > 60%, RCL is more efficient than all other locks

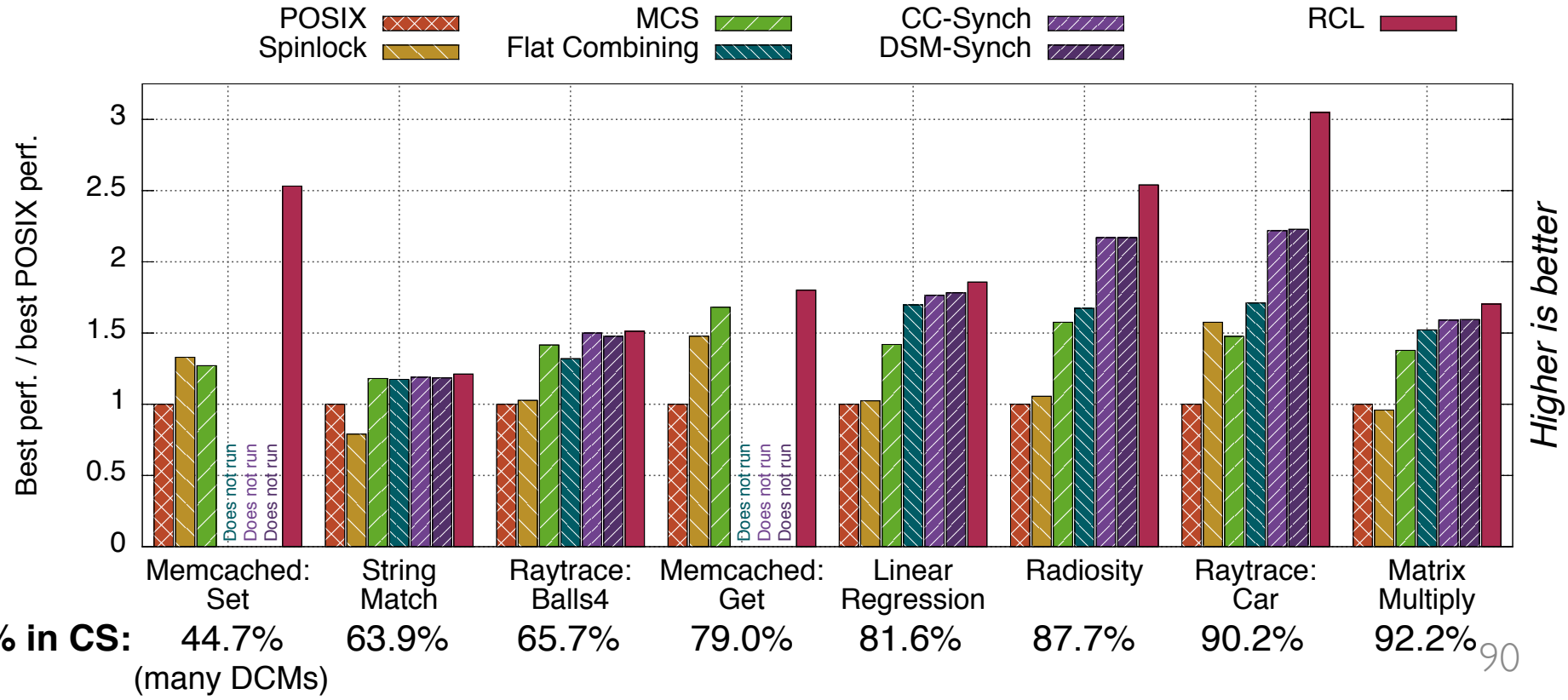



100
80
60
40
20
0
% of time in CS
Collapse of MCS (60,000 cycles): 60%
Collapse of POSIX (105,000 cycles): 15%
100
1000
10000
100000
1e+06
Delay (cycles)

Main results

Magnycours-48

- Better performance when time in CS > 60%
  - Performance improvement correlated with time in CS
- Only one or two locks replaced each time



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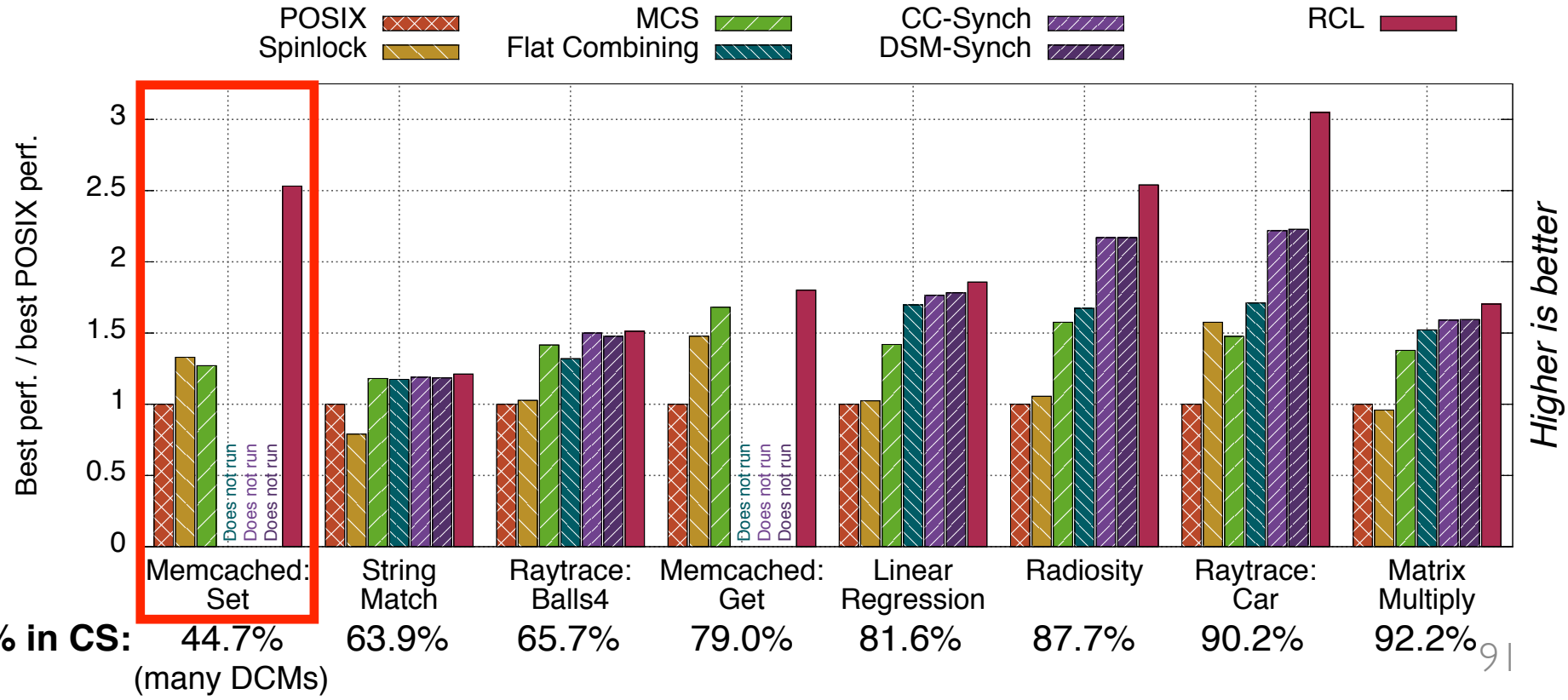

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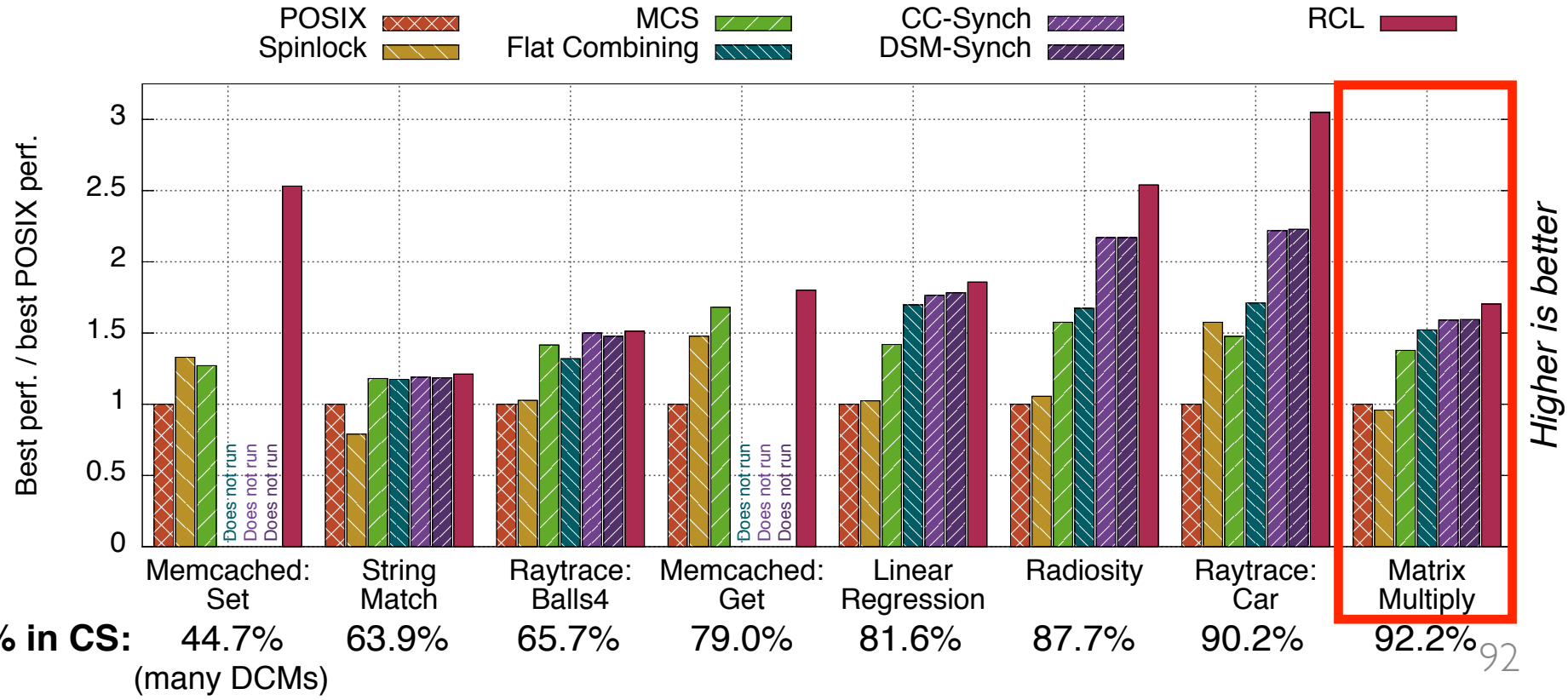
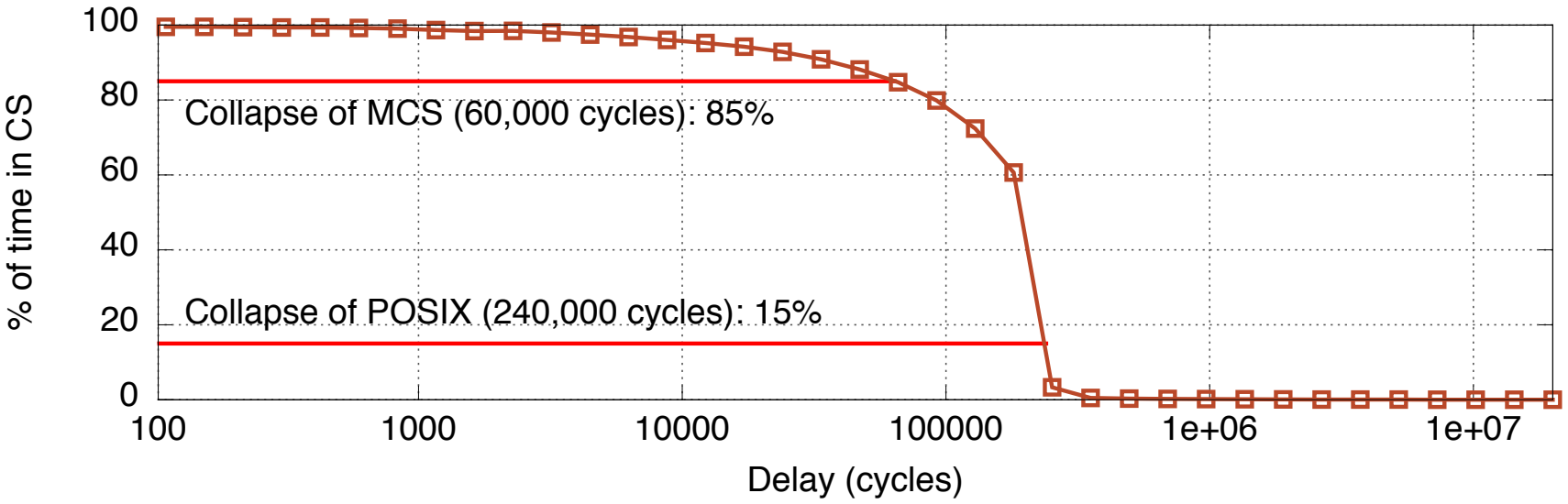


Main results

Niagara2-128

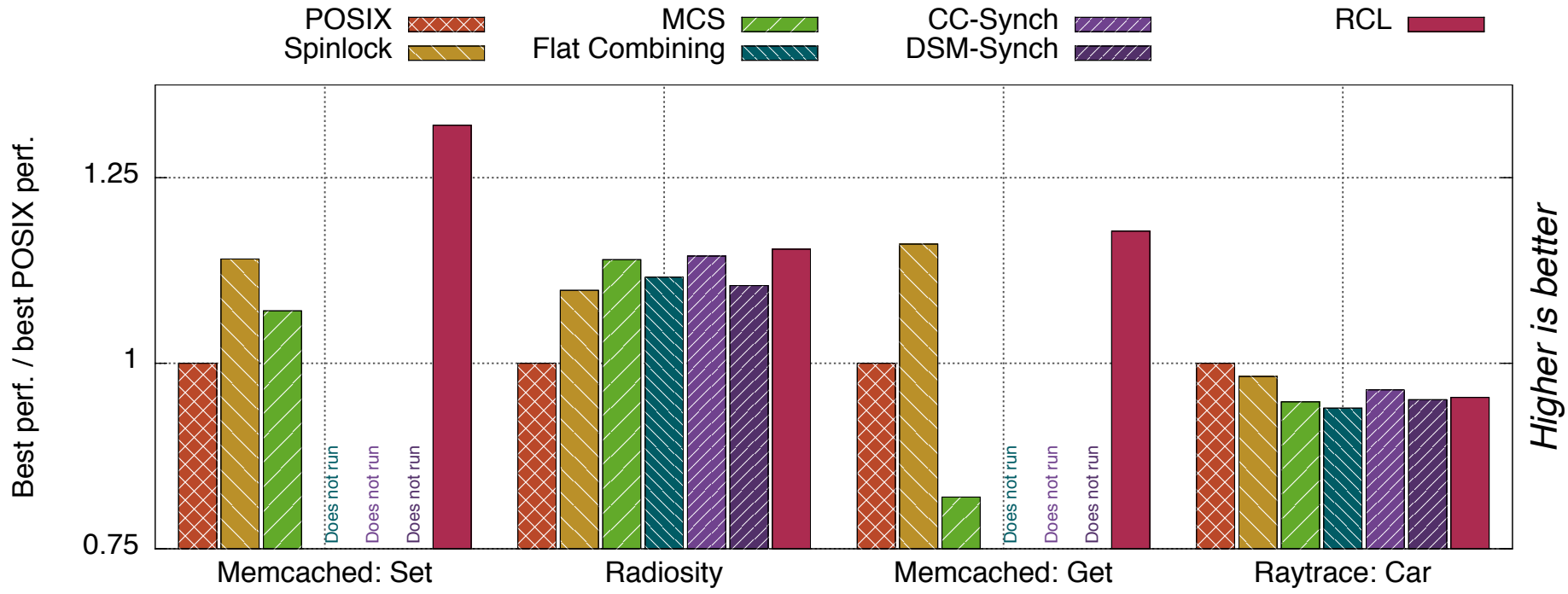
- On Niagara2-128: profiler thresholds = 15% / 85%



Main results

Niagara2-128

- On Niagara2-128, no bench > 85%
  - Faster communication / sequential speed, less issues with contention
- Still some performance gains when time in CS > 15%



% in CS:	20.2% (many DCMs)	38.7%	69.2%	79.1%

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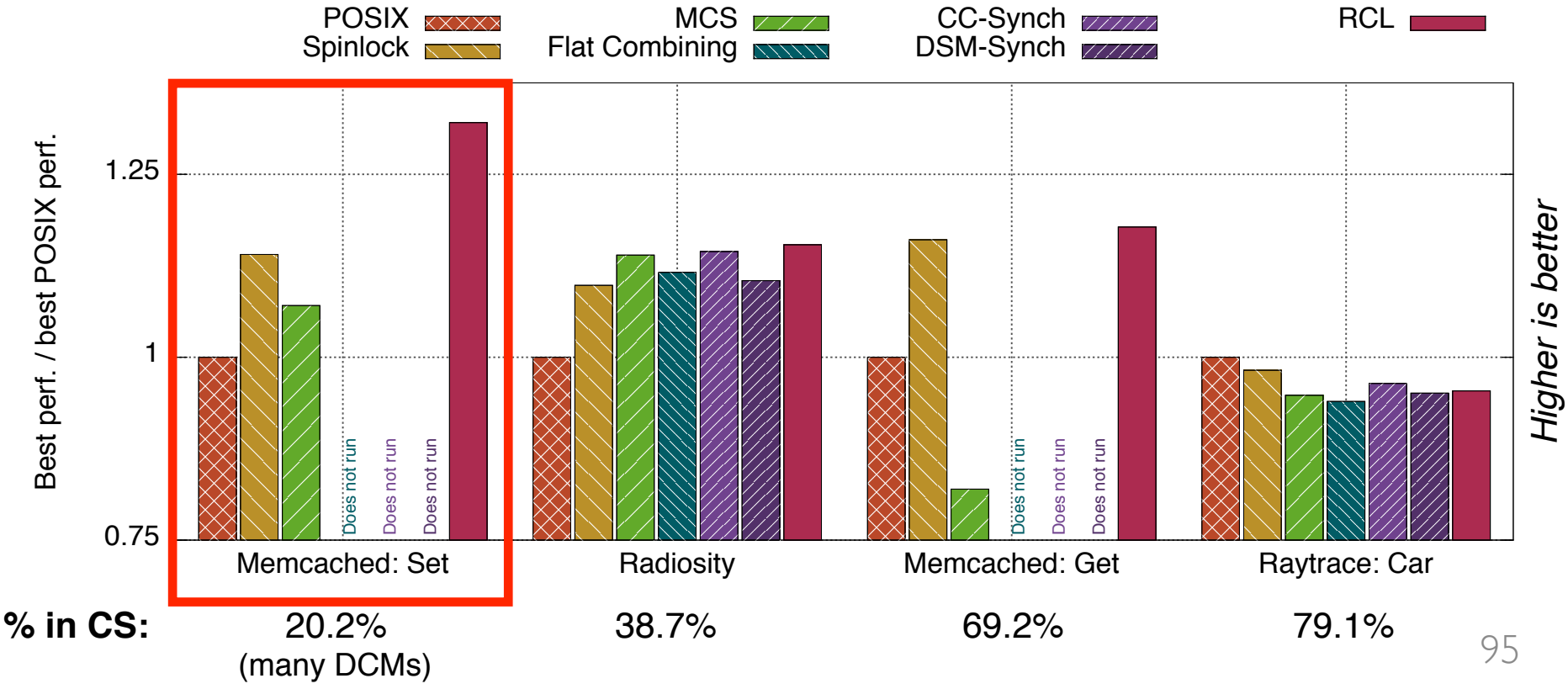

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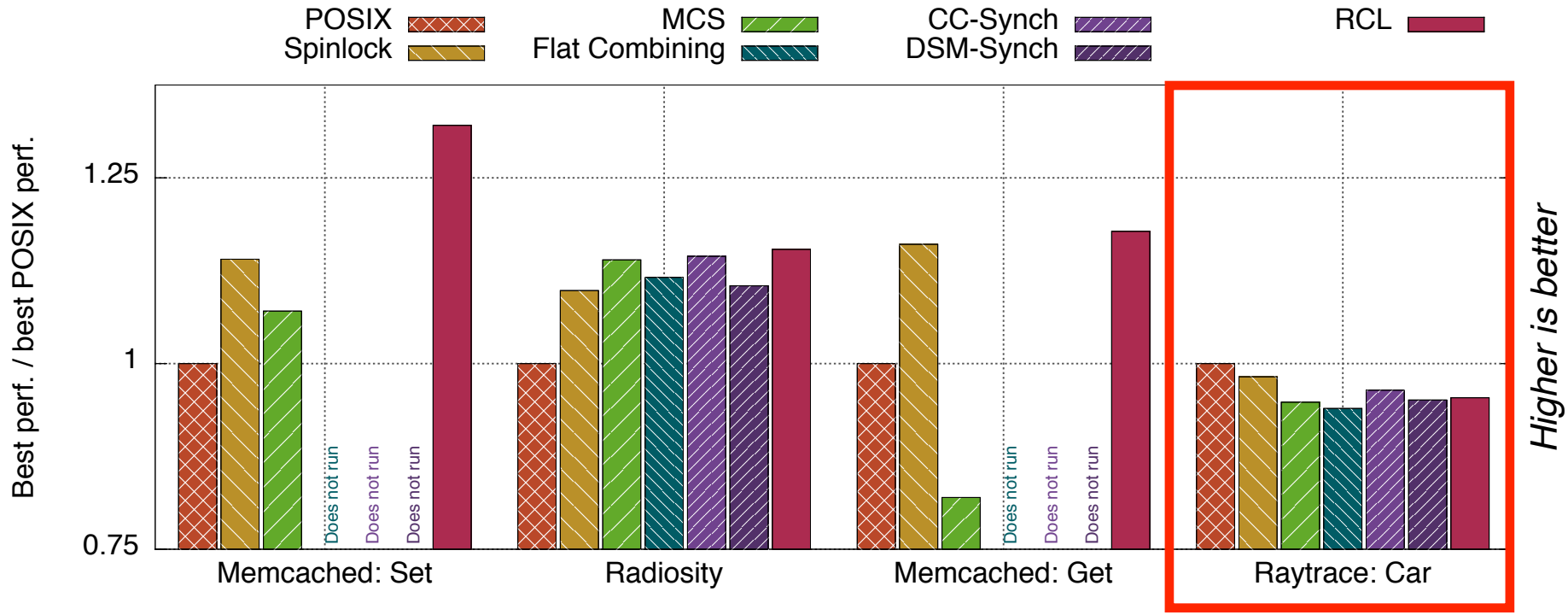

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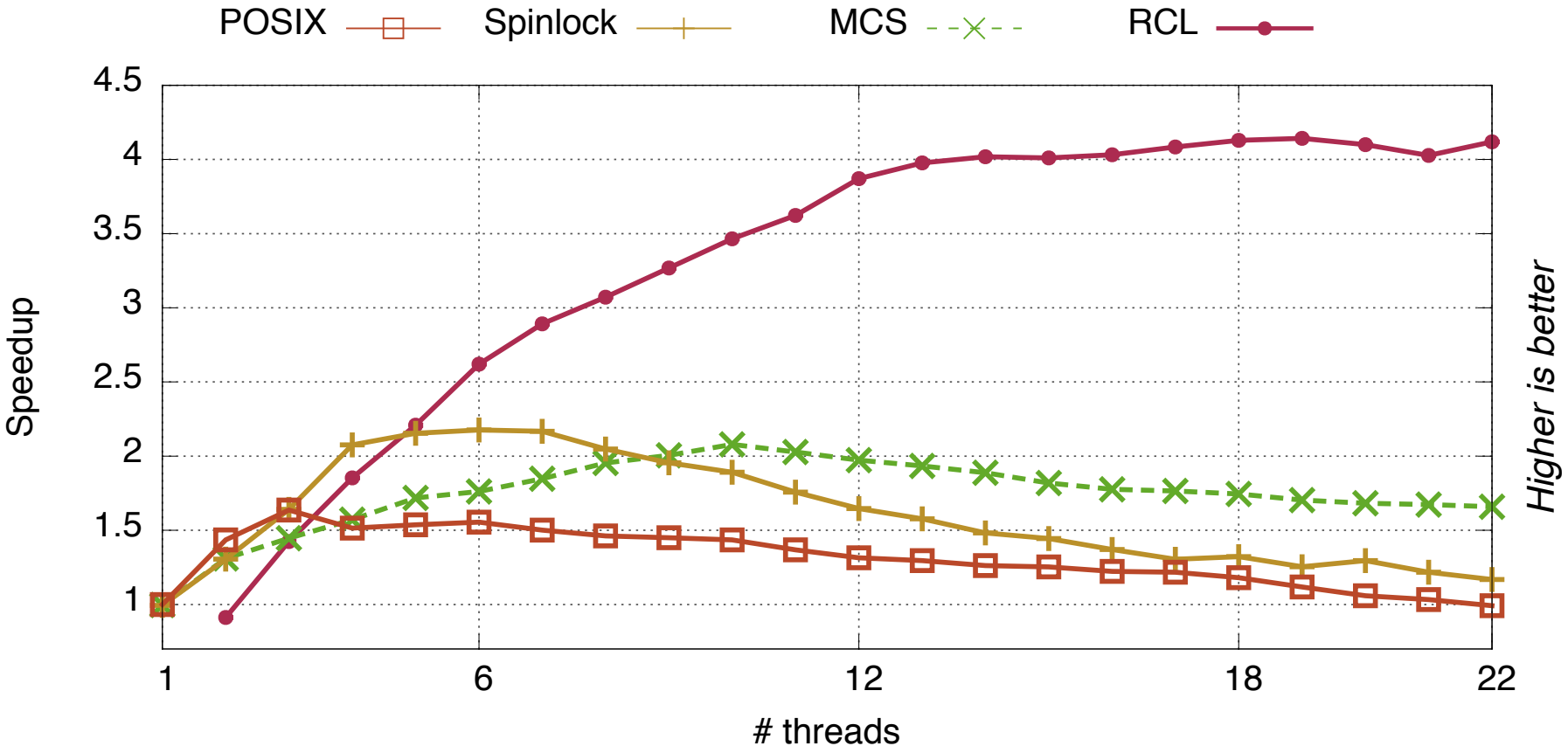
Scalability of RCL

- RCL not only improves performance, it also improves scalability
- Example: Memcached with Set requests
  - On Magnycours-48 and Niagara2-128
- Memcached uses condition variables
  - No results for combining locks

Scalability of RCL

- Memcached, Set requests:

Magnycours-48



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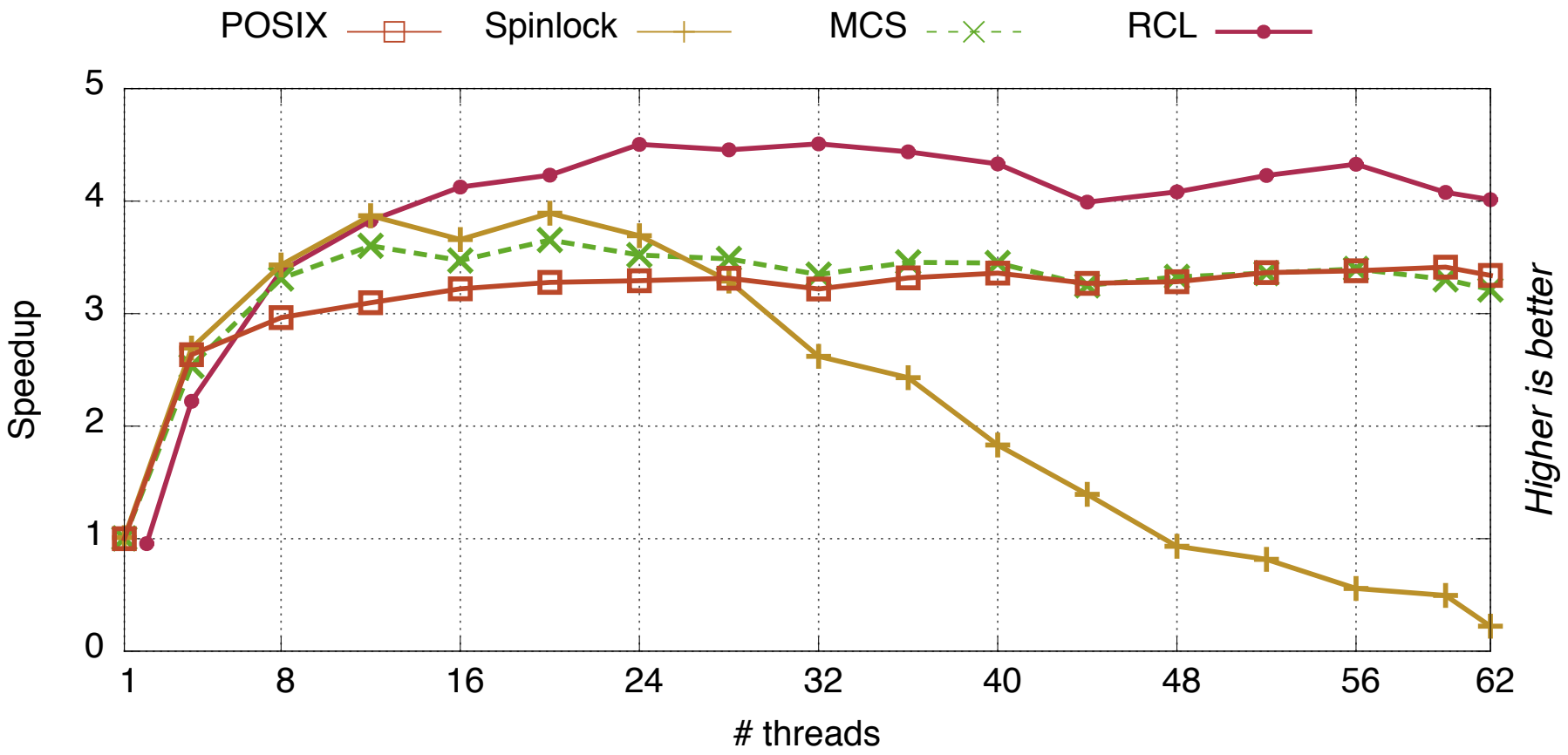
Niagara2-128



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More sw threads than hw threads

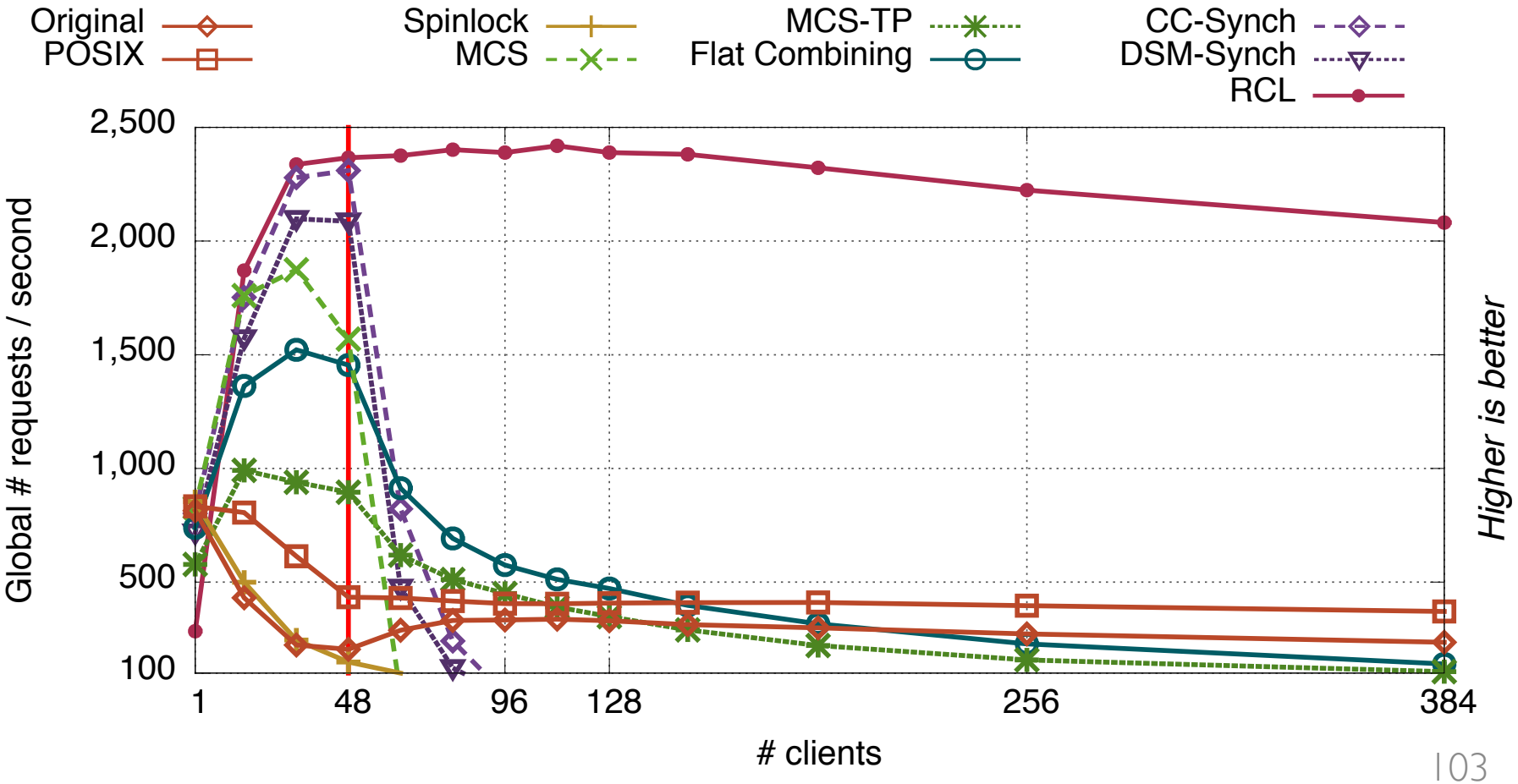
- Many locks perform poorly when many software threads
  - Some spinning threads get woken up
  - Possible interference with scheduling: convoy effect (very slow)

- RCL dedicates a core: it *always makes progress on the critical path*

More SW threads than HW threads

Magnycours-48

- Berkeley DB / TPC-C, Stock Level requests:



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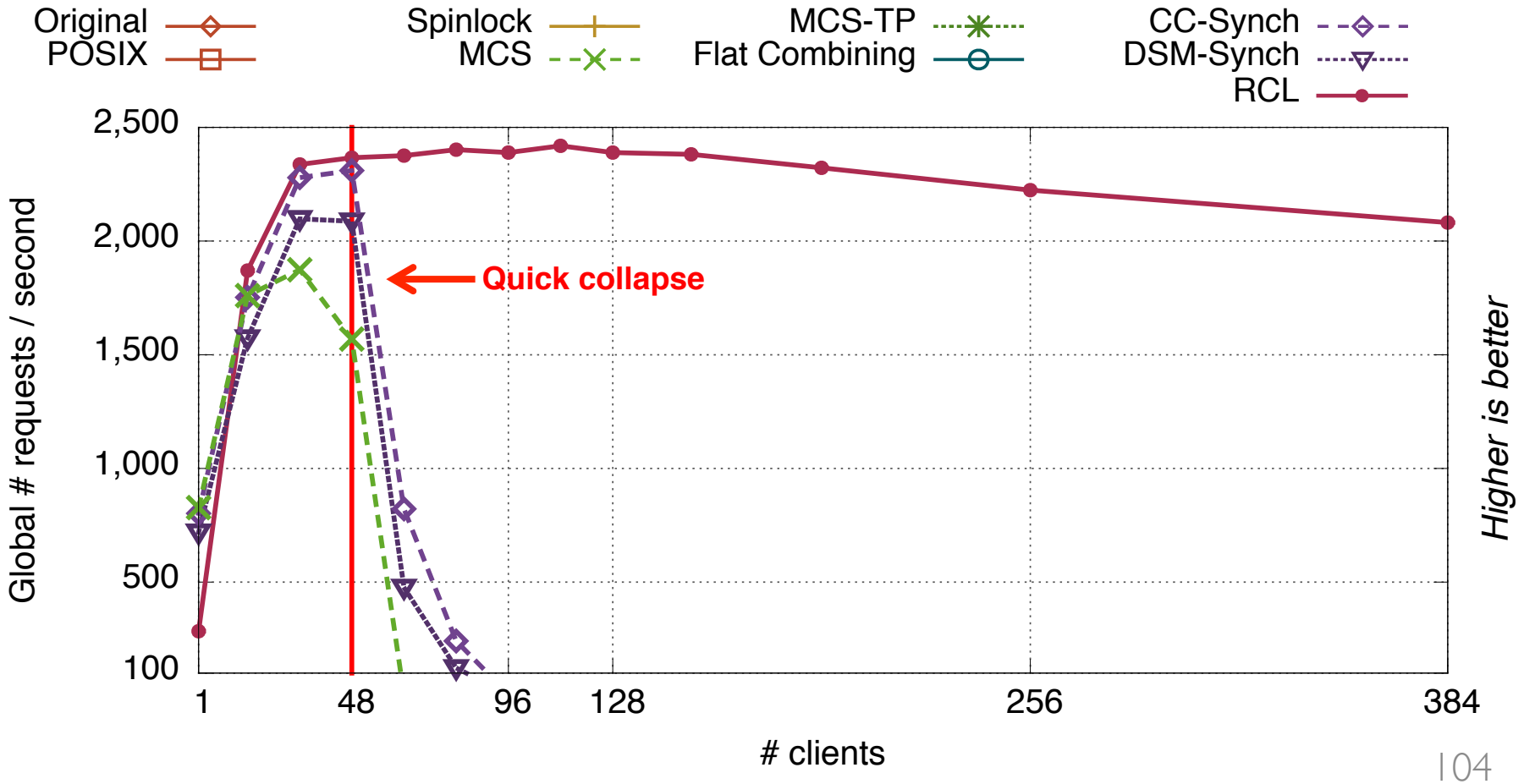

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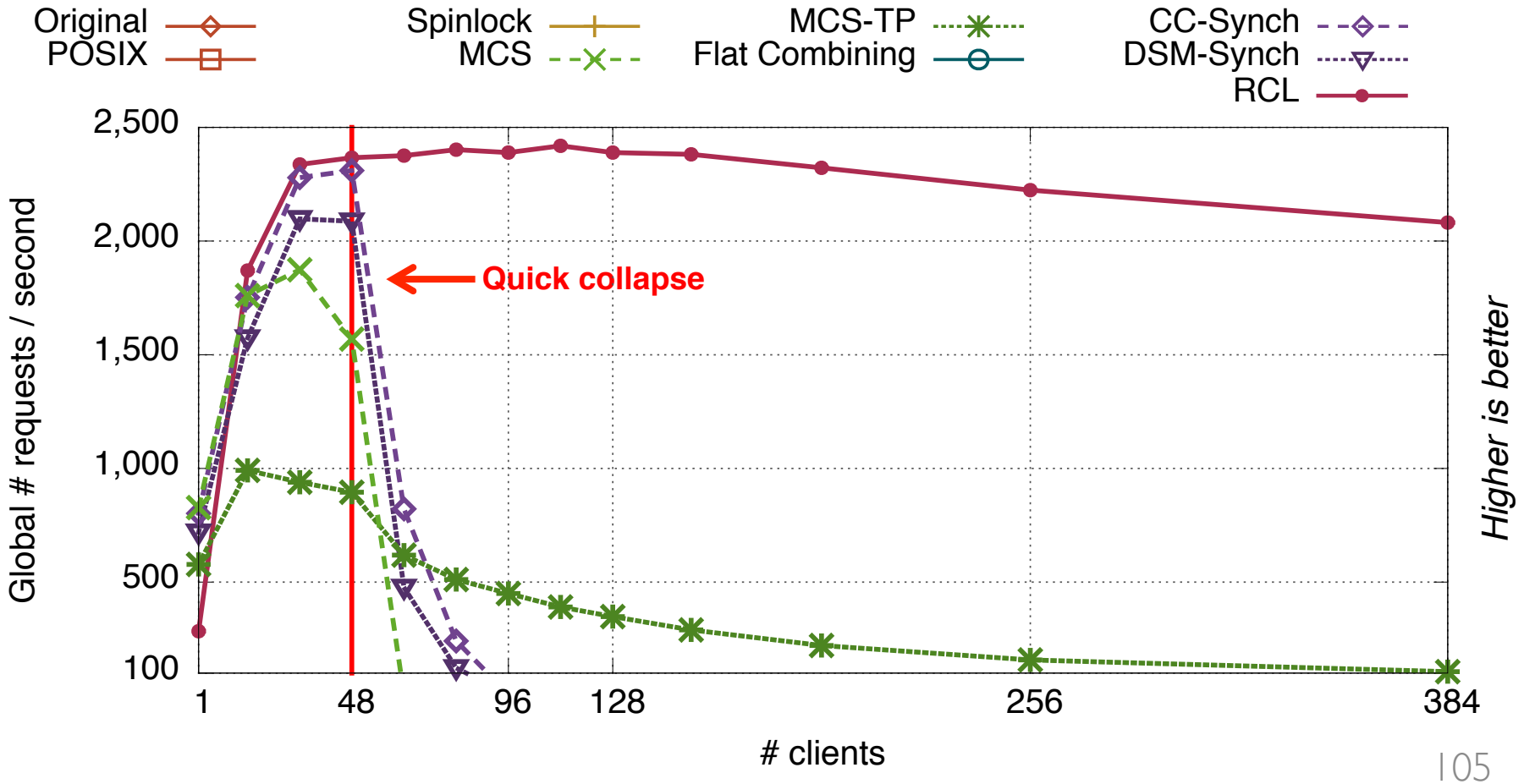
Magnycours-48

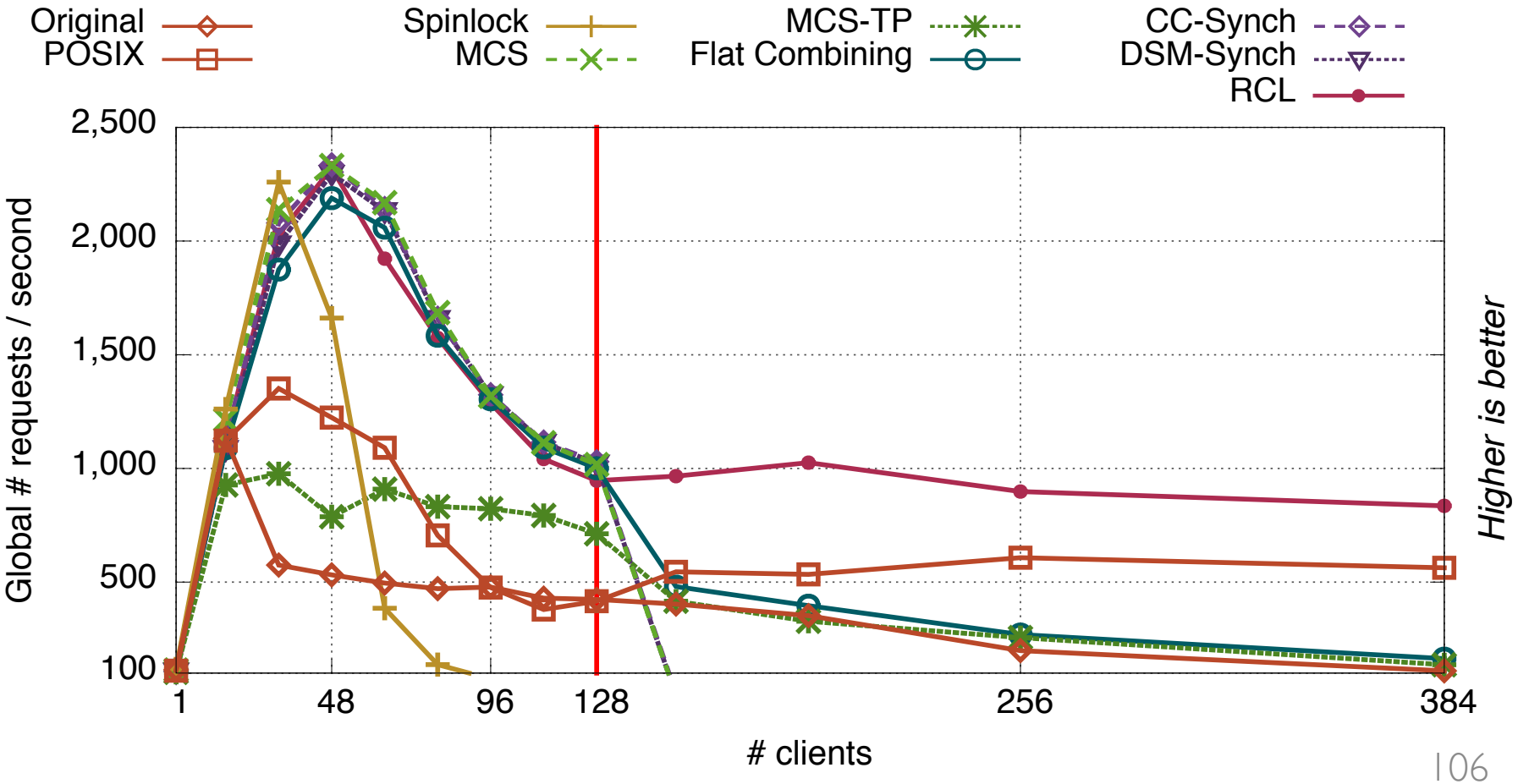
- Berkeley DB / TPC-C, Stock Level requests:



More SW threads than HW threads

Niagara2-128

- Berkeley DB / TPC-C, Stock Level requests:



Yielding the processor

Was that a fair comparison?

Yielding the processor

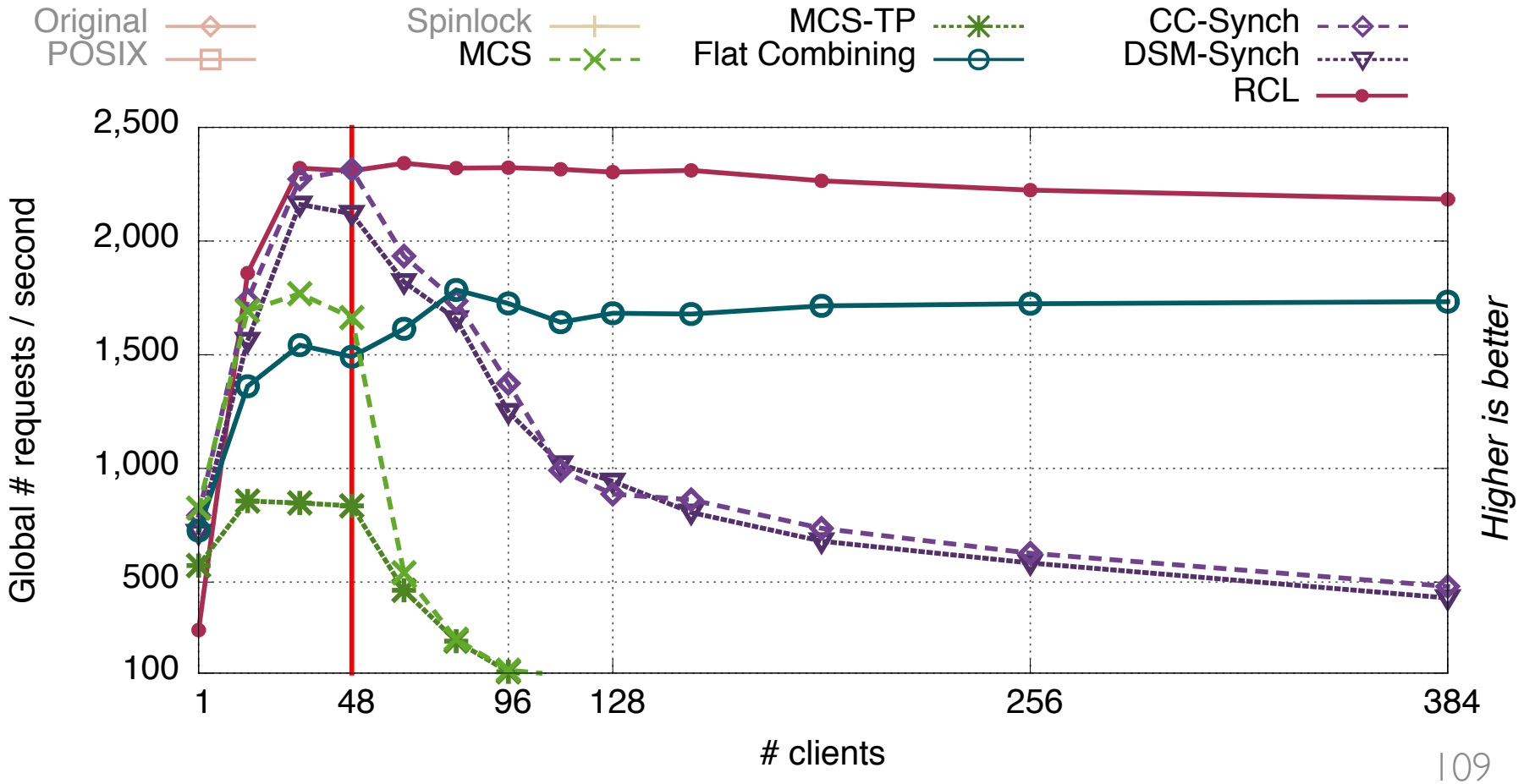
Was that a fair comparison?

- What if locks yield the CPU instead of spinning?
- Less reactive, but threads no longer woken up just to spin?
- Added calls to yield() in MCS, MCS-TP, Combining Locks
  - …and RCL clients

Yielding the processor

Magnycours-48

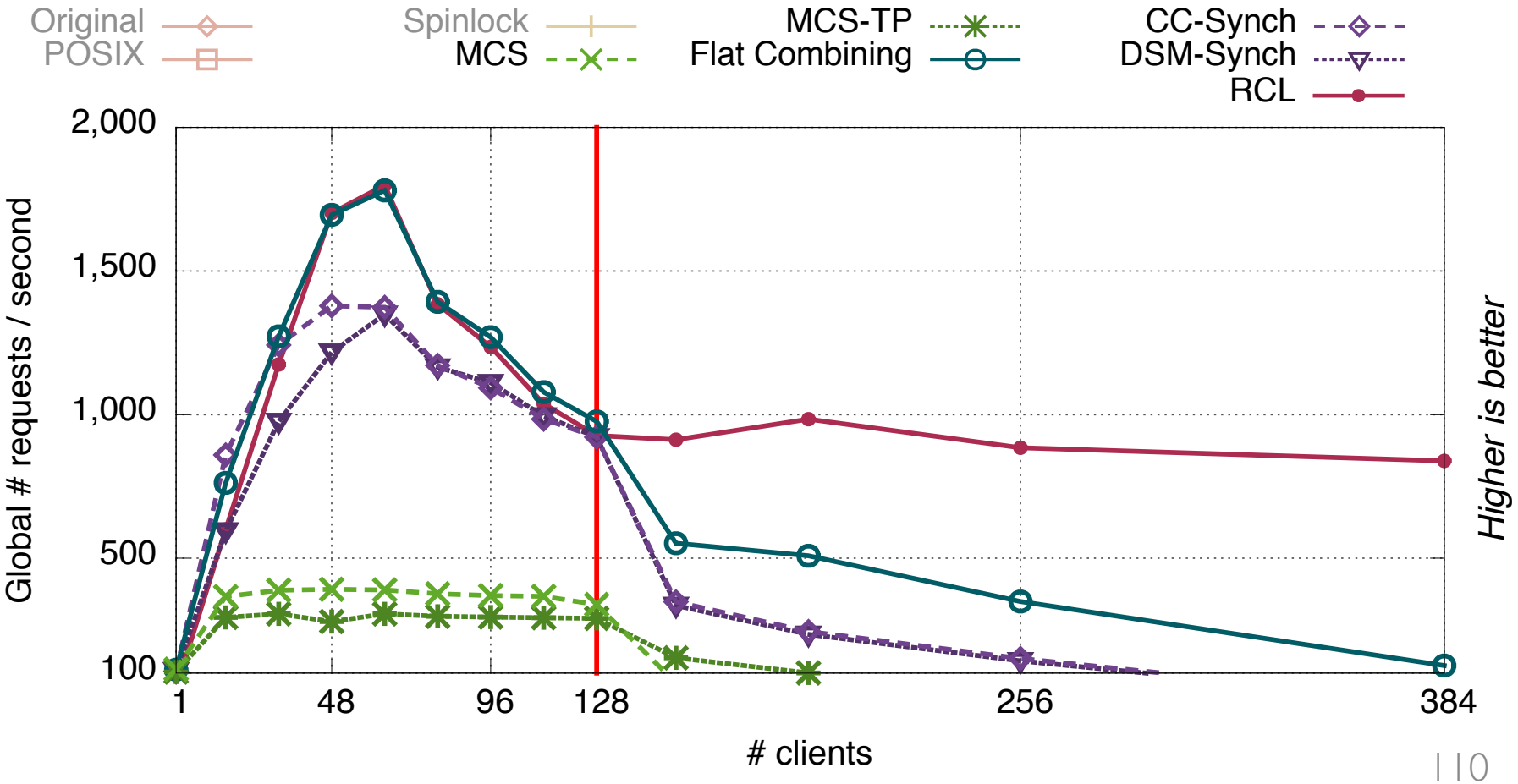
- Berkeley DB / TPC-C, Stock Level requests, yield():



Yielding the processor

Niagara2-128

- Berkeley DB / TPC-C, Stock Level requests, yield():



Outline

- Context: multicore architectures
- State of the art: locks
- Contribution: Remote Core Locking
- Evaluation in legacy applications
- **Perspectives and conclusion**

Perspectives

- Modified RCL implementations
  - Dynamic RCL runtime
  - Hierarchical RCL
  - RCL for embedded architectures

- HTMs: supported by Haswell
  - What can RCL do for transactional memories?
  - Hassan et al. [IPDPS '14] propose a STM algorithm…
    - …that runs commit and invalidation on dedicated remote server threads
    - …with cache-aligned communication
    - …and uses RCL for locks

Perspectives

- Non-cache-coherent architectures
  - Could RCL provide performance improvements on non-cache-coherent architectures?
  - Petrović et al. [PPoPP '14] propose an algorithm inspired by RCL for partially cache-coherent architectures
  - Major performance improvements on TILE-Gx CPUs.

Conclusion

- RCL reduces lock acquisition time and improves data locality
  - Cost: uses a few cores and may perform worse with few threads
- Profiler to detect when RCL can be useful
- Tool to ease the transformation of legacy code
- Future work:
  - Modified RCL implementations
  - Applying ideas from RCL to HTMs and NCC architectures
  - Started by others