Callisto-RTS: Fine-Grain Parallel Loops

Tim Harris, Oracle Labs
Stefan Kaestle, ETH Zurich

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Setting: parallel loops on shared-memory machines

```
for (uint64_t node = 0; node < G.num_nodes(); node++) {
    double val = 0.0;
    for (edge_t w_idx = G.r_begin[node];
          w_idx < G.r_begin[node+1];
          w_idx ++)  {
       node_t w = G.r_node_idx [w_idx];
       val += G_pg_rank[w] / (G.begin[w+1] - G.begin[w]);
    }
    G_pg_rank_nxt[node] = (1 - d) / N + d * val;
}
```

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Loop index type and bounds

Loop body (C++ lambda)

Batch size / load imbalance trade-off

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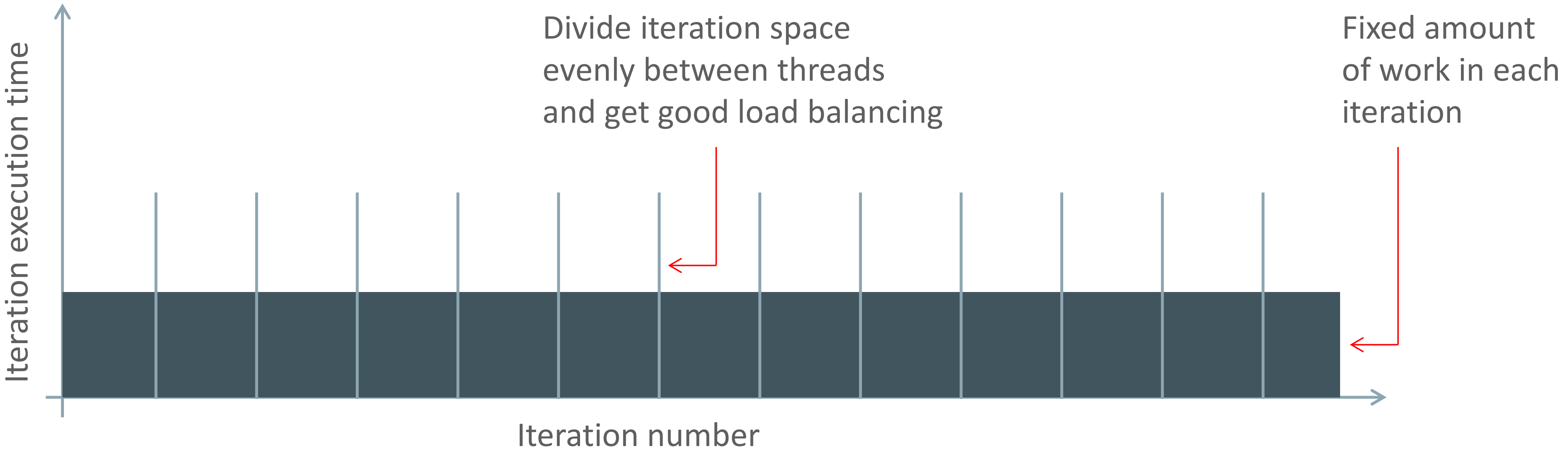

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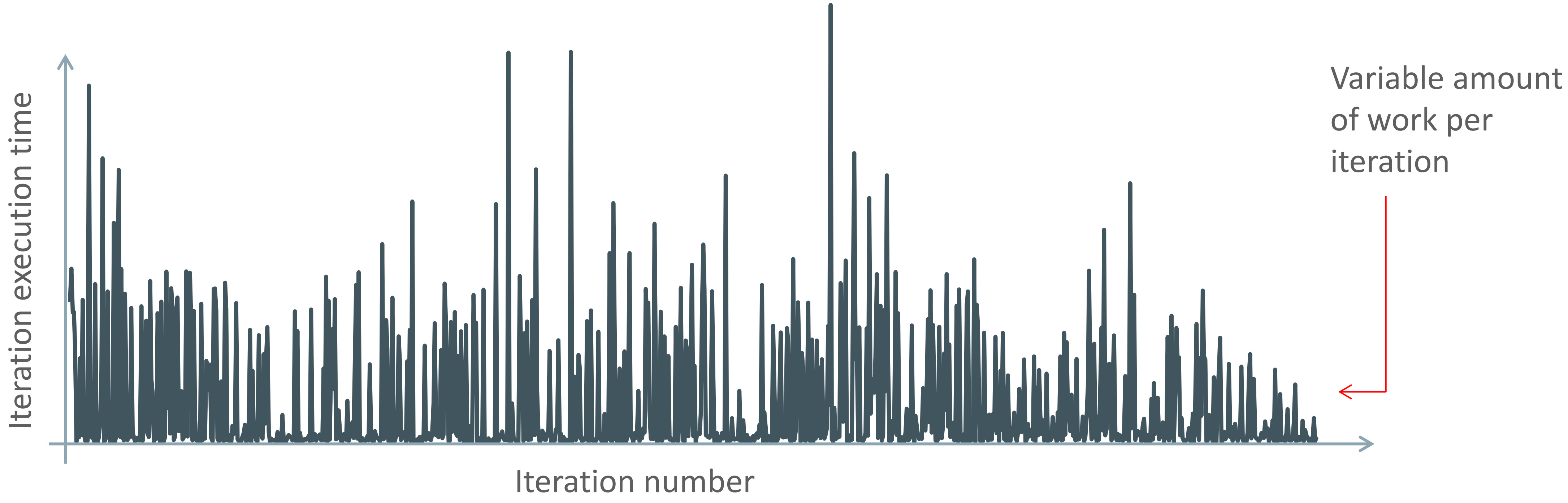


(Actual data – #out-edges of the top 1000 nodes in the SNAP Twitter dataset)

Batch size / load imbalance trade-off

Divide into large batches

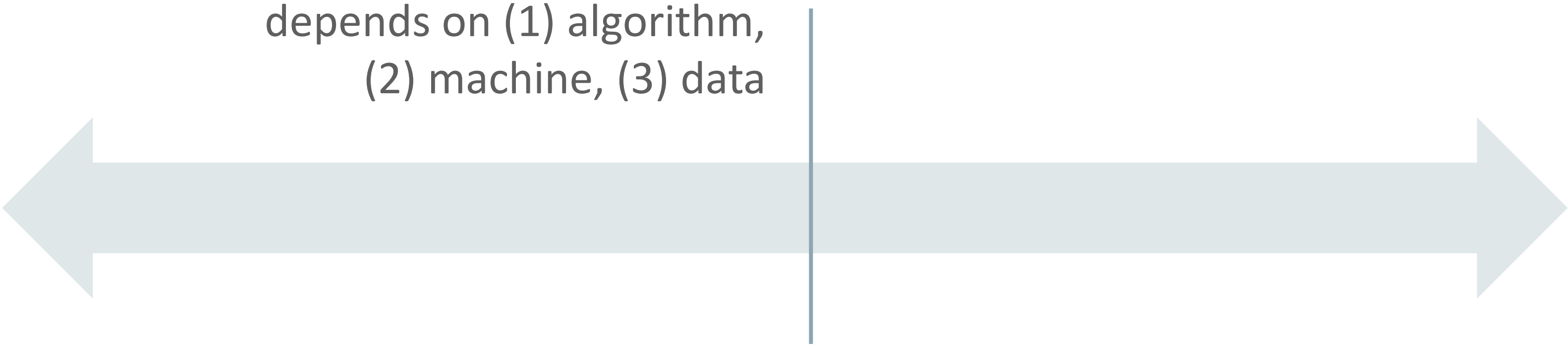
Reduce contention distributing work
Risk load imbalance

Divide into small batches

Increase contention distributing work
Achieve better load balance

Batch size / load imbalance trade-off

Typically, choose manually –
but getting this right
depends on (1) algorithm,
(2) machine, (3) data



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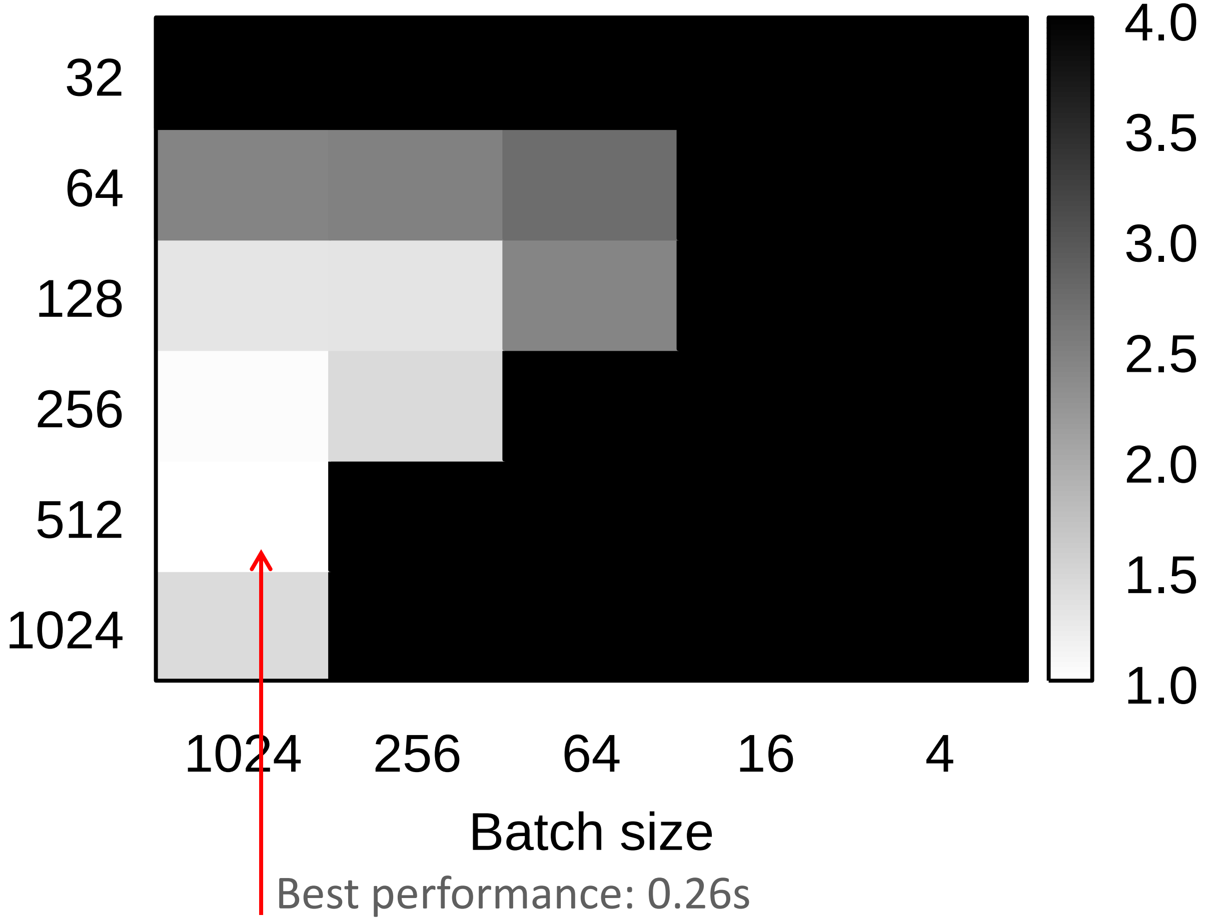
Example performance

OpenMP static & dynamic loops



8-socket SPARC T5
16 cores per socket
8 h/w threads per core

PageRank
SNAP LiveJournal data set

Batch size / load imbalance trade-off

Typically, choose manually – but getting this right depends on (1) algorithm, (2) machine, (3) data

Our approach: support efficient small batches

Divide into large batches

Reduce contention
Risk load imbalance

Divide into small batches

Increase contention distributing work
Achieve better load balance

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Overview

1. Request combining
2. Asynchronous work requests
3. Non-work-conserving nested loops
4. Results

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Approach, consider a loop 0..65536, batch size 8

8 sockets

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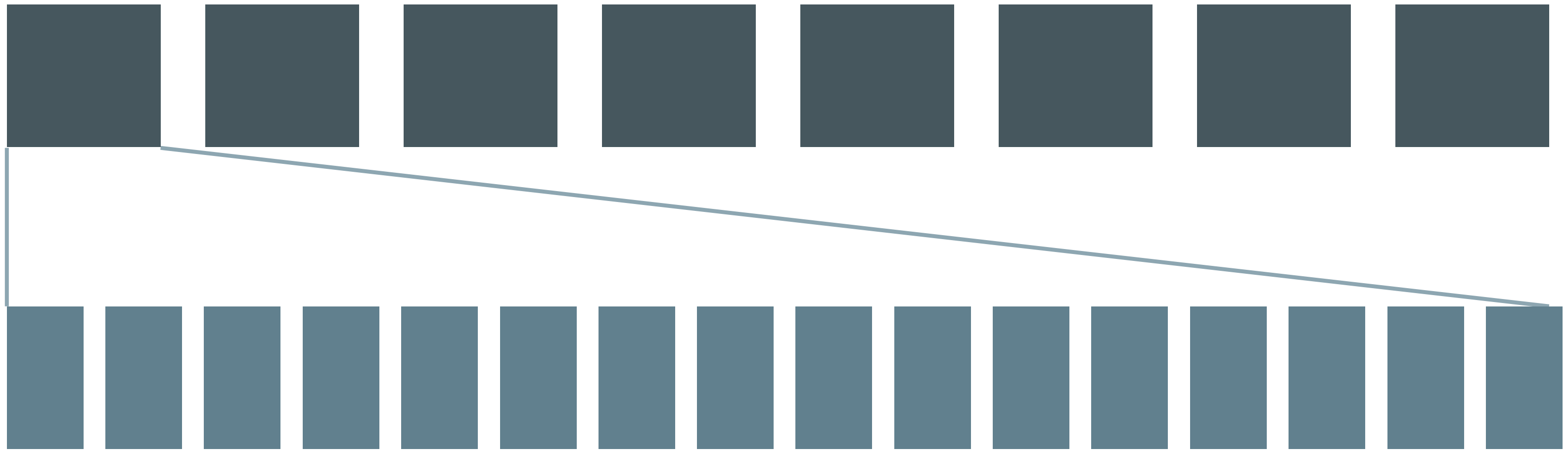

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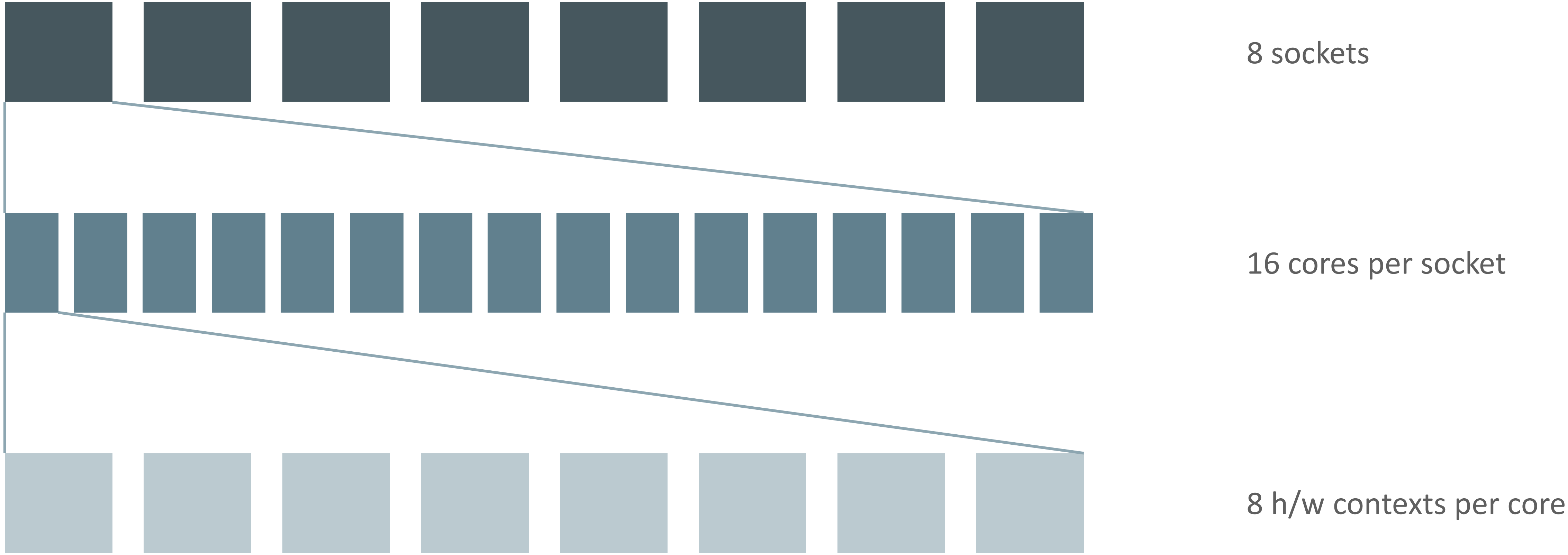

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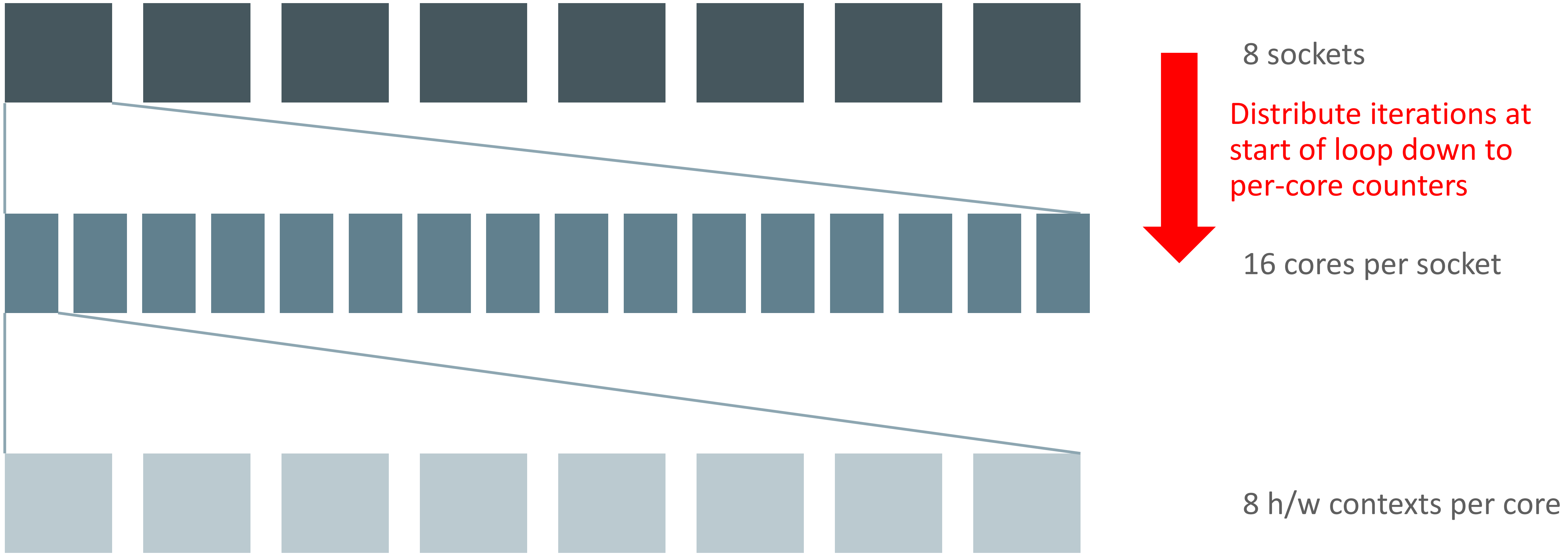

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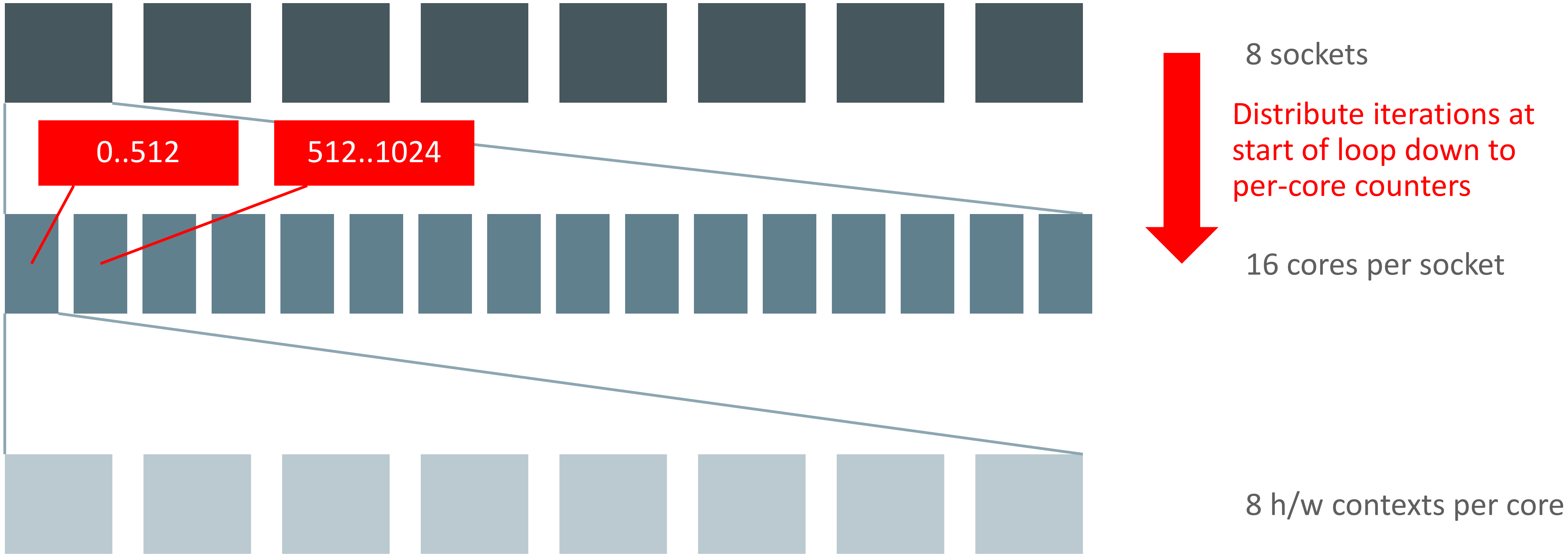

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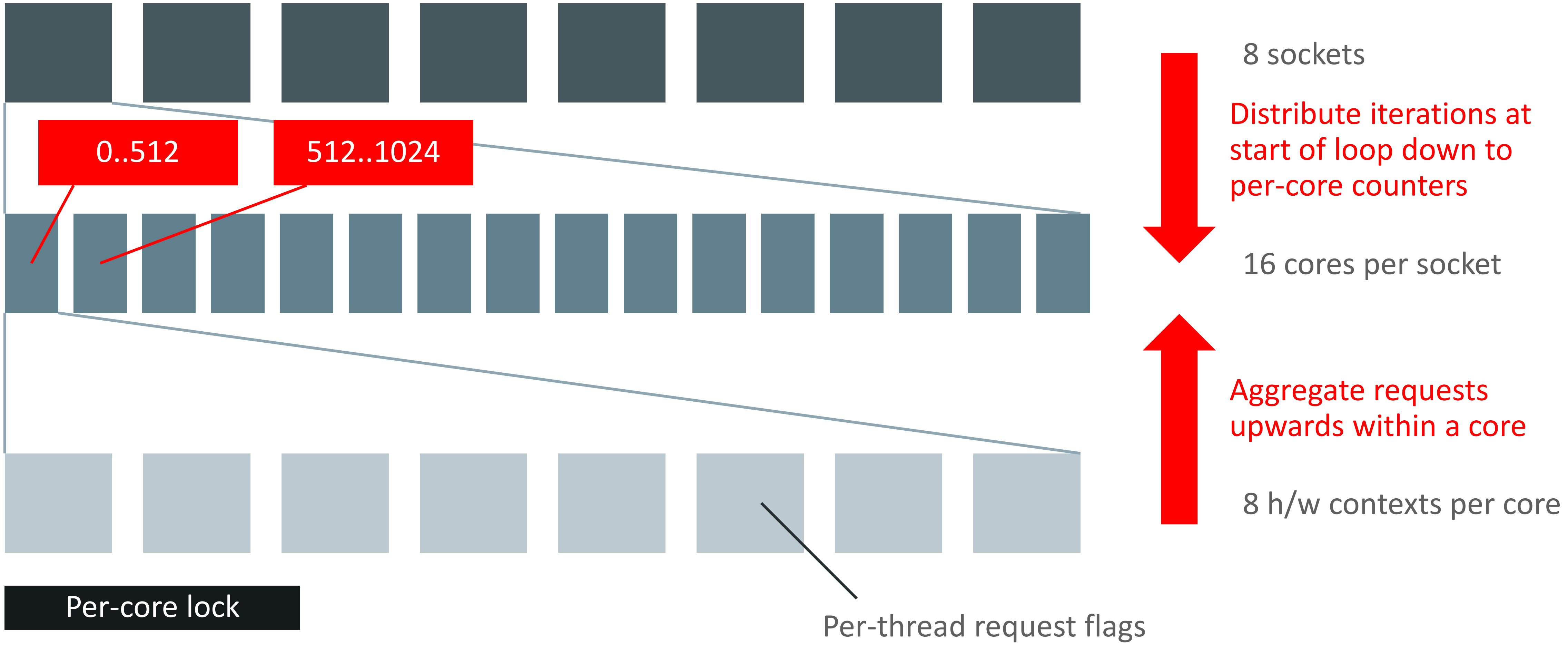

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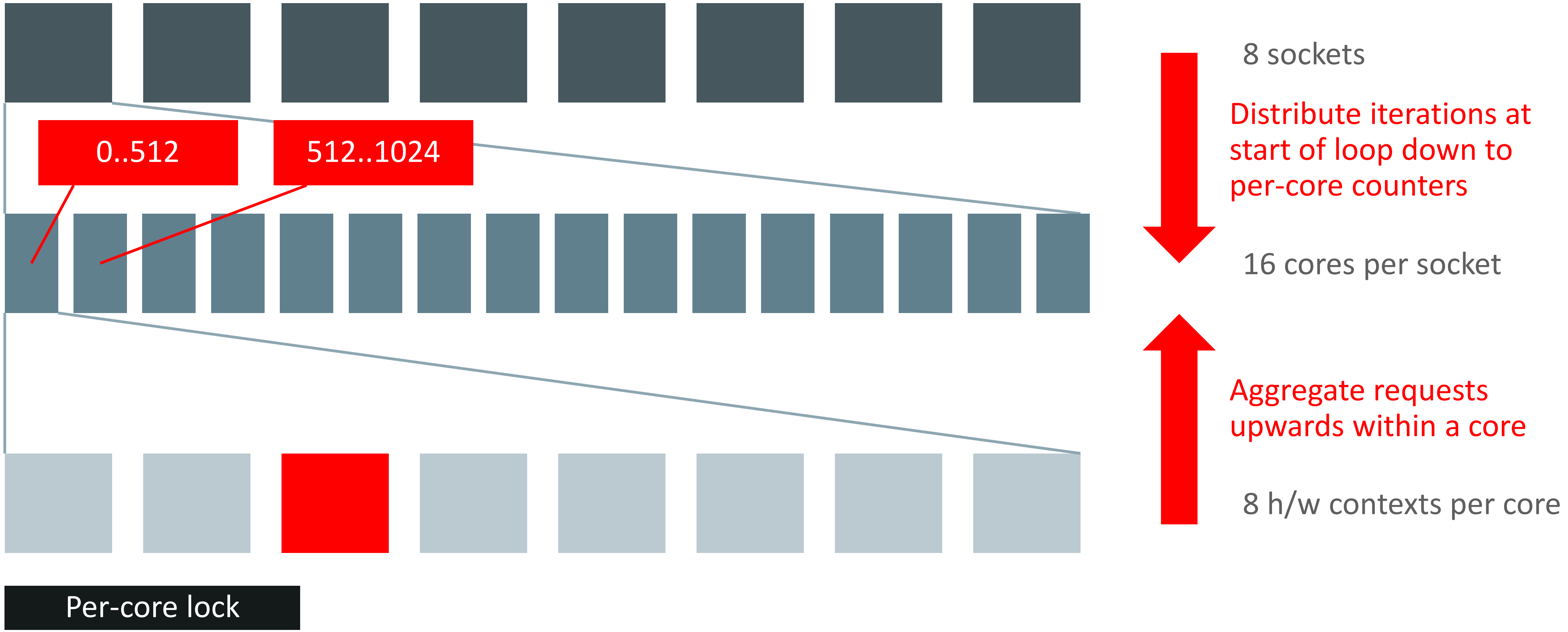

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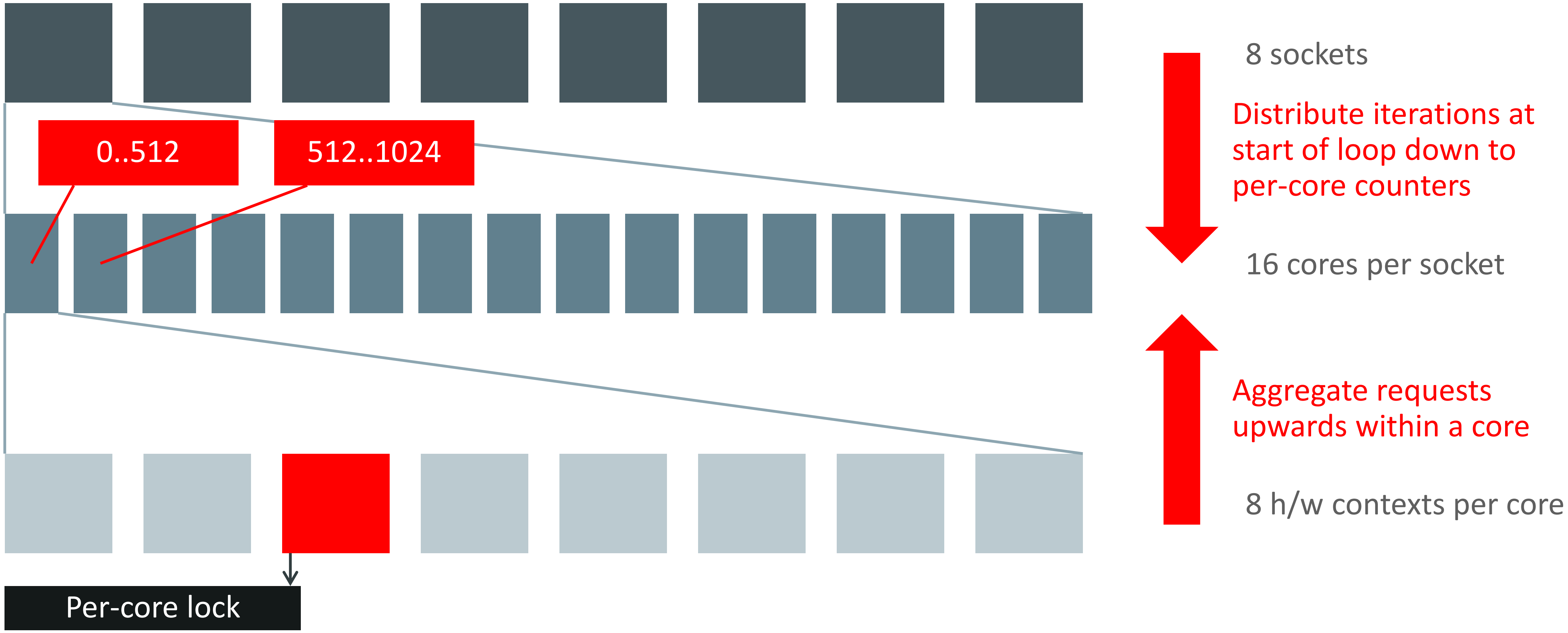

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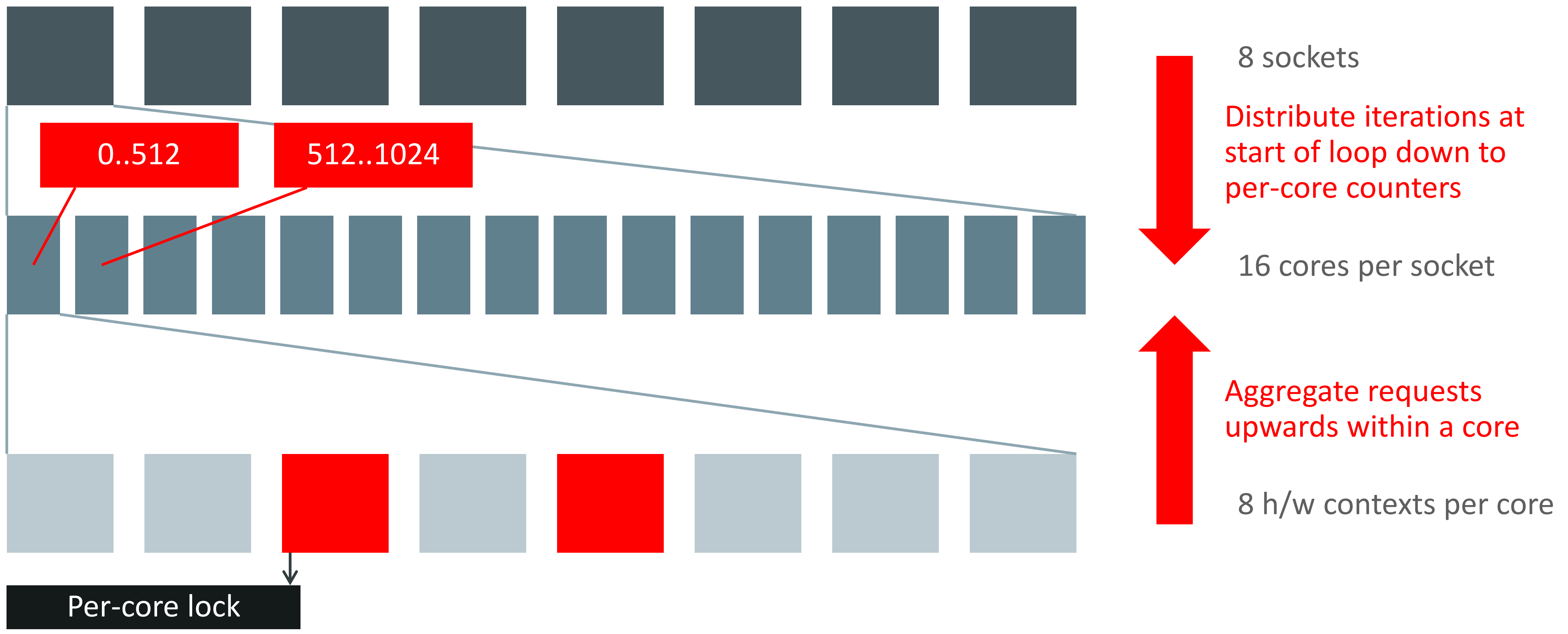

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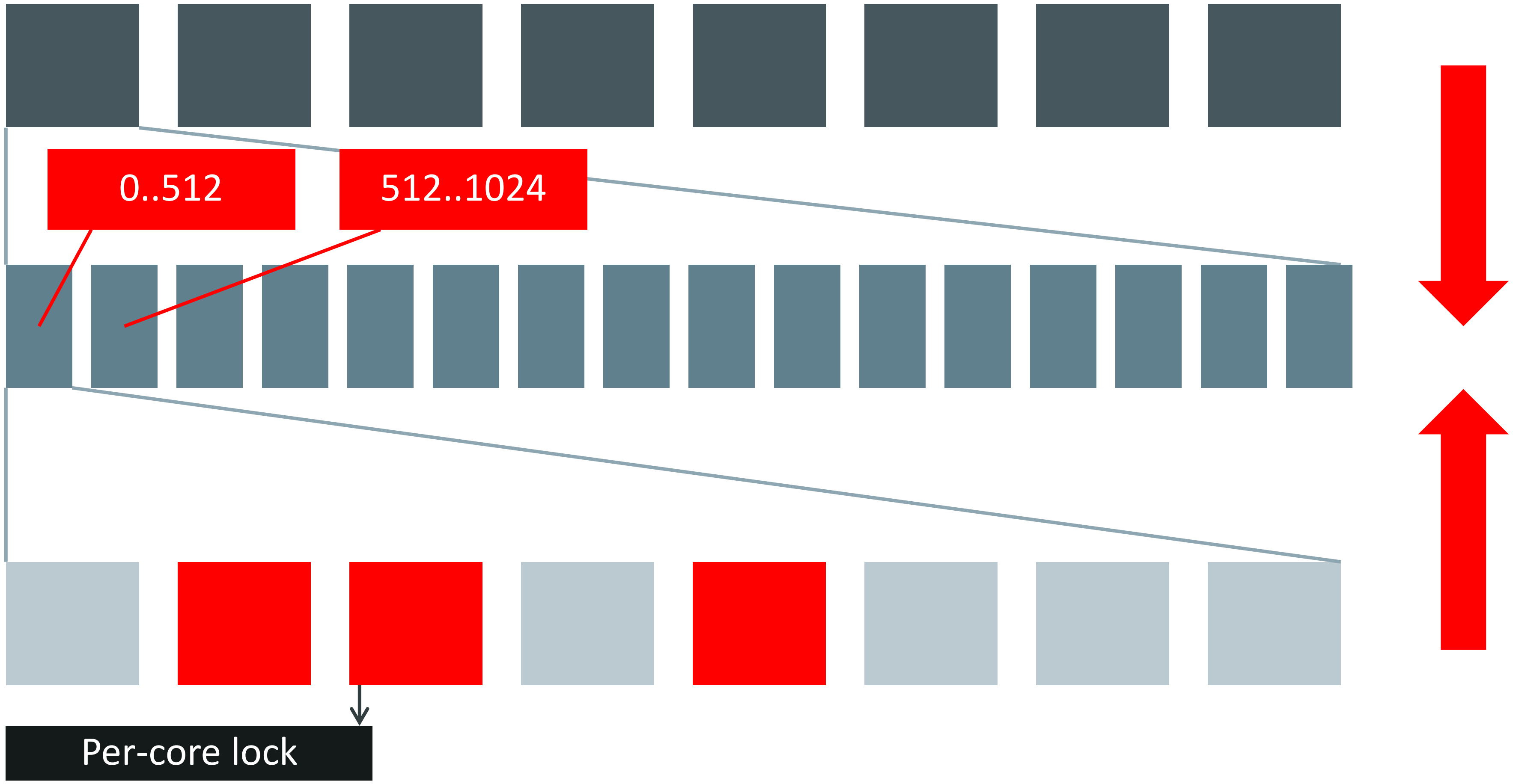


8 sockets

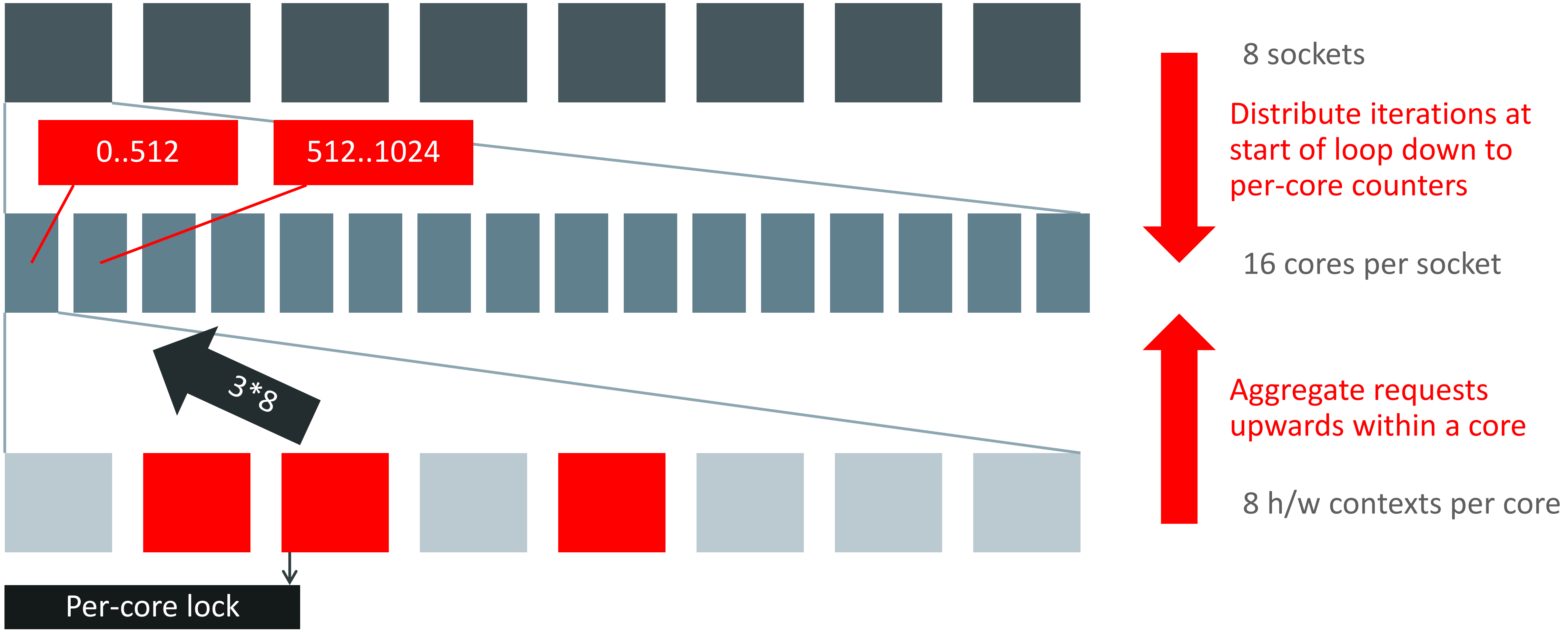
Distribute iterations at start of loop down to per-core counters

16 cores per socket

Aggregate requests upwards within a core

8 h/w contexts per core

Approach, consider a loop 0..65536, batch size 8



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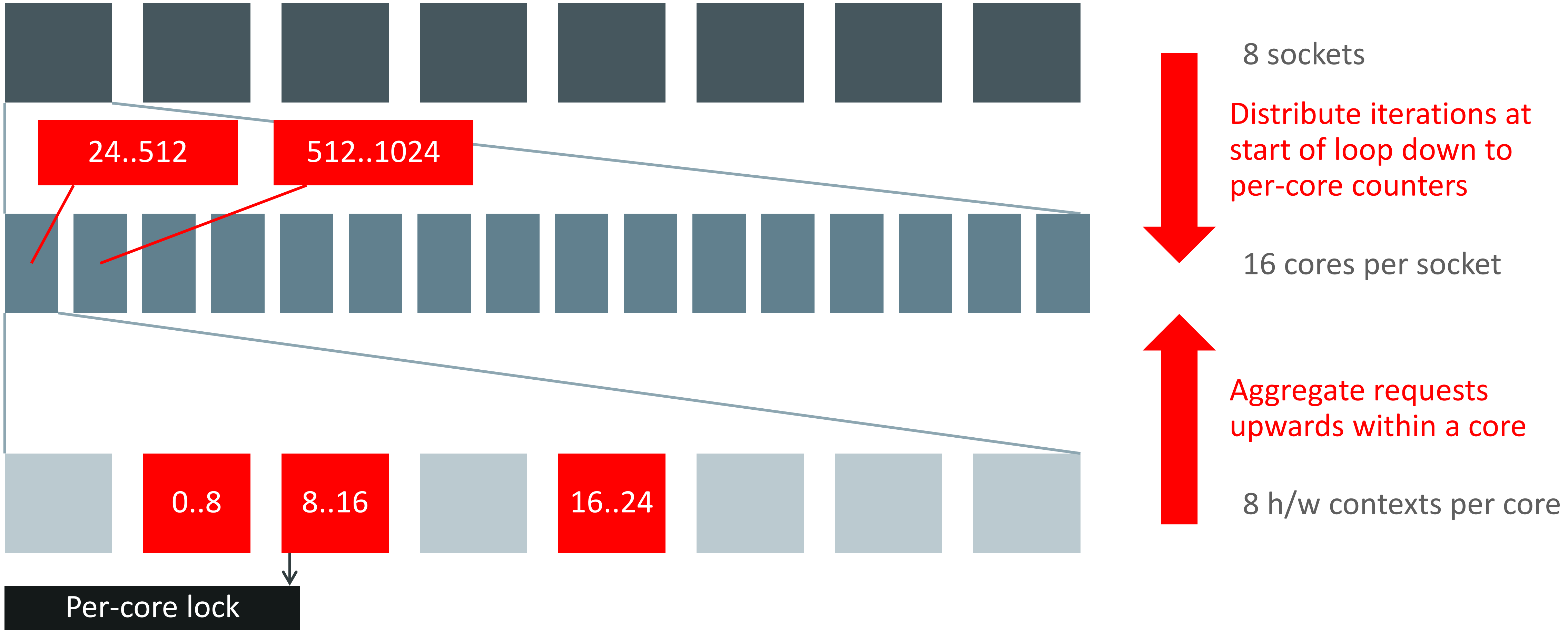

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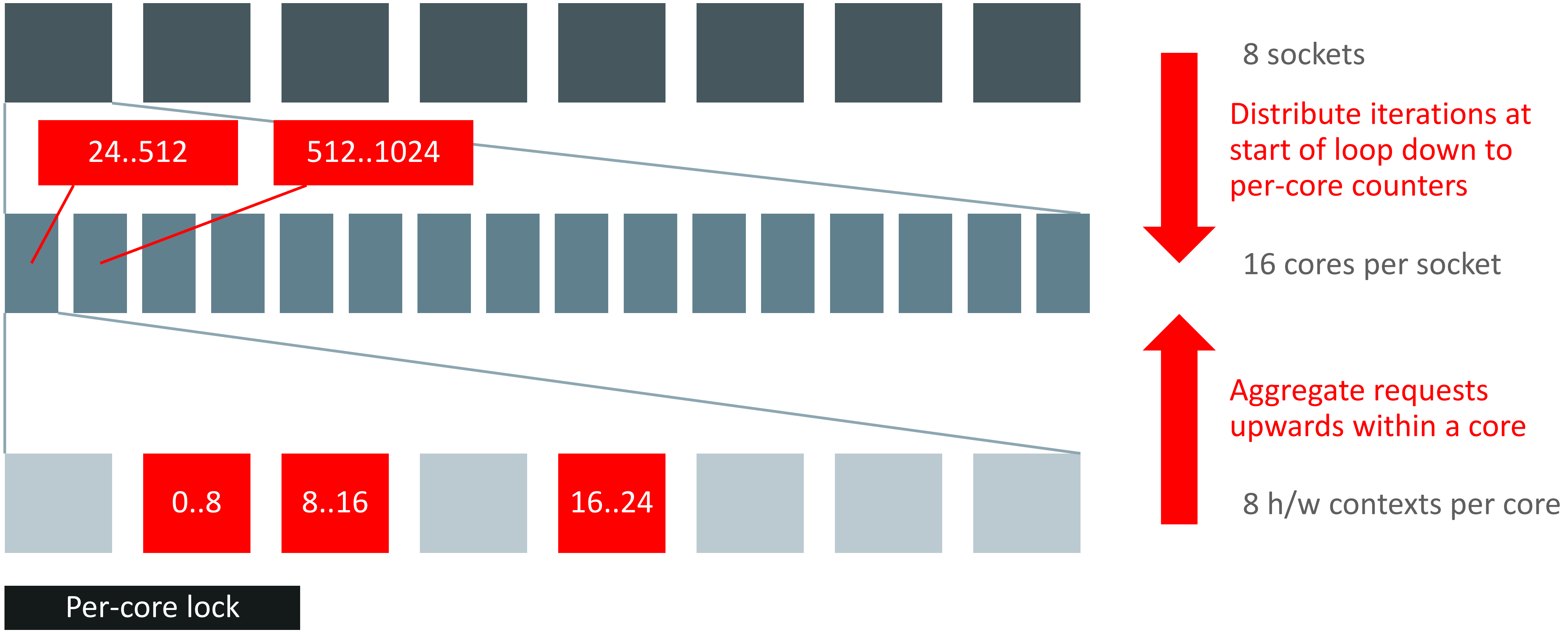

Hierarchical distribution with request combining

- Combining implemented over flags in a single line in the shared L1 D$
- On TSO: no memory fences
- Synchronization remains core-local if work is evenly distributed
- Threads waiting for combining can use mwait

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Asynchronous combining of requests

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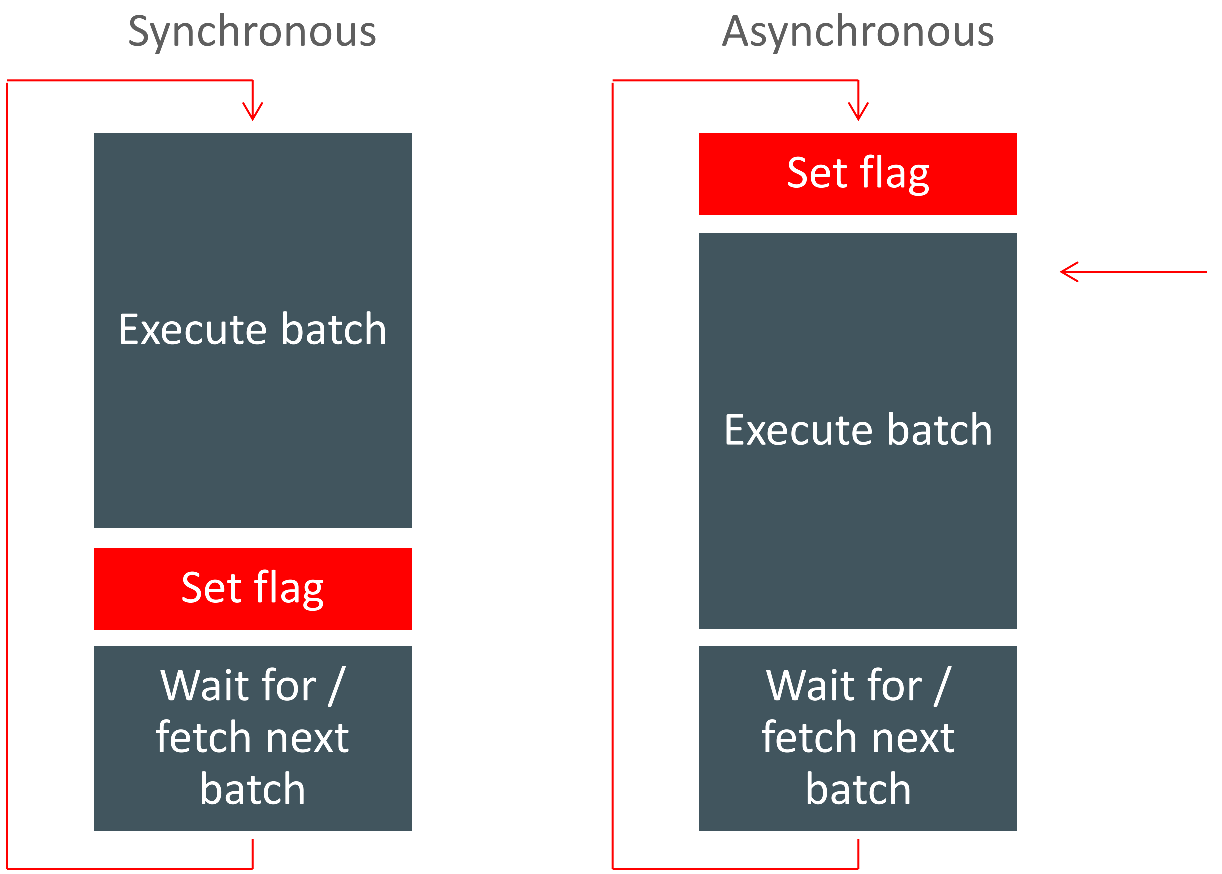

Intuition: the time taken to execute the current batch provides an opportunity for other cores to service our request without us needing to wait

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Nested loops

- Abundant parallelism, why use nesting?

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Nested loops

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- Contention between iterations of an outer loop
- E.g., betweenness-centrality:
  - Iterate over vertices
  - BFS traversal from each vertex (plus additional work)

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↑

Better cache locality within each traversal
than between (unrelated) traversals

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Nested loops

- Abundant parallelism, why use nesting?
- Contention between iterations of an outer loop
- E.g., betweenness-centrality:
  - Iterate over vertices
  - BFS traversal from each vertex (plus additional work)

Better cache locality within each traversal than between (unrelated) traversals → Run at most one of these per L2 D$

Nested loops

Controlling thread -> loop allocation

- Number loops “inside out”
  - Level 0 => innermost
  - Level 1 => may contain a level-0 loop
- Each thread also has a level
  - It will execute iterations <= its own level
  - Level 0 thread: only executes inner-most loop iterations
  - …

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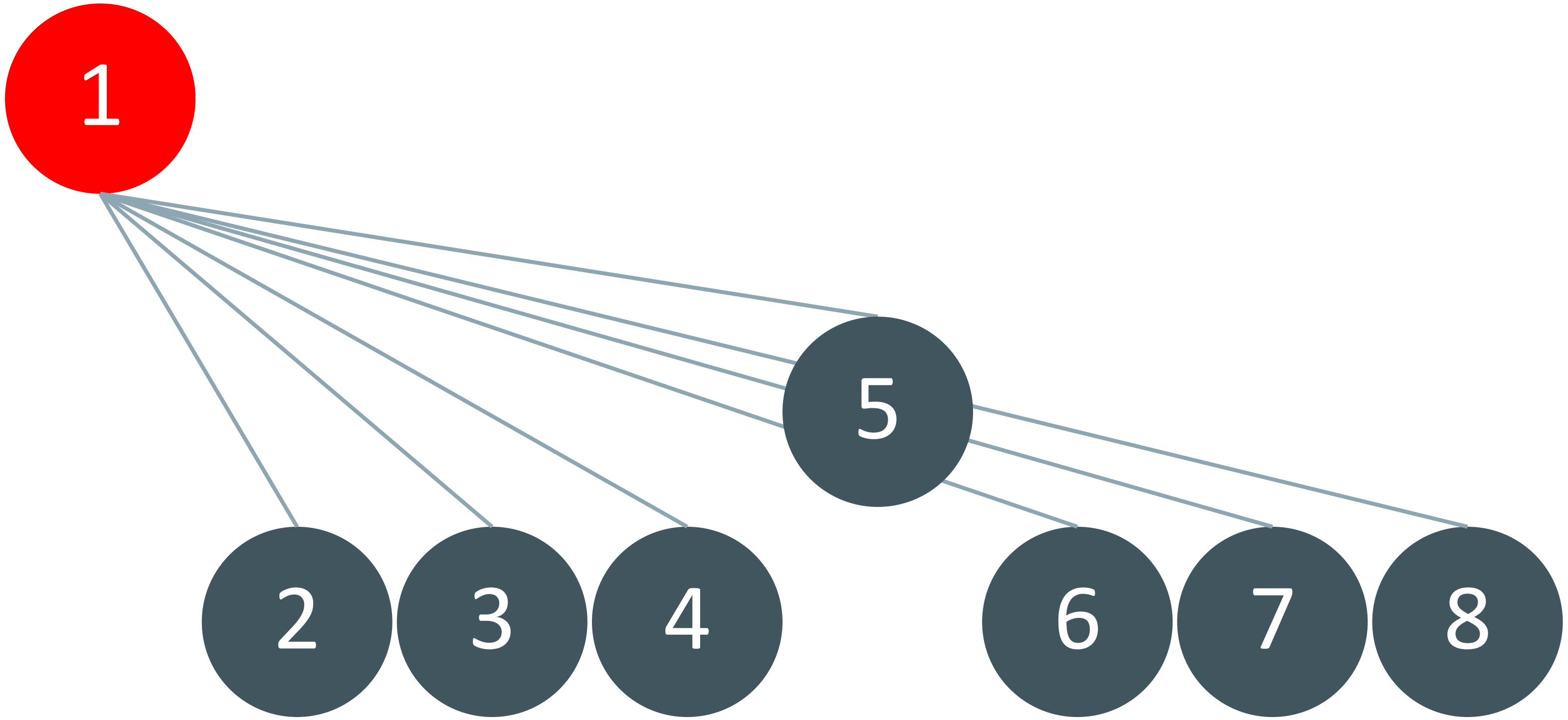
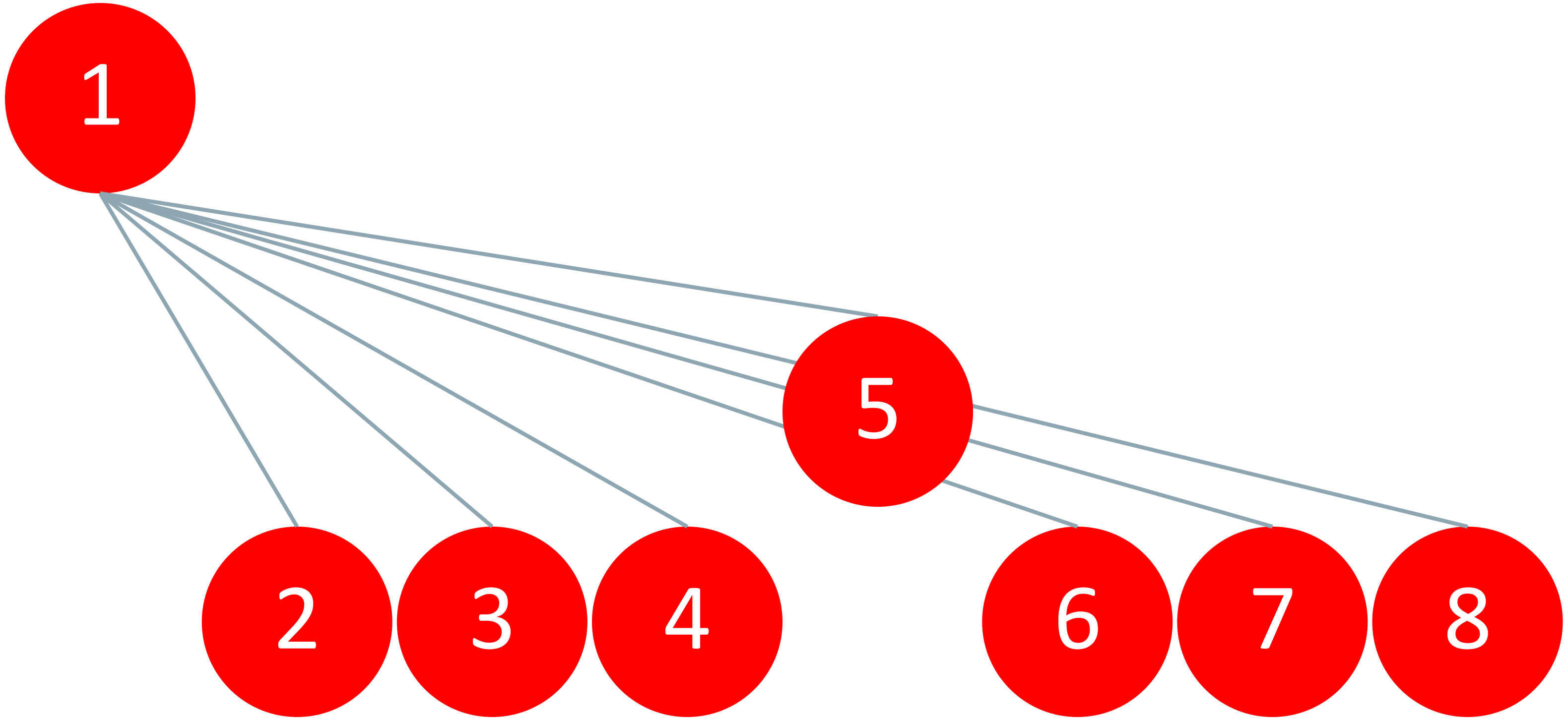
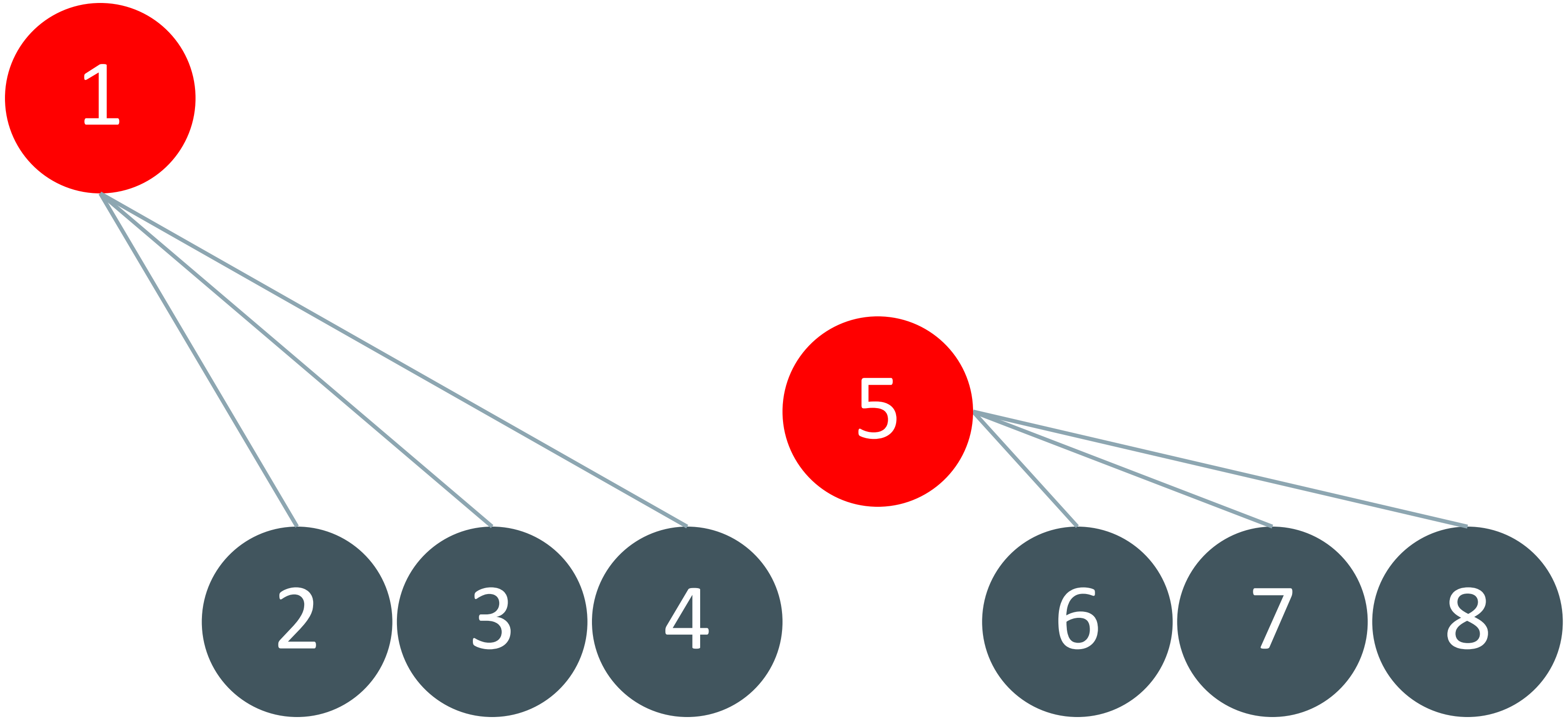
Nested loops



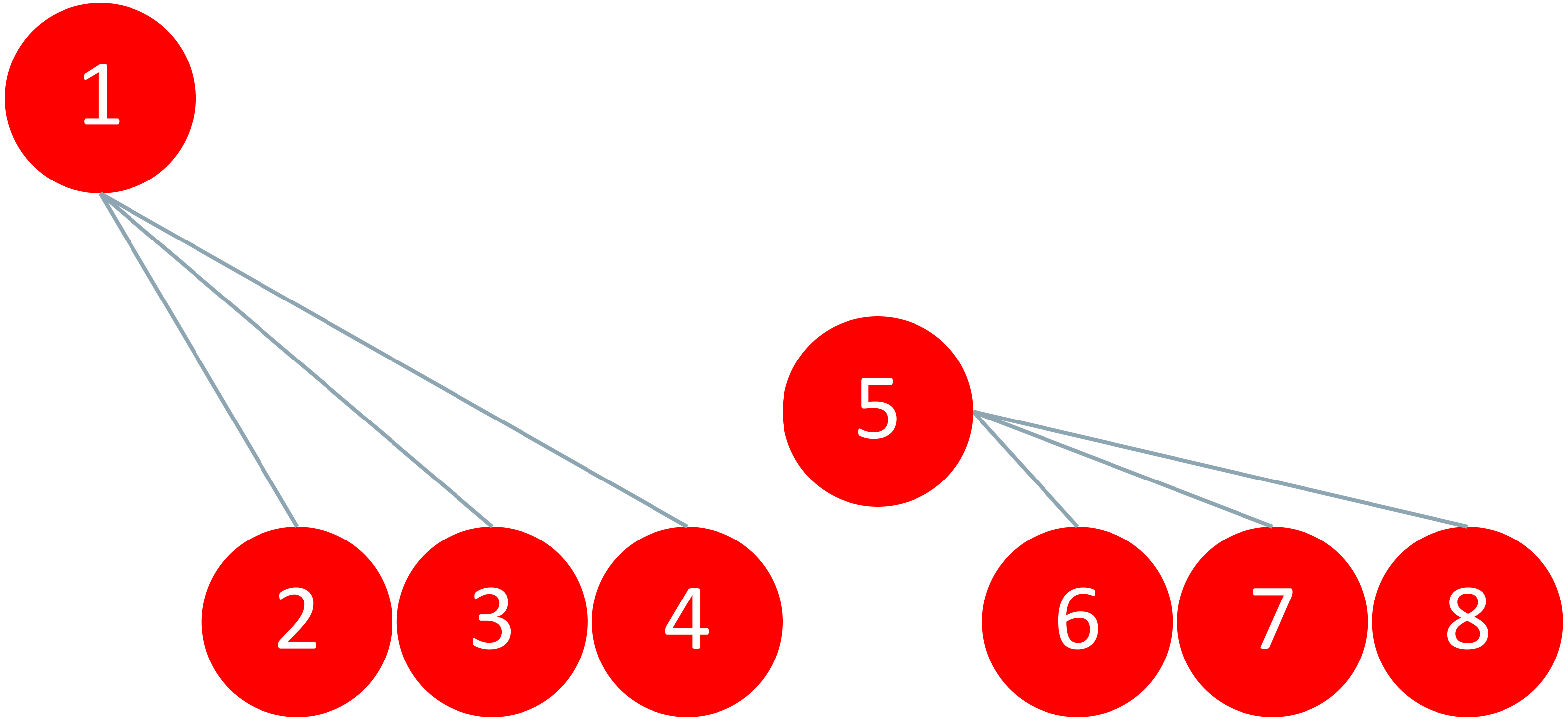
Nested loops: non-nested level 0 – all threads participate



Nested loops: outer (level 1) – just 1+5 participate



Nested loops: inner (level 0) –help respective leaders



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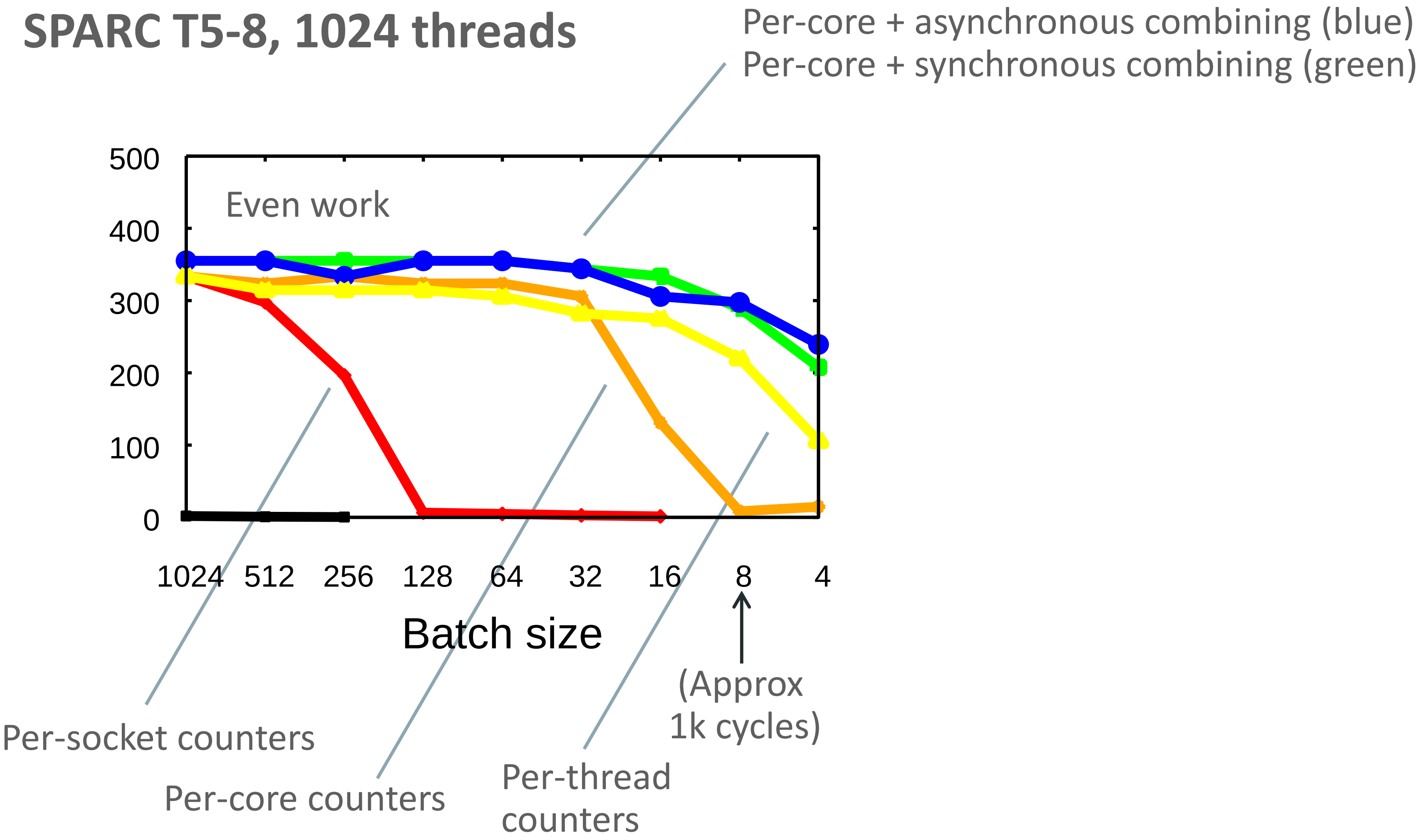
Microbenchmark results

SPARC T5-8, 1024 threads



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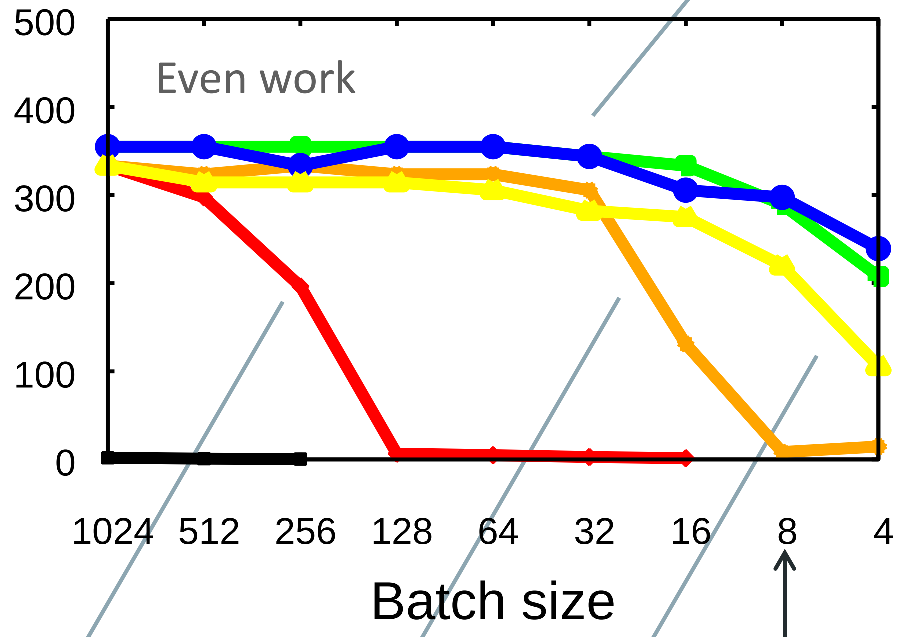
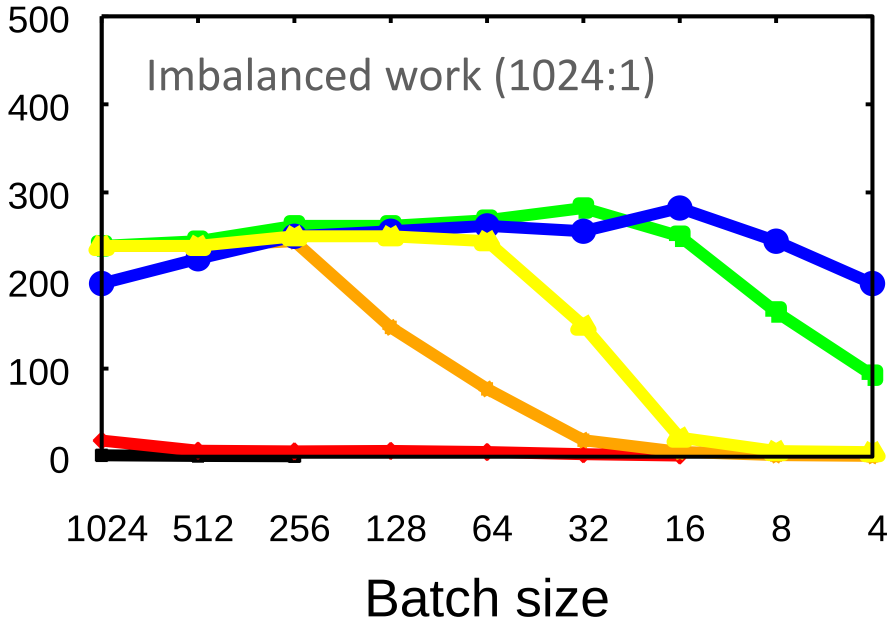
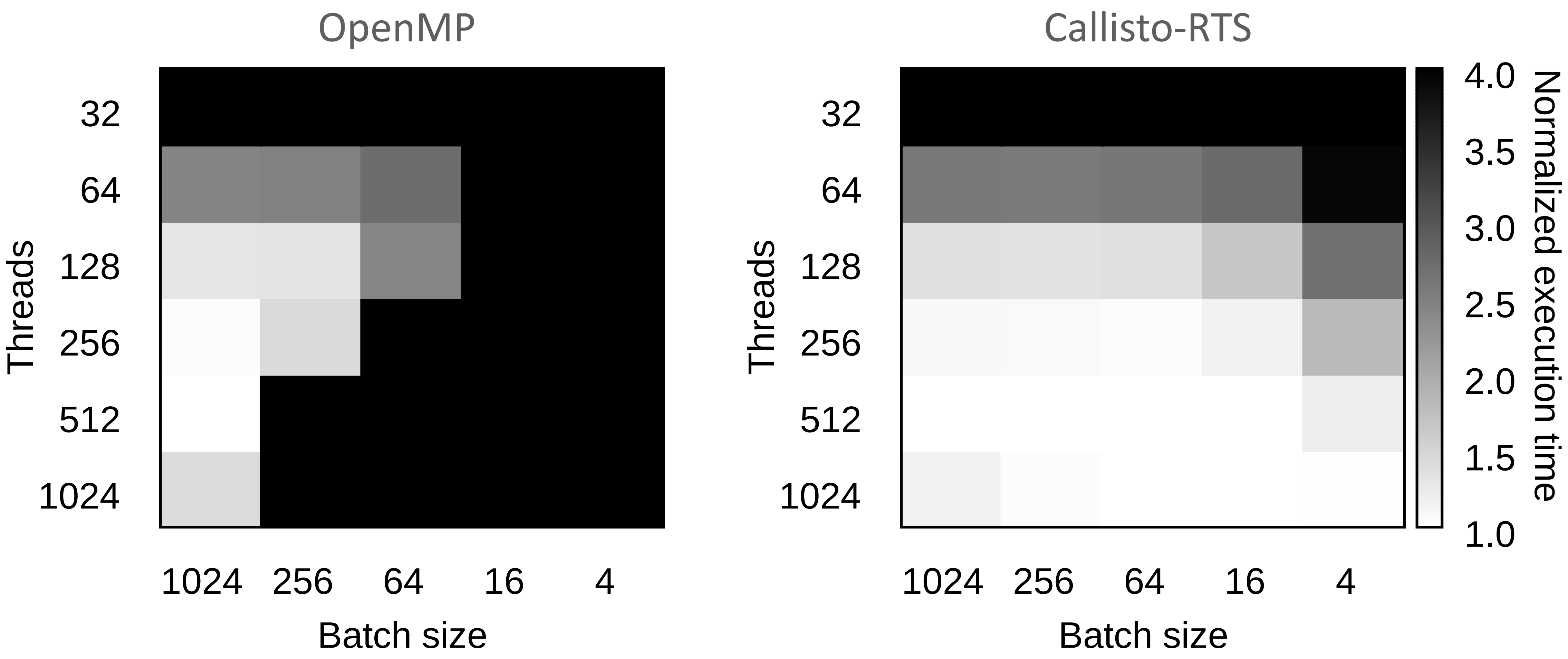




PageRank – SNAP LiveJournal (4.8M vertices, 69M edges)



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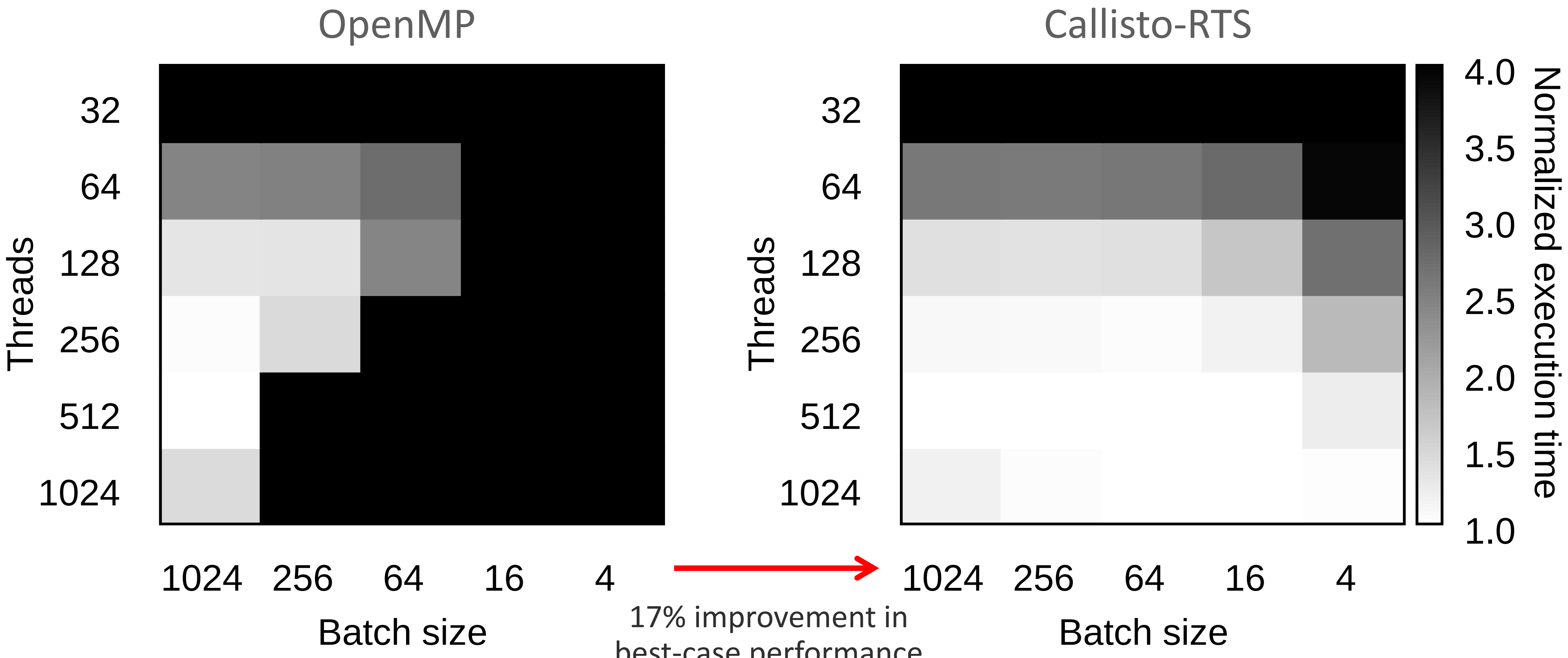

17% improvement in best-case performance

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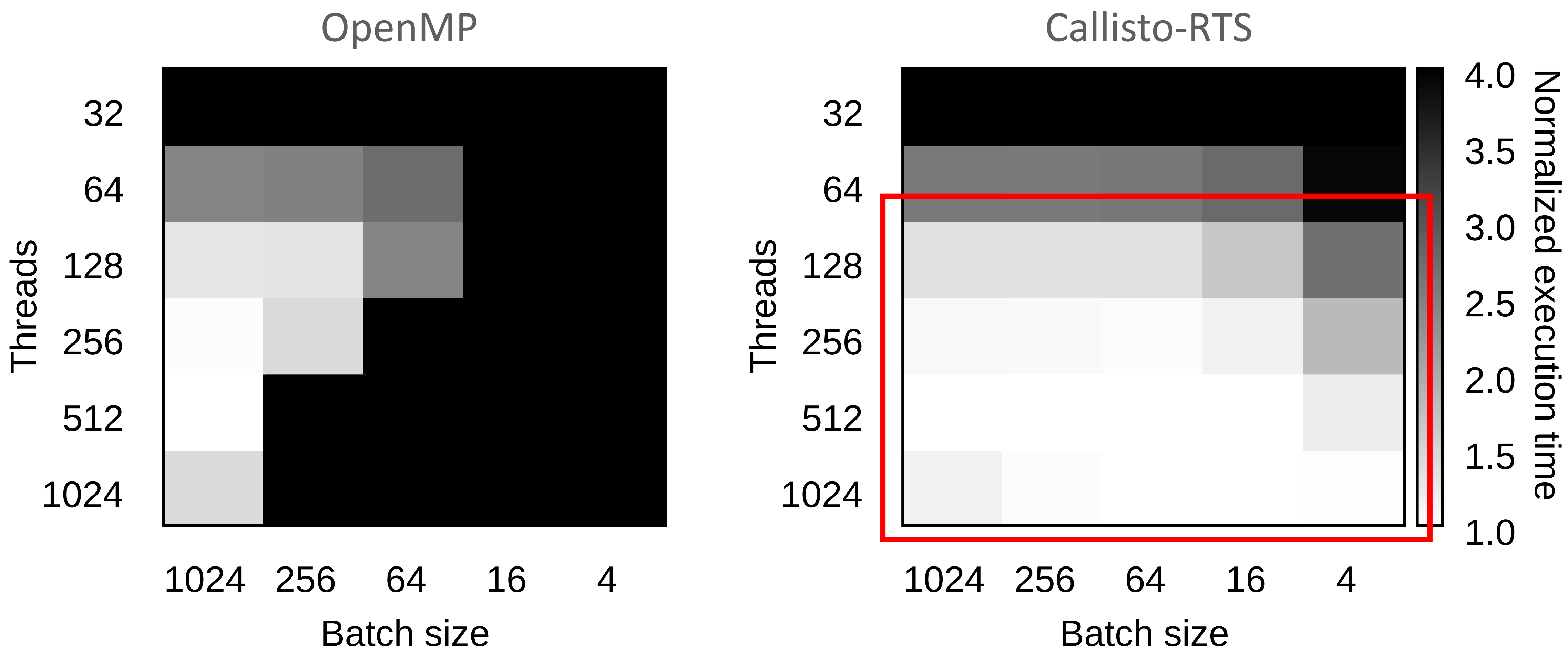
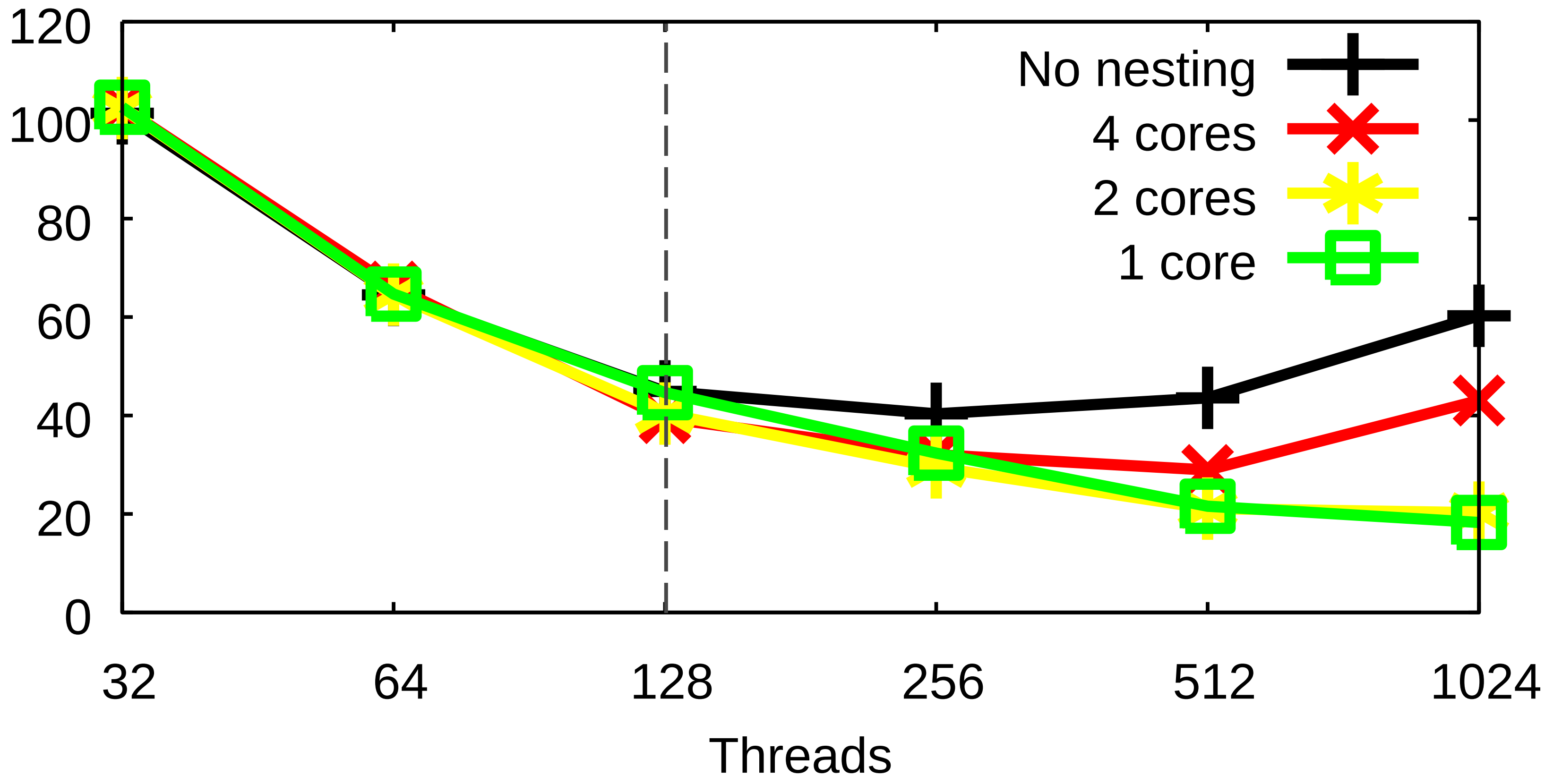


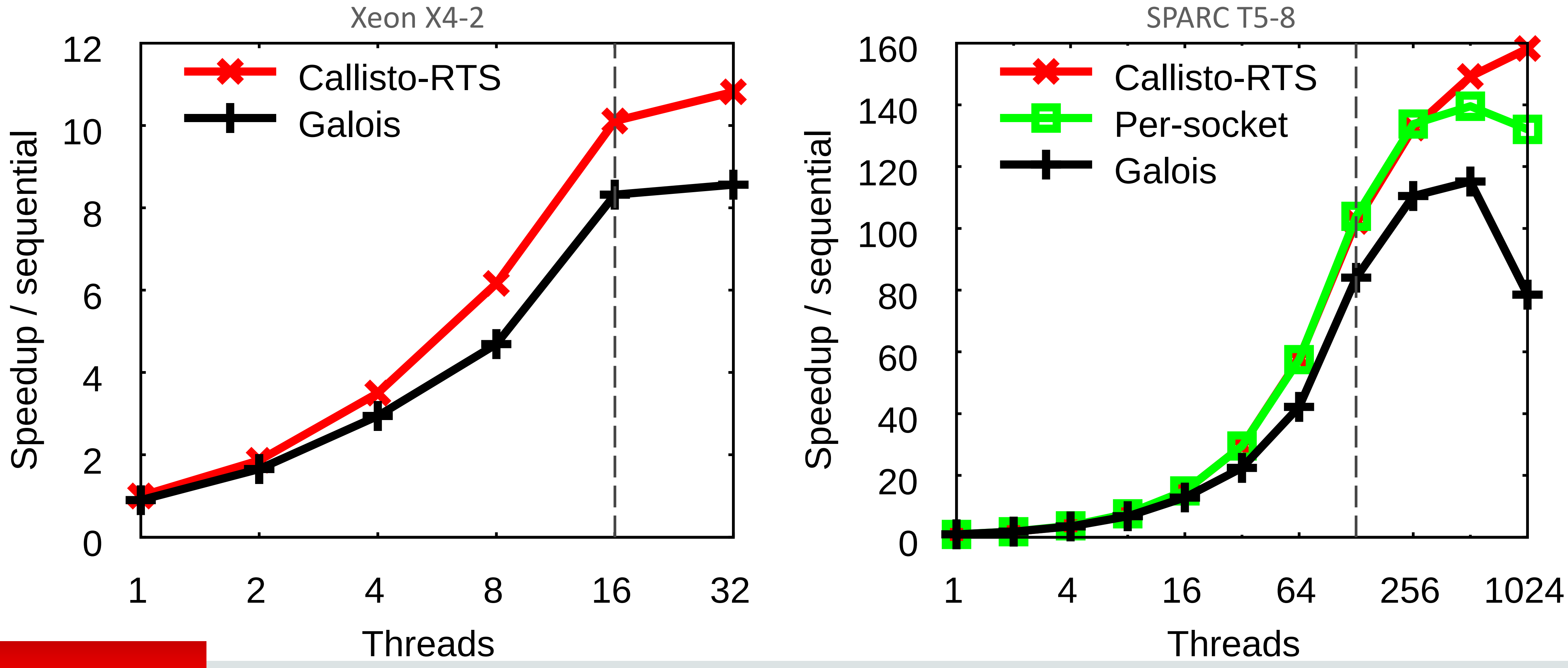
Betweenness-centrality

SNAP Slashdot data set (82.1K nodes, 948K edges), T5-8



Comparison with Galois

SNAP Twitter data set



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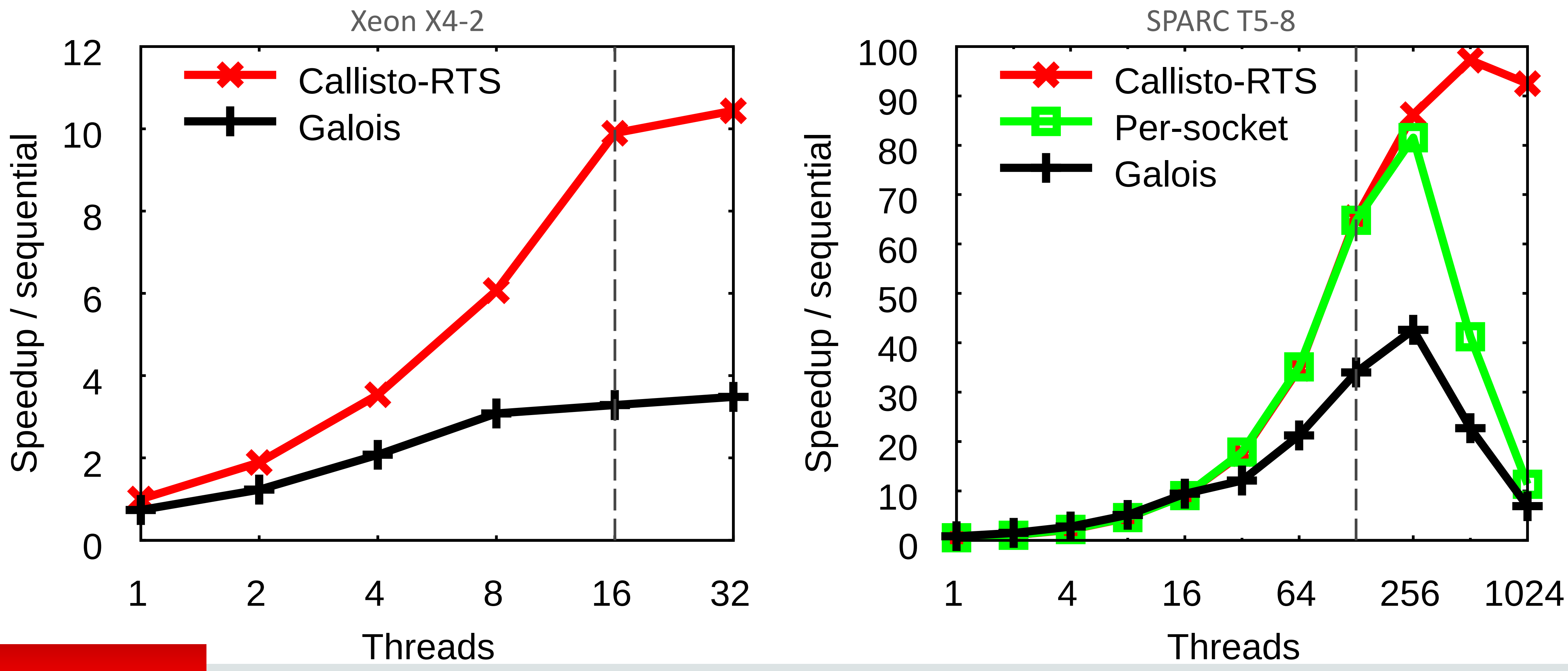

Future work

- Continuing development of the programming model
- Control over data placement as well as threads
  - Initial examples from graph workloads generally have random accesses: spread data and threads widely in the machine
  - (See “Shoal”, USENIX ATC 2015)
- Interactions between multiple parallel workloads
  - OS/runtime system interaction (ref our prior work at EuroSys 2014)
  - Placement in the machine
  - Control over degree of parallelism

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Integrated Cloud

Applications & Platform Services