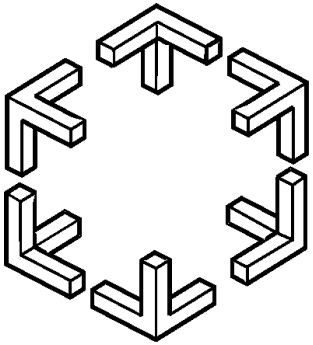

Cache-Aware Lock-Free Queues for Multiple Producers/Consumers and Weak Memory Consistency

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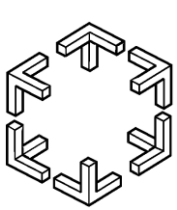
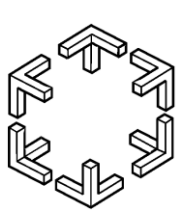
Chalmers University of Technology

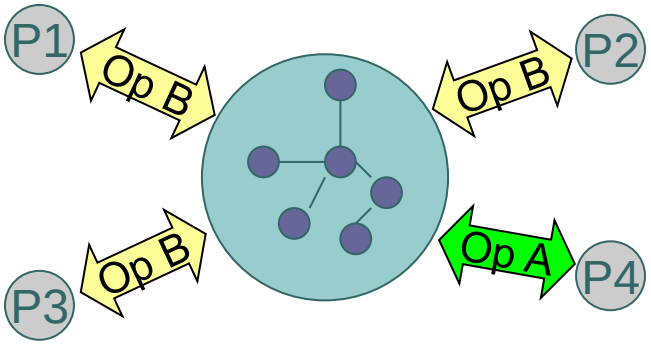


Outline

- Introduction
  - Lock-free synchronization
  - The Problem & Related work
- The new lock-free queue algorithm
- Experiments
- Conclusions



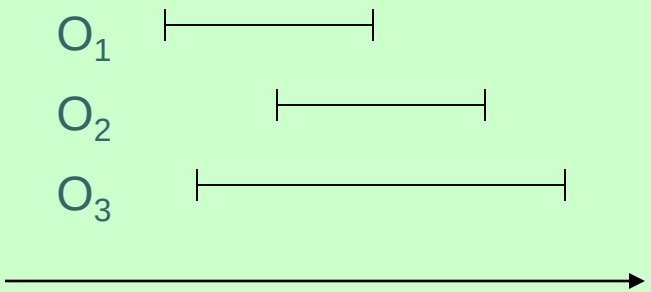
Synchronization on a shared object



- Lock-free synchronization
  - Concurrent operations without enforcing mutual exclusion
  - Avoids:
    - Blocking (or busy waiting), convoy effects, priority inversion and risk of deadlock
  - *Progress Guarantee*
    - At least one operation always makes progress

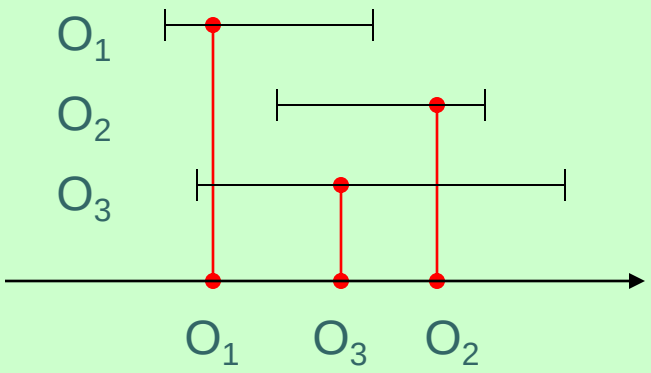
Correctness of a concurrent object

- Desired semantics of a shared data object
  - Linearizability [Herlihy & Wing, 1990]
    - For each operation invocation there must be one single time instant during its duration where the operation appears to take effect.
    - The observed effects should be consistent with a sequential execution of the operations in that order.



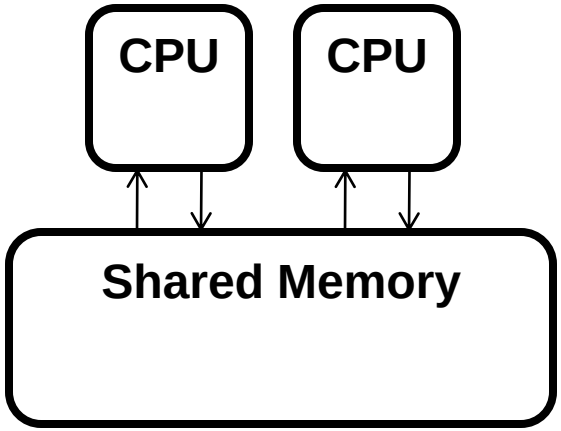
Correctness of a concurrent object

- Desired semantics of a shared data object
  - Linearizability [Herlihy & Wing, 1990]
    - For each operation invocation there must be one single time instant during its duration where the operation appears to take effect.
    - The observed effects should be consistent with a sequential execution of the operations in that order.



System Model

- Processes can read/write single memory words
- Synchronization primitives
  - Built into CPU and memory system
  - Atomic read-modify-write (i.e. a critical section of one instruction)
    - Examples: Compare-and-Swap, Load-Linked / Store-Conditional

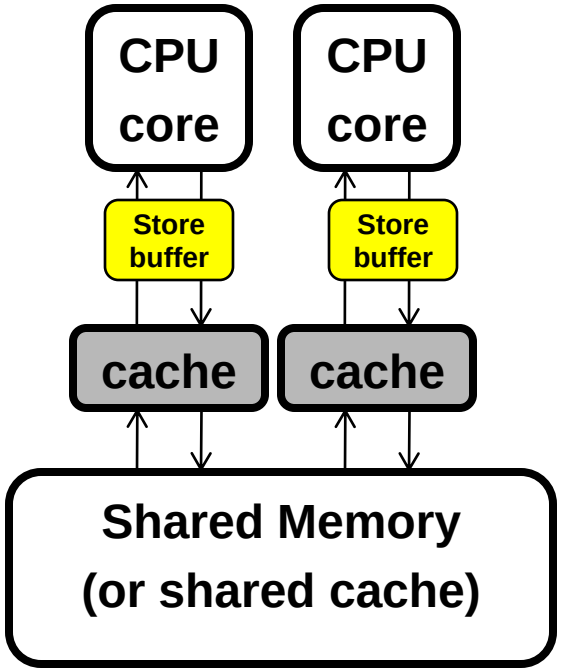


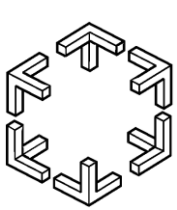
System Model: Memory Consistency

A process'

- Reads/writes may reach memory out of order
- Reads of own writes appear in program order
- Atomic synchronization primitive/instruction
  - Single word Compare-and-Swap
  - Atomic
  - Acts as memory barrier for the process' own reads and writes
    - All own reads/writes before are done before
    - All own reads/writes after are done after

  The affected cache block is held exclusively





Outline

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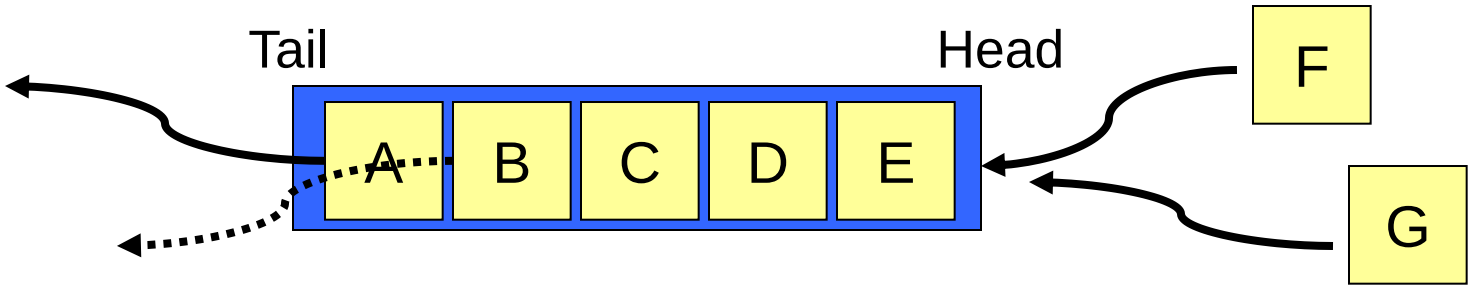
The Problem

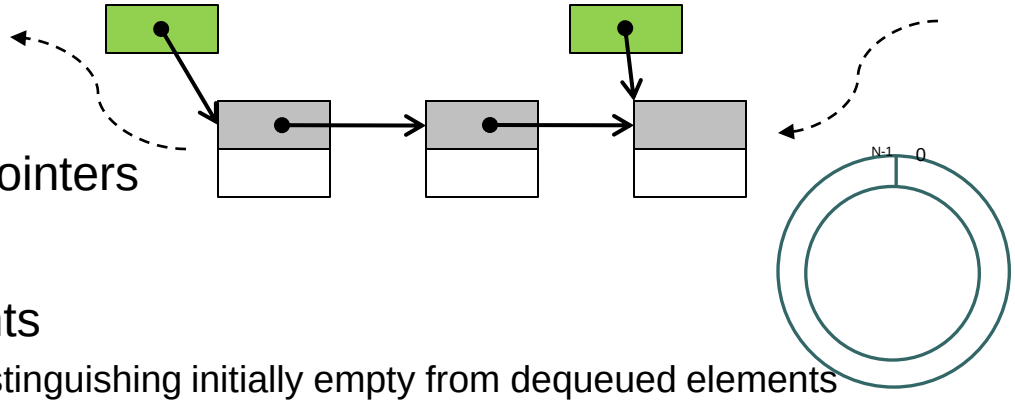
- Concurrent FIFO queue shared data object
  - Basic operations: enqueue and dequeue



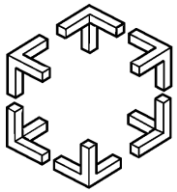
  - Desired Properties
    - Linearizable and Lock-free
    - Dynamic size (maximum only limited by available memory)
    - Bounded memory usage (in terms of live contents)
    - Fast on real systems

Related Work: Lock-free Multi-P/C Queues

- [Michael & Scott, 1996]
  - Linked-list, one element/node
  - Global shared head and tail pointers



- [Tsigas & Zhang, 2001]
  - Static circular array of elements
    - Two different NULL values for distinguishing initially empty from dequeued elements
  - Global shared head and tail indices, lazily updated
- [Michael & Scott, 1996] + Elimination [Moir, Nussbaum, Shalev & Shavit, 2005]
  - Same as the above + elimination of concurrent pairs of enqueue and dequeue when the queue is near empty
- [Hoffman, Shalev & Shavit, 2007] Baskets queue
  - Linked-list, one element/node
  - Reduces contention between concurrent enqueues after conflict
  - Needs stronger memory management than M&S (SLFRC or Beware&Cleanup)



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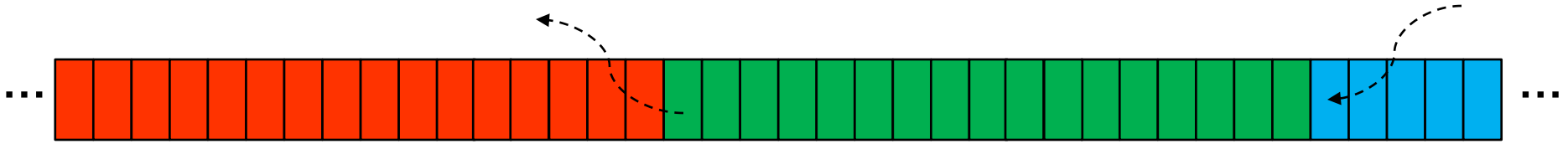
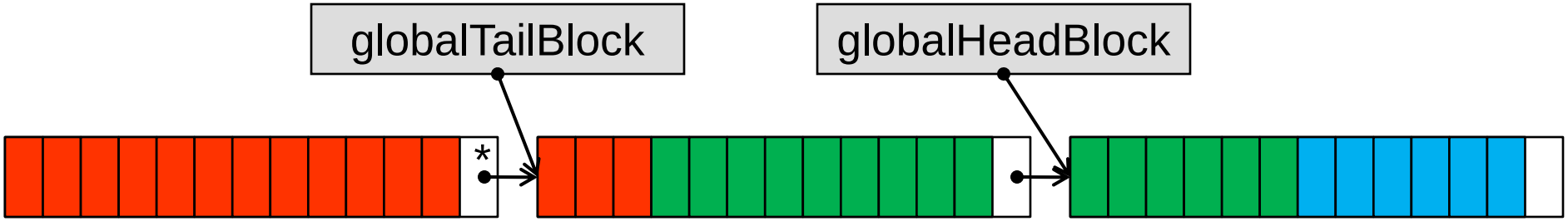
The Algorithm



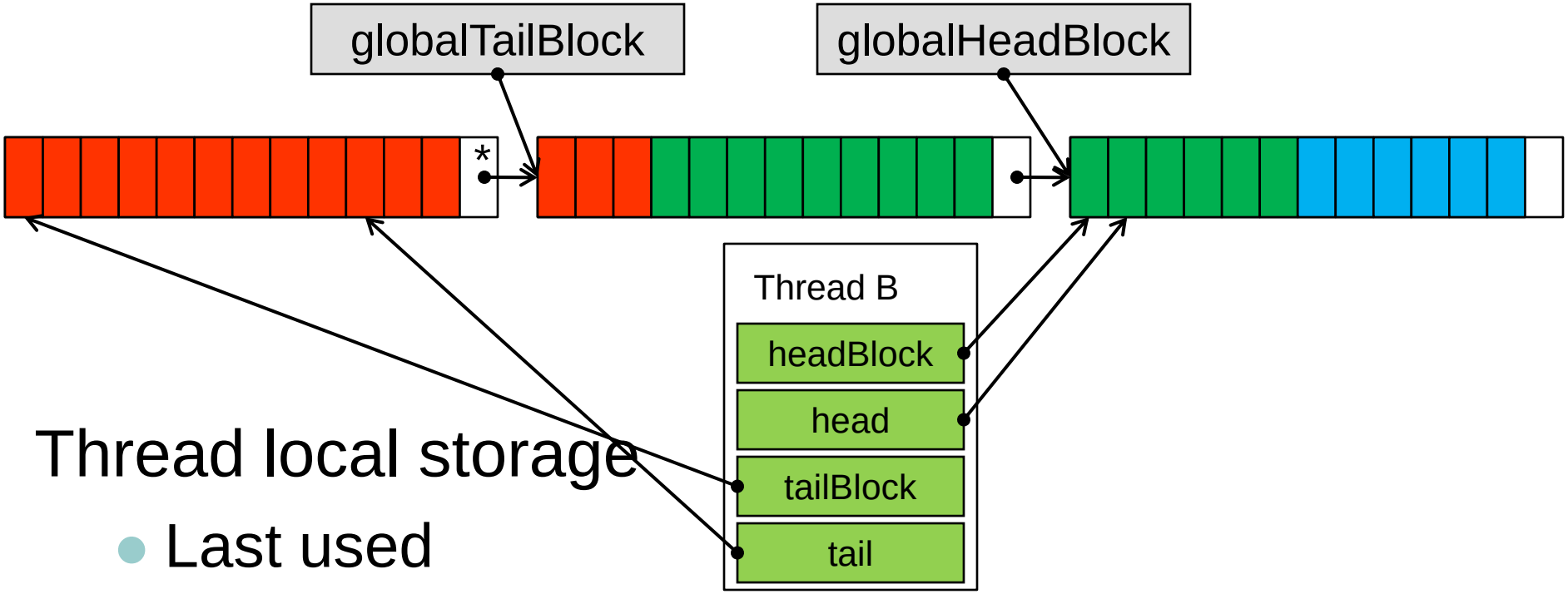
- Basic idea:
  - Cut and unroll the circular array queue
  - Primary synchronization on the elements
    - Compare-And-Swap
      (NULL1 -> Value -> NULL2 avoids the ABA problem)
  - Head and tail both move to the right
    - Need an “infinite” array of elements

The Algorithm



- Basic idea:
  - Creating an “infinite” array of elements.
  - Divide into blocks of elements, and link them together
    - New empty blocks added as needed
    - Emptied blocks are marked deleted and eventually reclaimed
    - Block fields: Elements, next, (filled, emptied flags), deleted flag.
  - Linked chain of dynamically allocated blocks
    - Lock-free memory management needed for safe reclamation!
    - Beware&Cleanup [Gidenstam, Papatriantafilou, Sundell & Tsigas, 2009]

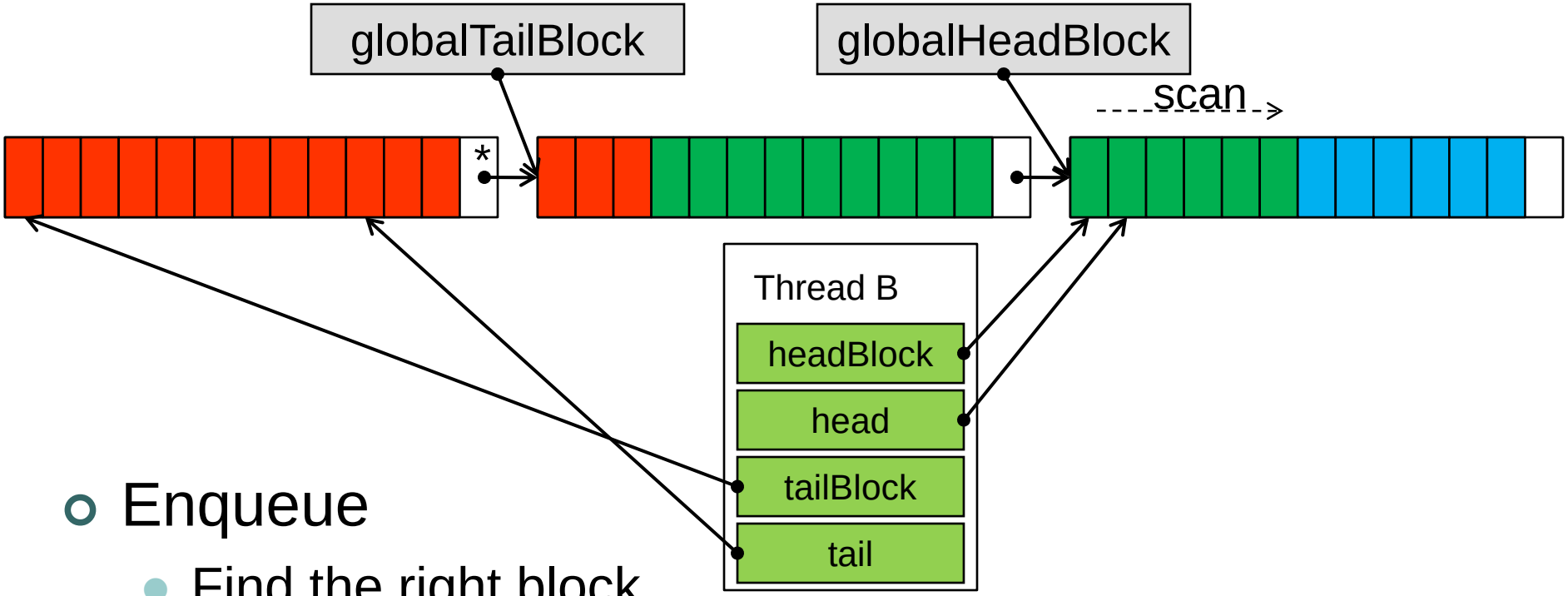
The Algorithm



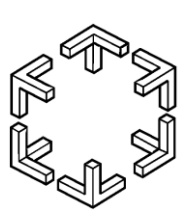
Thread local storage

- Last used
  - Head block/index for Enqueue
  - Tail block/index for Dequeue
- Reduces need to read/update global shared variables

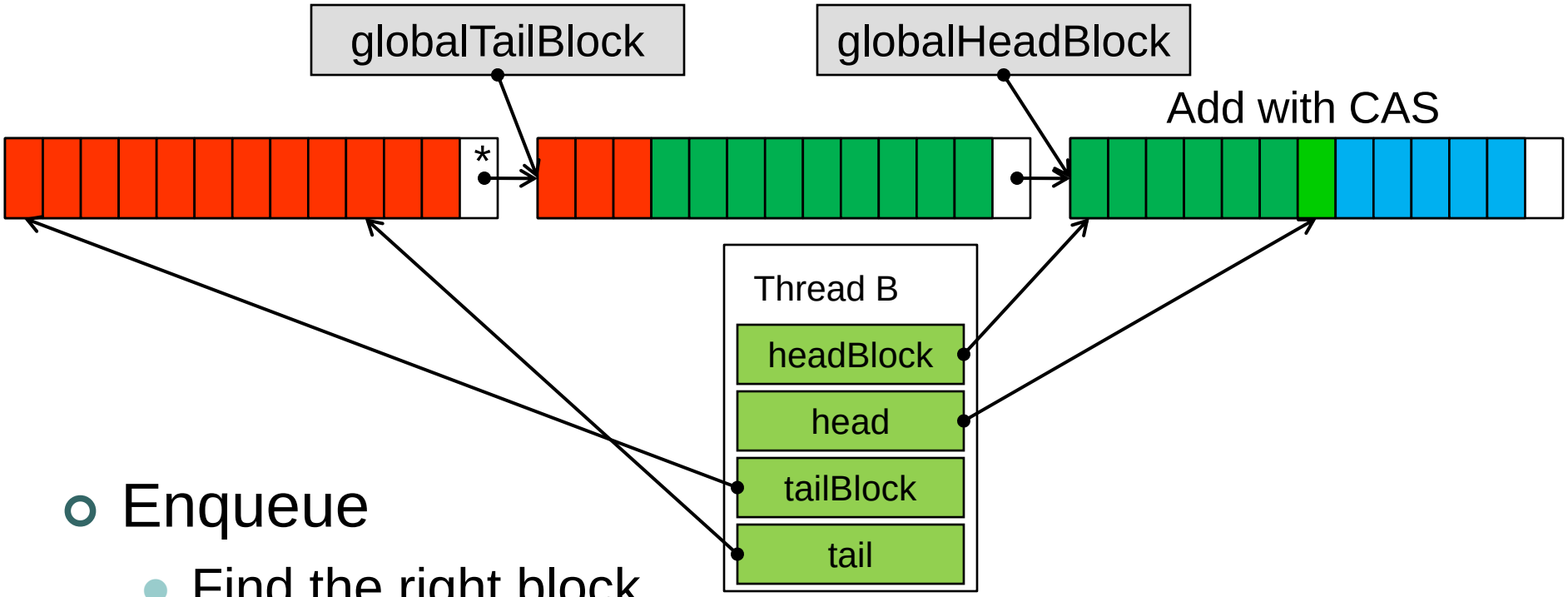
The Algorithm



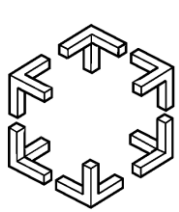
- Enqueue
  - Find the right block
    (first via TLS, then TLS->next or globalHeadBlock)
  - Search the block for the first empty element



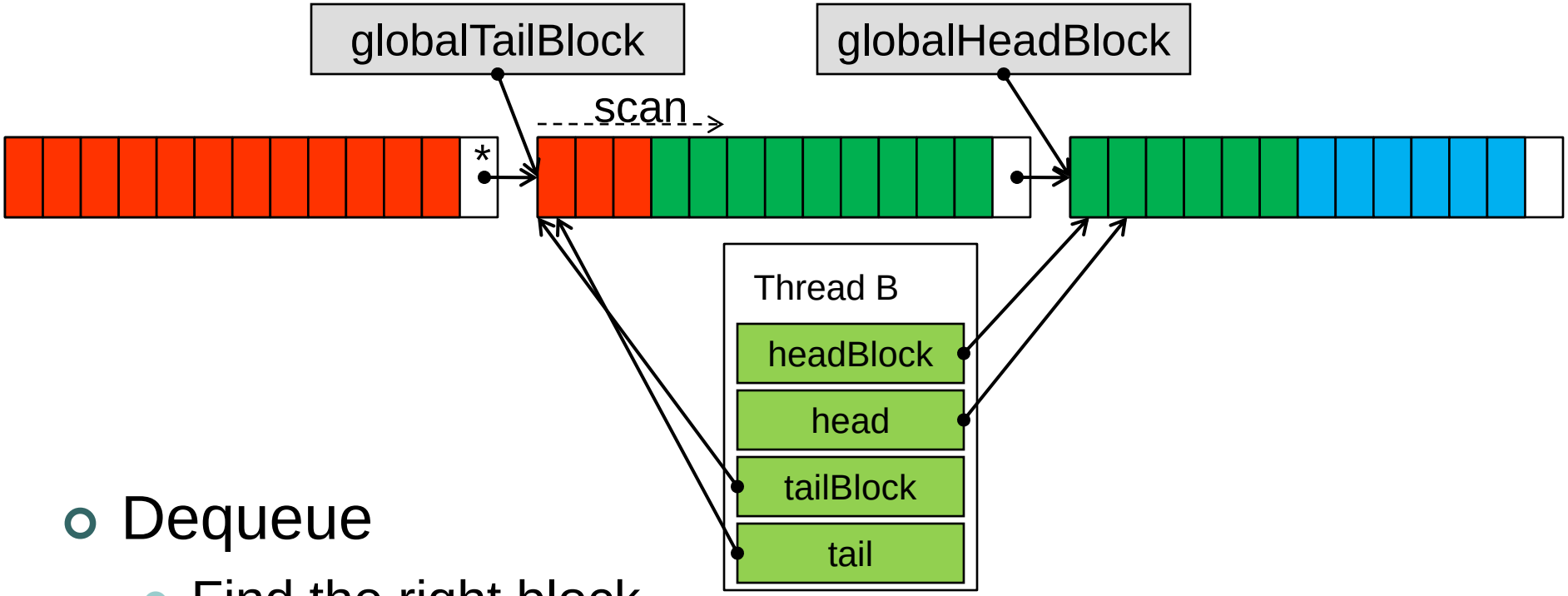
The Algorithm



- Enqueue
  - Find the right block
    (first via TLS, then TLS->next or globalHeadBlock)
  - Search the block for the first empty element
  - Update element with CAS (Also, the linearization point)

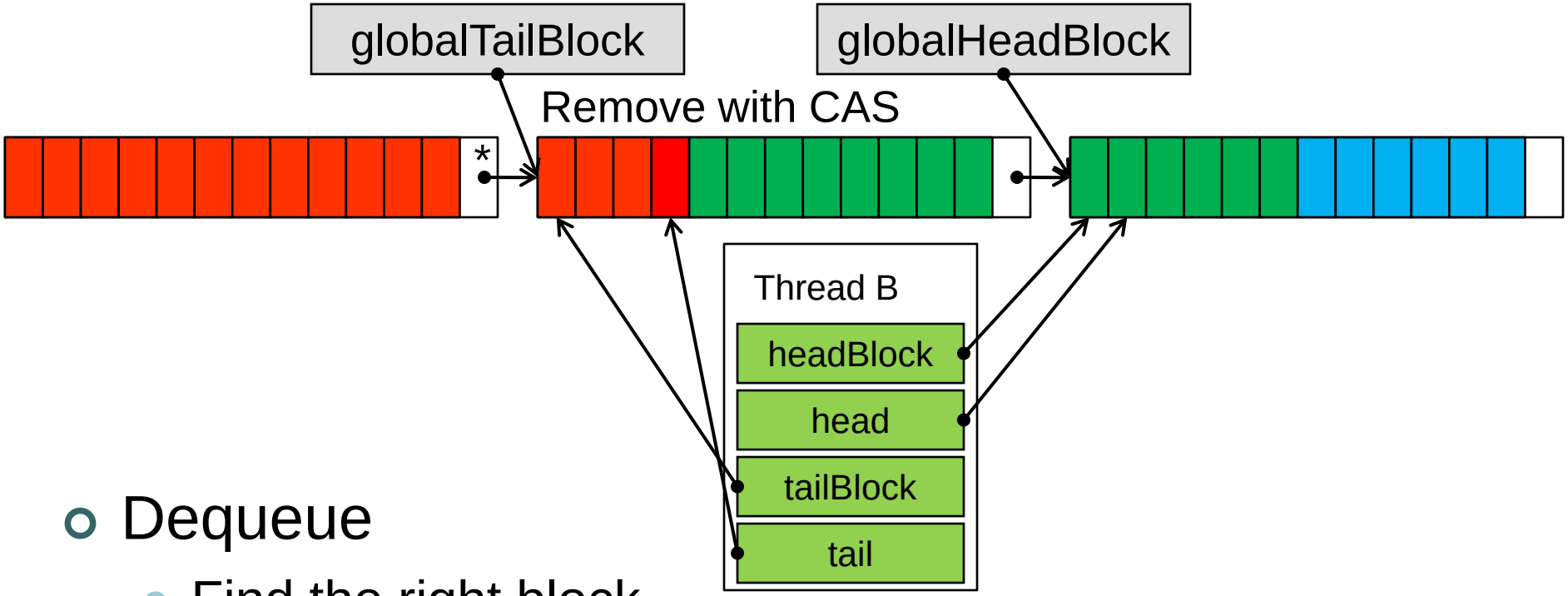


The Algorithm



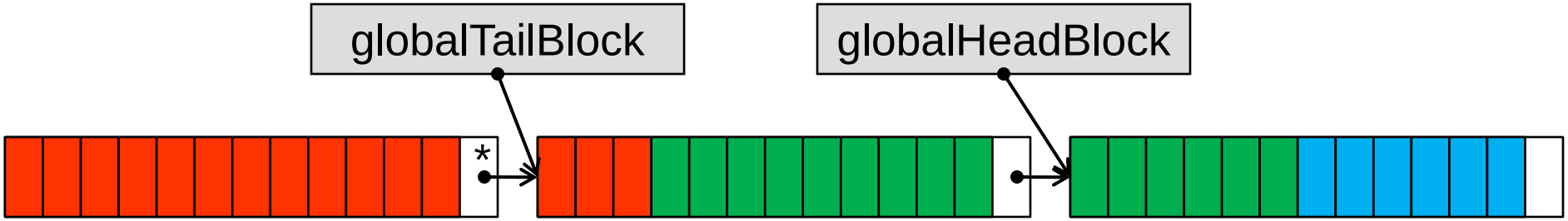
- Dequeue
  - Find the right block
    (first via TLS, then TLS->next or globalTailBlock)
  - Search the block for the first valid element

The Algorithm



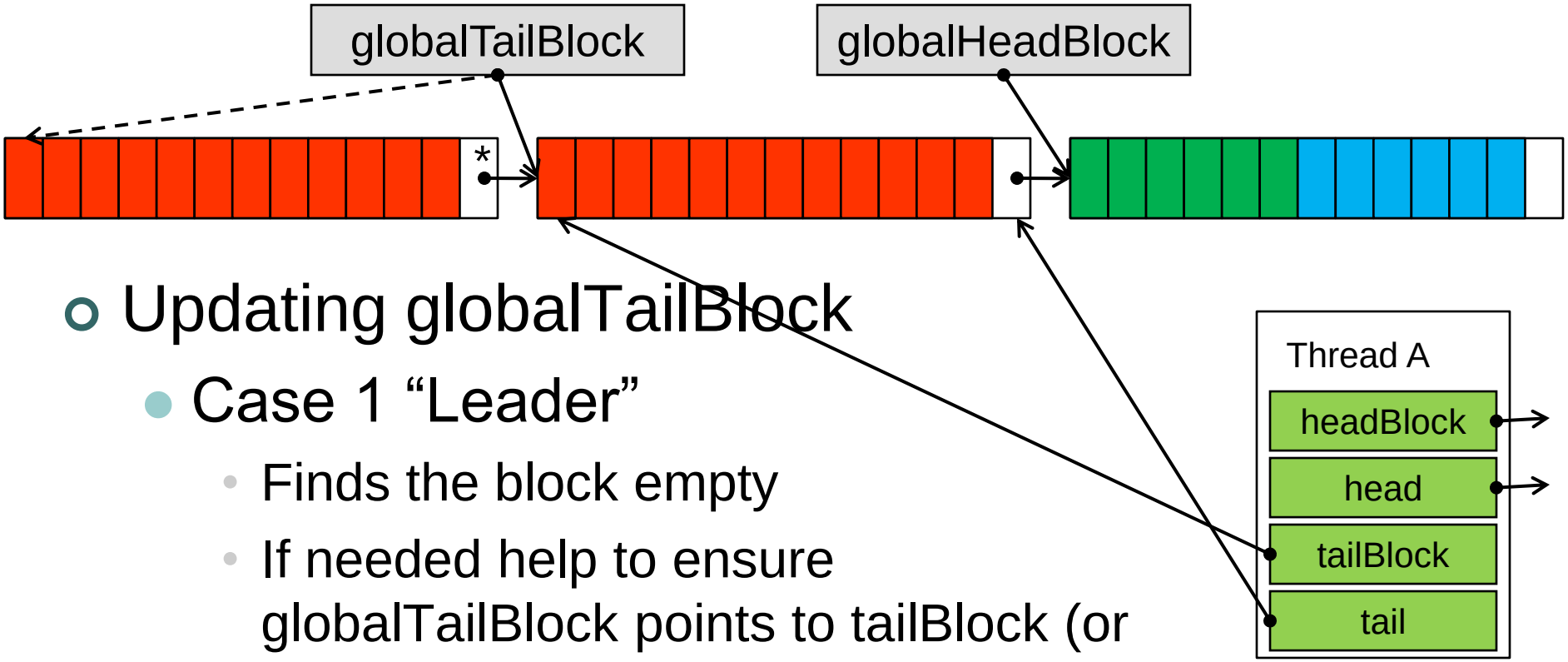
- Dequeue
  - Find the right block
    (first via TLS, then TLS->next or globalTailBlock)
  - Search the block for the first valid element
  - Remove with CAS, replace with NULL2 (linearization point)

The Algorithm

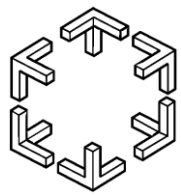


- Maintaining the chain of blocks
  - Helping scheme when moving between blocks
  - Invariants to be maintained
    - globalHeadBlock points to
      - The newest block or the block before it
    - globalTailBlock points to
      - The oldest active block (not deleted) or the block before it

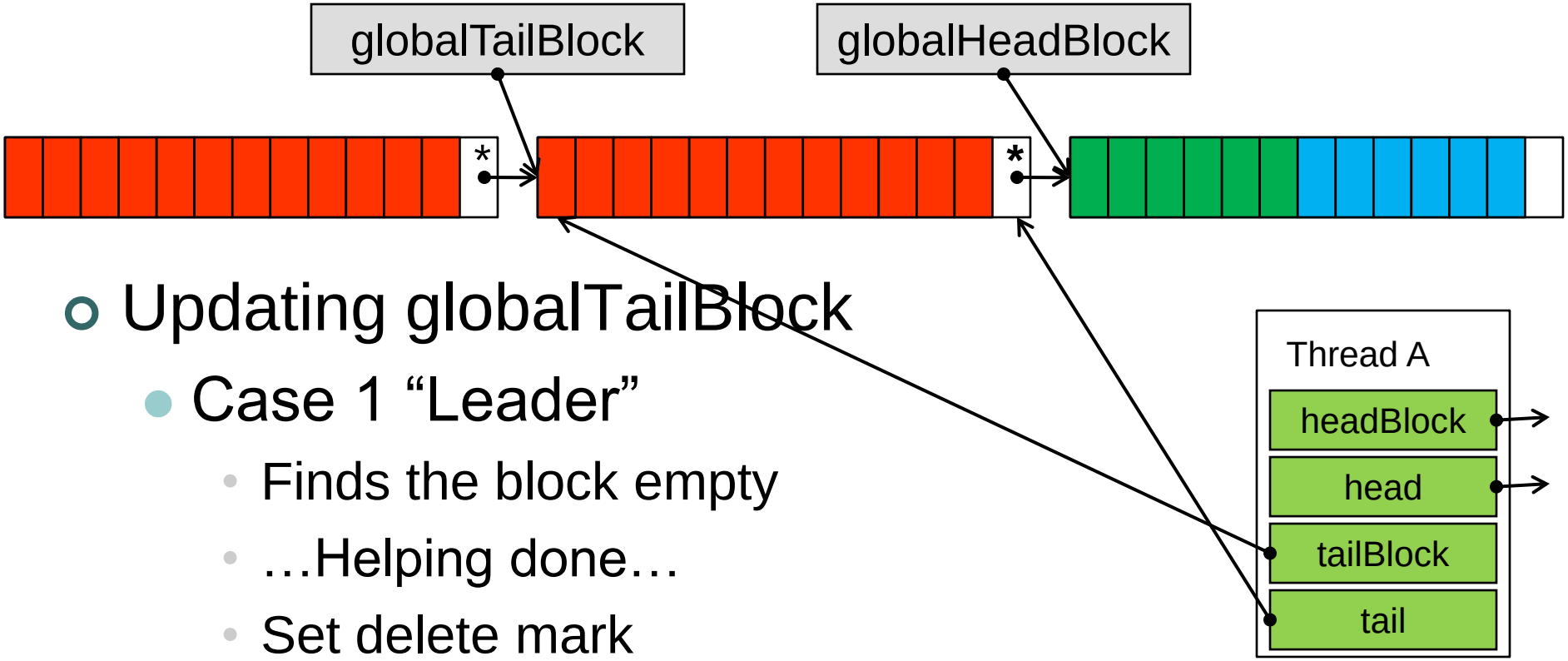
Maintaining the chain of blocks



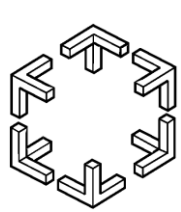
- Updating globalTailBlock
  - Case 1 “Leader”
    - Finds the block empty
    - If needed help to ensure globalTailBlock points to tailBlock (or a newer block)



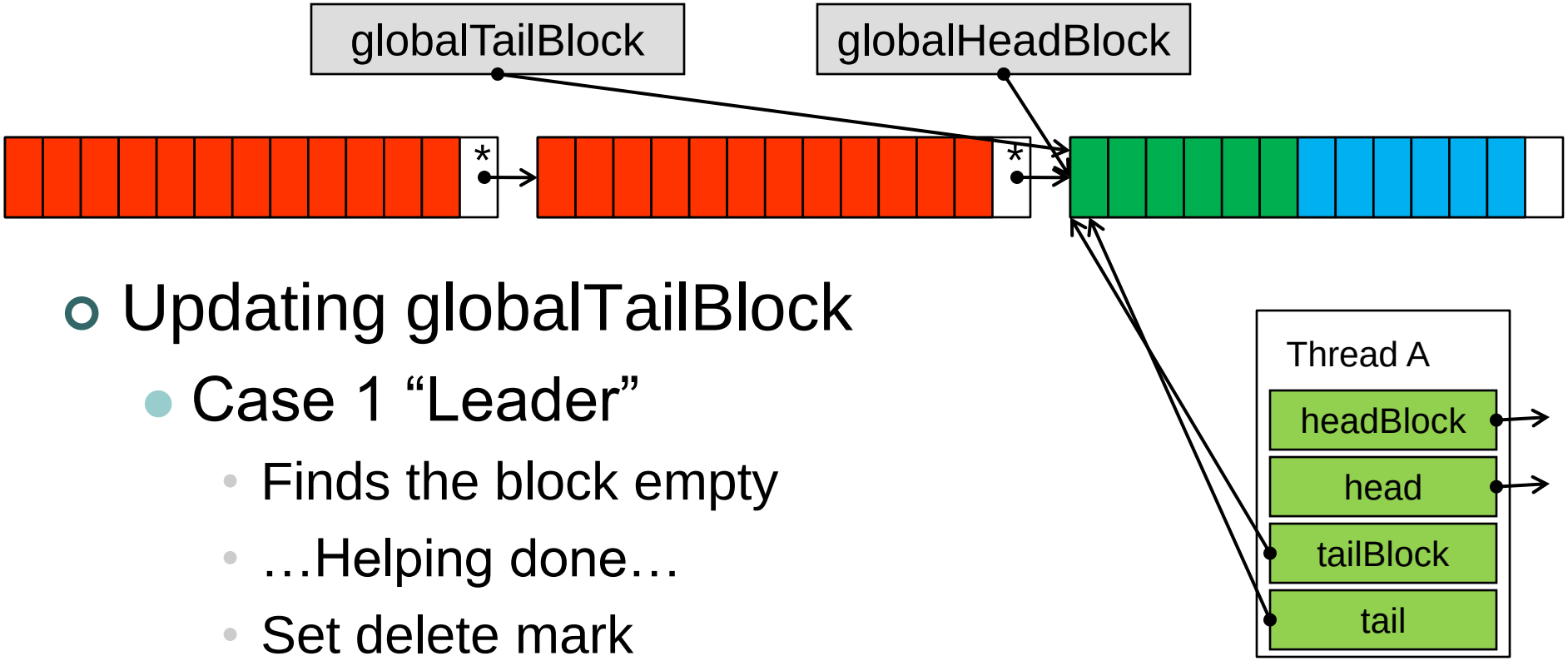
Maintaining the chain of blocks



- Updating globalTailBlock
  - Case 1 “Leader”
    - Finds the block empty
    - …Helping done…
    - Set delete mark

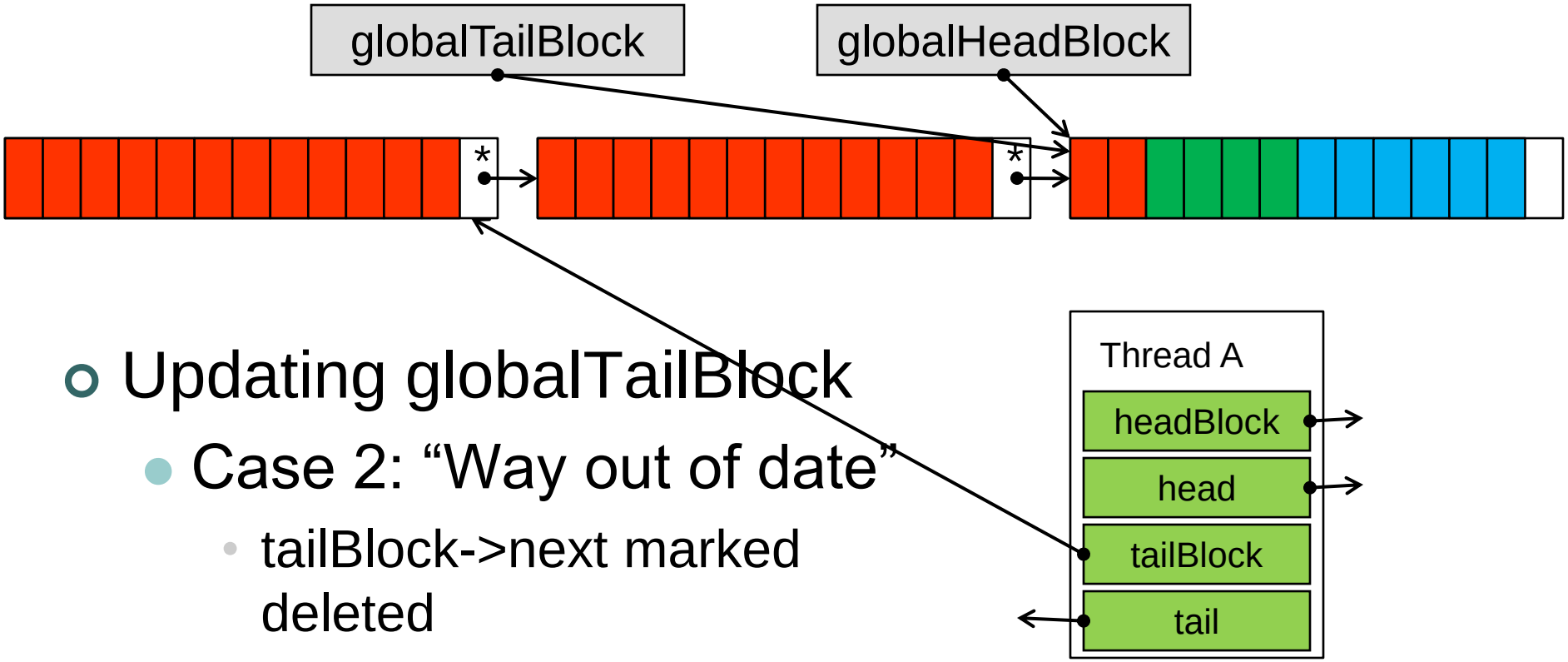


Maintaining the chain of blocks



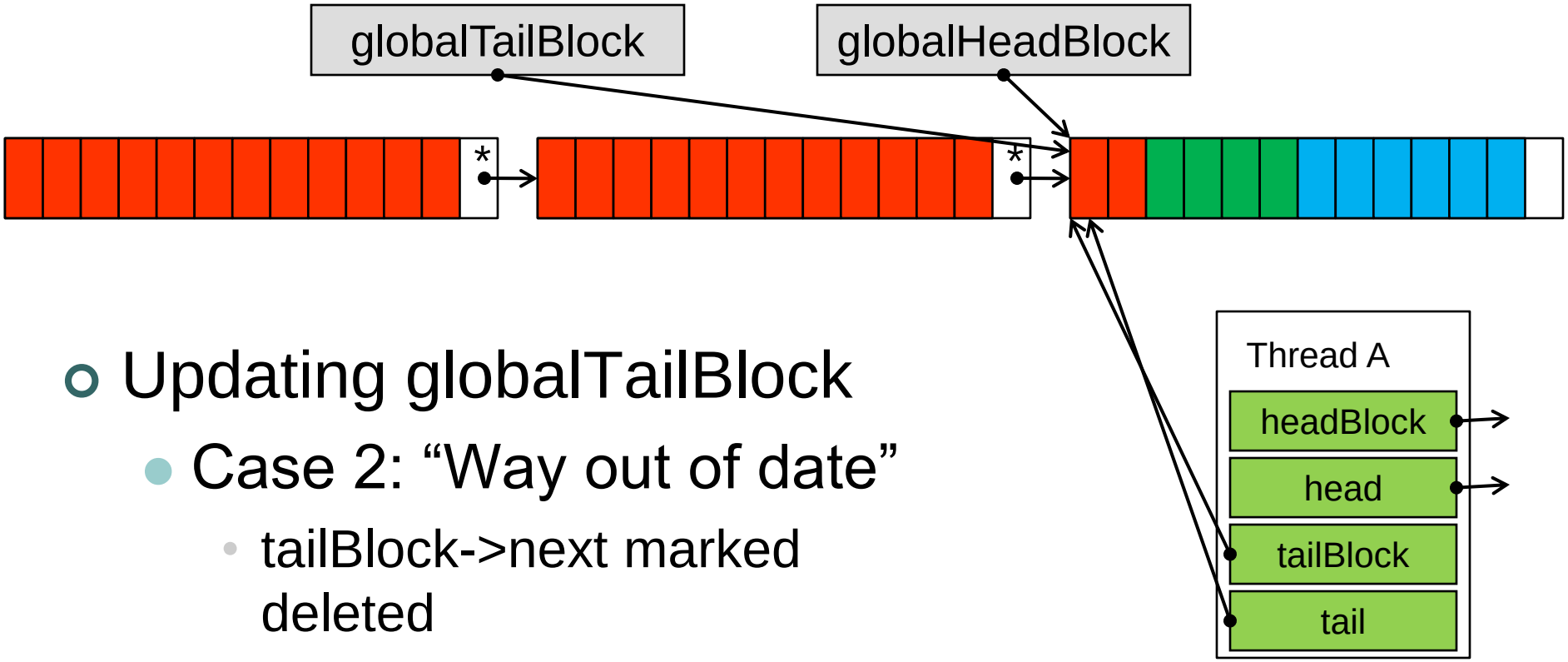
- Updating globalTailBlock
  - Case 1 “Leader”
    - Finds the block empty
    - …Helping done…
    - Set delete mark
    - Update globalTailBlock pointer
    - Move own tailBlock pointer

Maintaining the chain of blocks



- Updating globalTailBlock
  - Case 2: “Way out of date”
    - tailBlock->next marked deleted
    - Restart with globalTailBlock

Maintaining the chain of blocks



- Updating globalTailBlock
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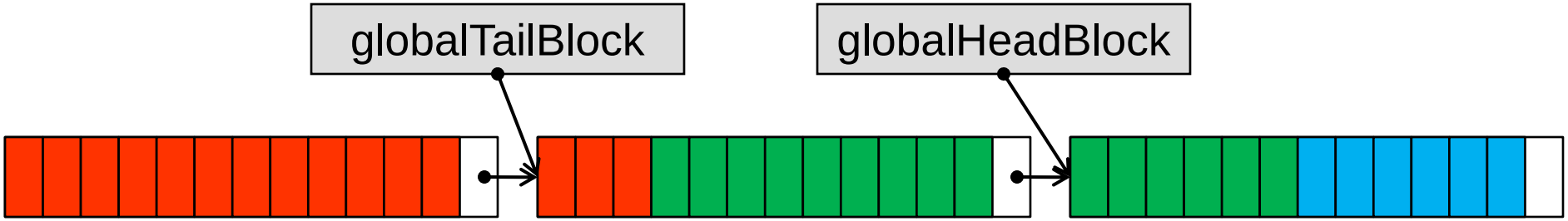
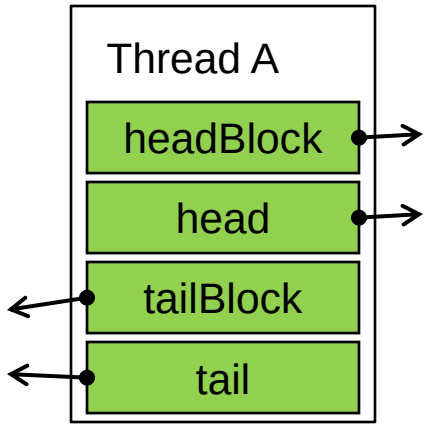
    - tailBlock->next marked deleted
    - Restart with globalTailBlock

Minding the Cache



- Blocks occupy one cache-line
- Cache-lines for enqueue v.s. dequeue are disjoint (except when near empty)
- Enqueue/dequeue will cause coherence traffic for the affected block
- Scanning for the head/tail involves one cache-line



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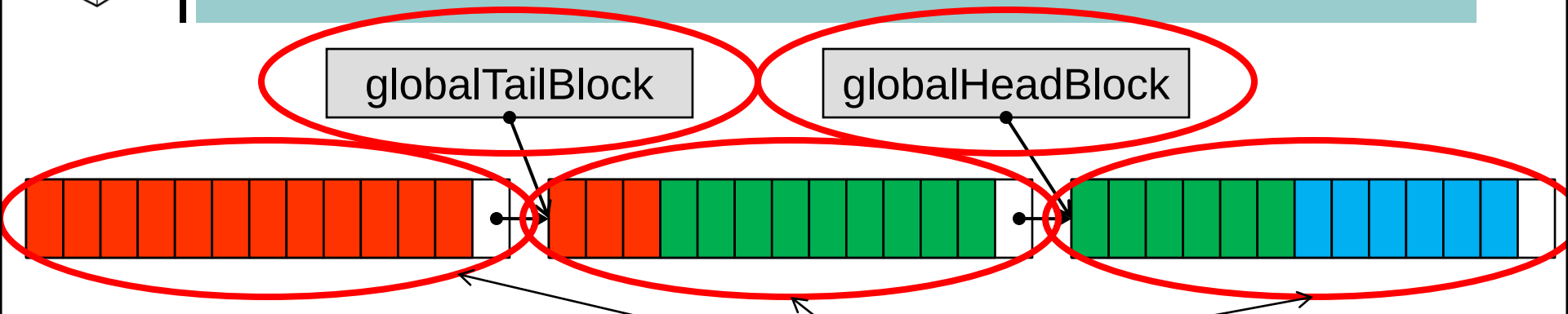

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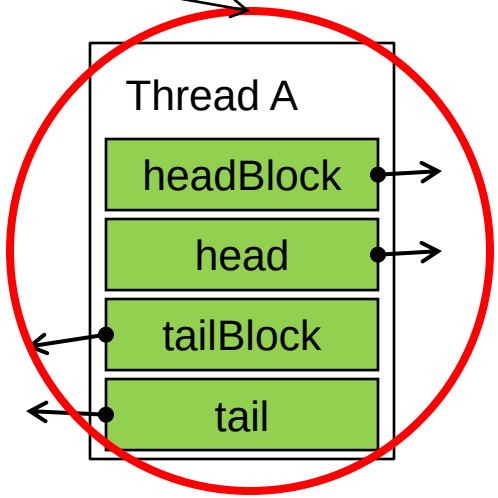
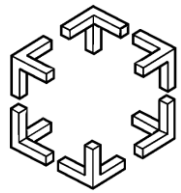
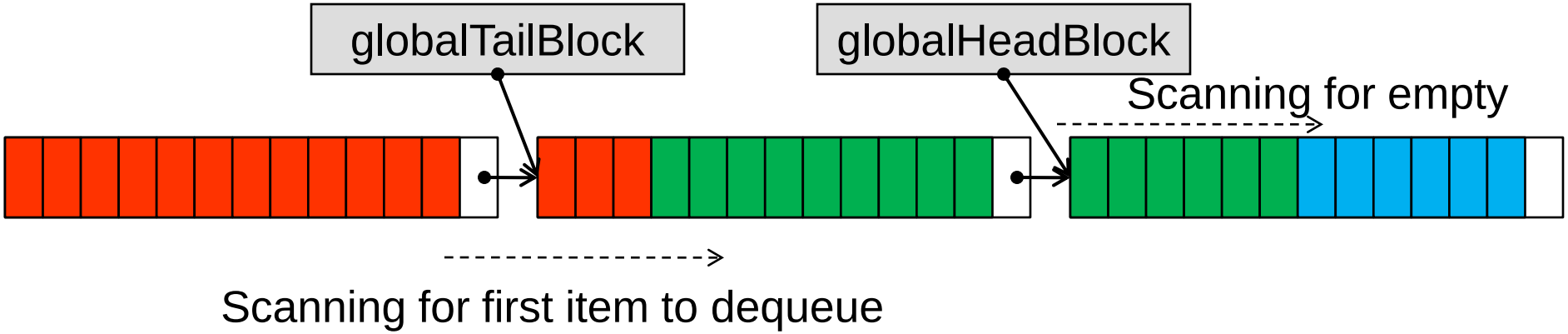
Cache-lines

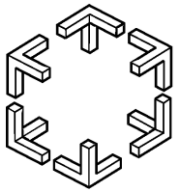




Scanning in a weak memory model?



- Key observations
  - Life cycle for element values (NULL1 -> value -> NULL2)
  - Elements are updated with CAS thus requiring the old value to be the expected one.
  - Scanning only skips values later in the life cycle
    - Reading an old value is safe (will try CAS and fail)



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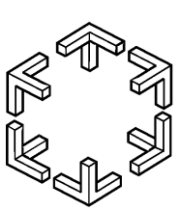
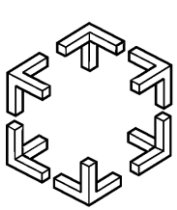


Experimental evaluation

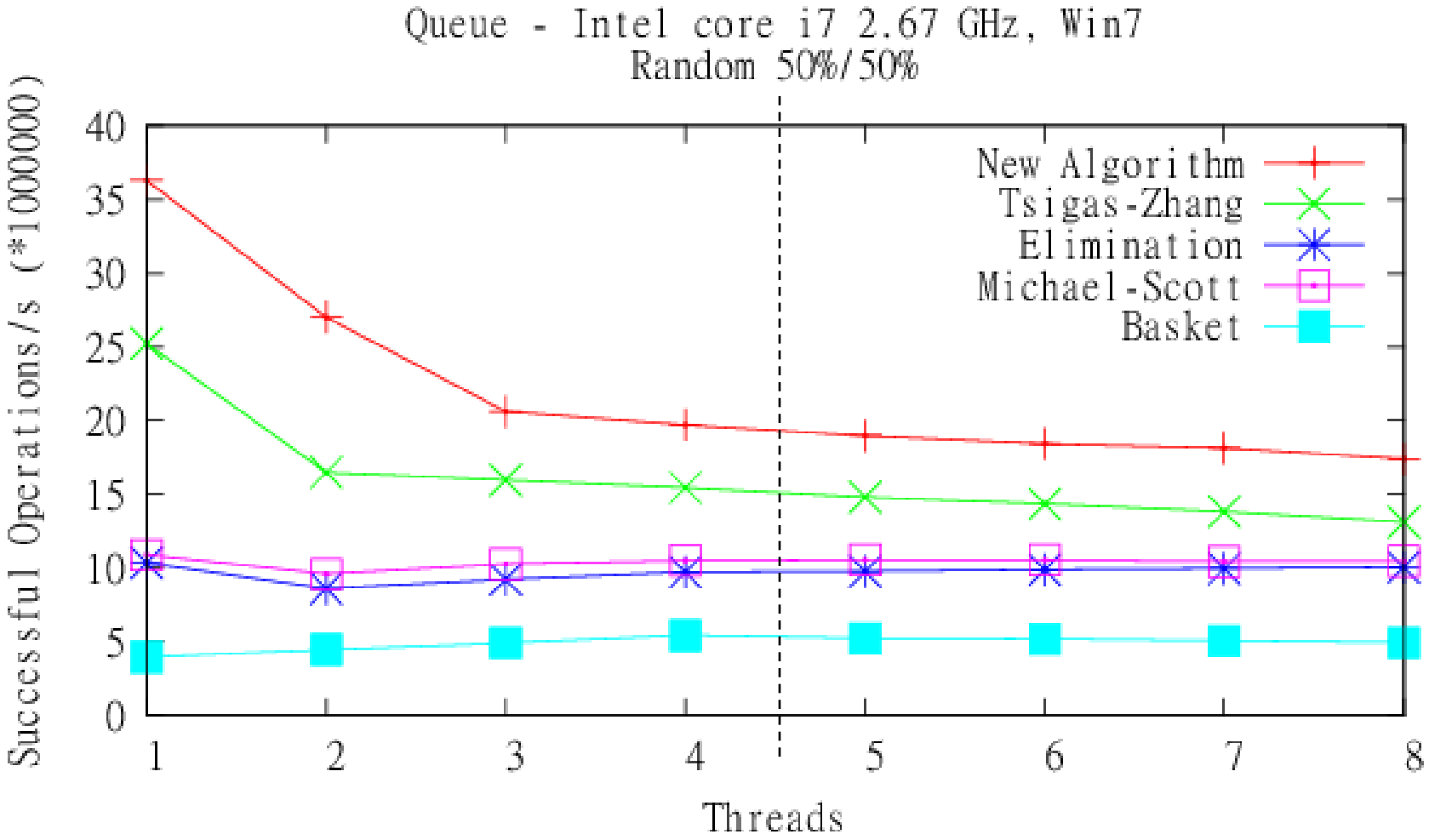
- Micro benchmark
  - Threads execute enqueue and dequeue operations on a shared queue
    - High contention.
  - Test Configurations
    1. Random *50%* / *50%*, initial size *0*
    2. Random *50%* / *50%*, initial size *1000*
    3. *1* Producer / *N-1* Consumers
    4. *N-1* Producers / *1* Consumer
  - Measured throughput in items/sec
    - #dequeues not returning EMPTY



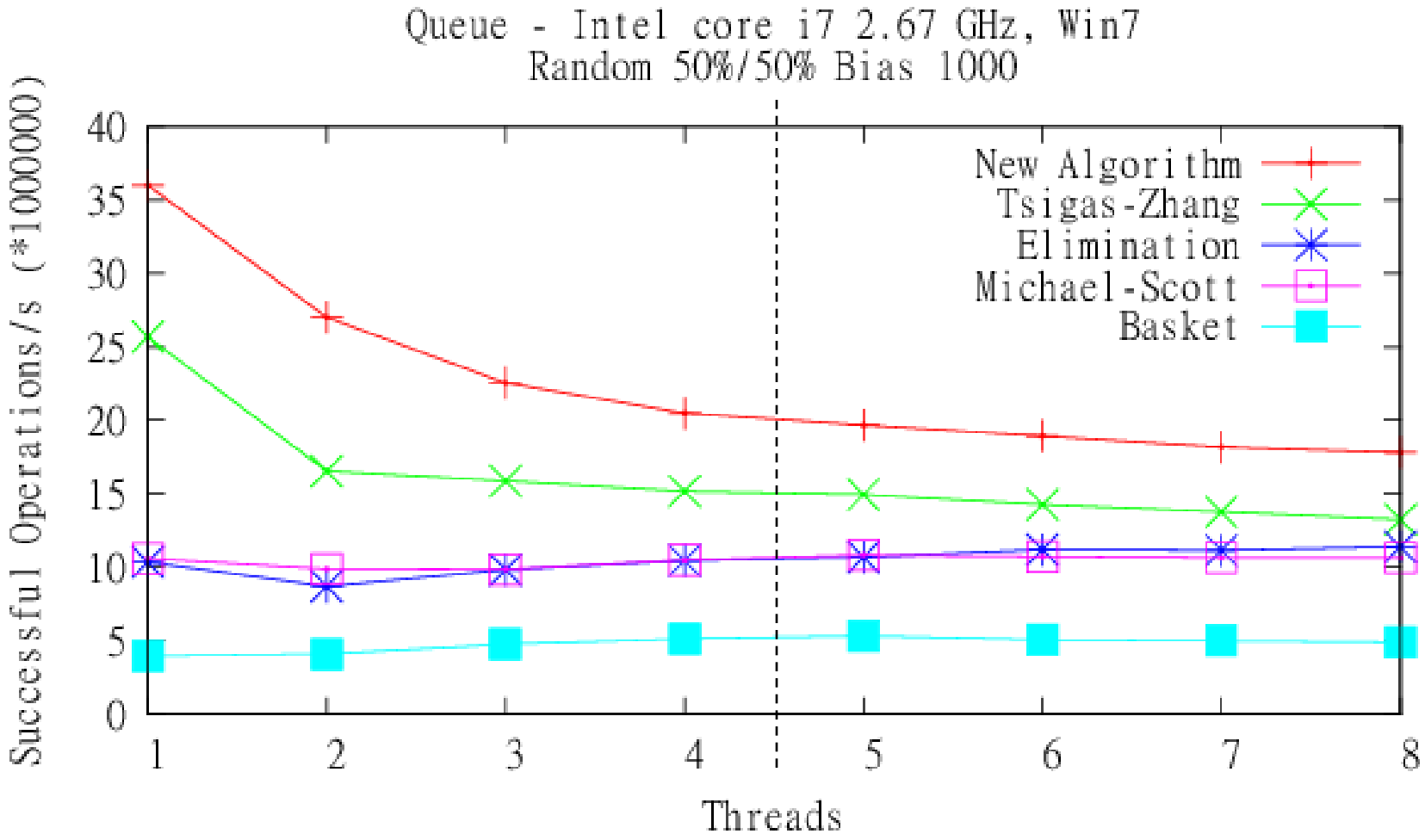
Experimental evaluation

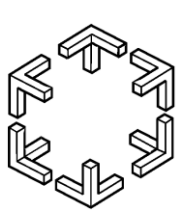
- Micro benchmark
  - Algorithms
    - [Michael & Scott, 1996]
    - [Michael & Scott, 1996] +
      Elimination [Moir, Nussbaum, Shalev & Shavit, 2005]
    - [Hoffman, Shalev & Shavit, 2007]
    - [Tsigas & Zhang, 2001]
    - The new Cache-Aware Queue [Gidenstam, Sundell & Tsigas, 2010]
  - PC Platform
    - CPU: Intel Core i7 920 @ 2.67 GHz
    - 4 cores with 2 hardware threads each
    - RAM: 6 GB DDR3 @ 1333 MHz
    - Windows 7 64-bit

Experimental evaluation (i)

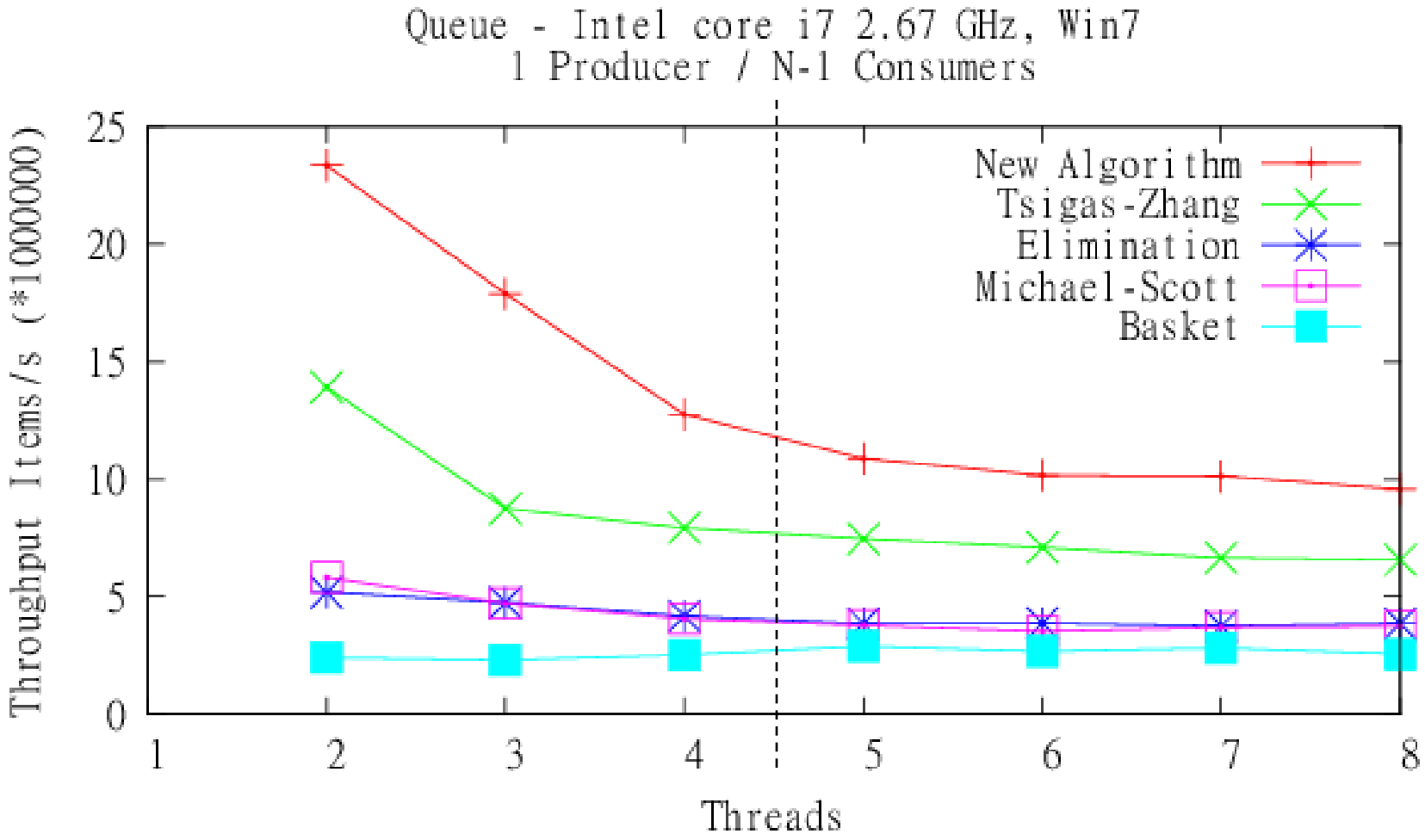


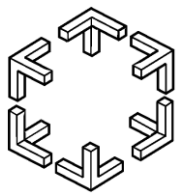
Experimental evaluation (ii)



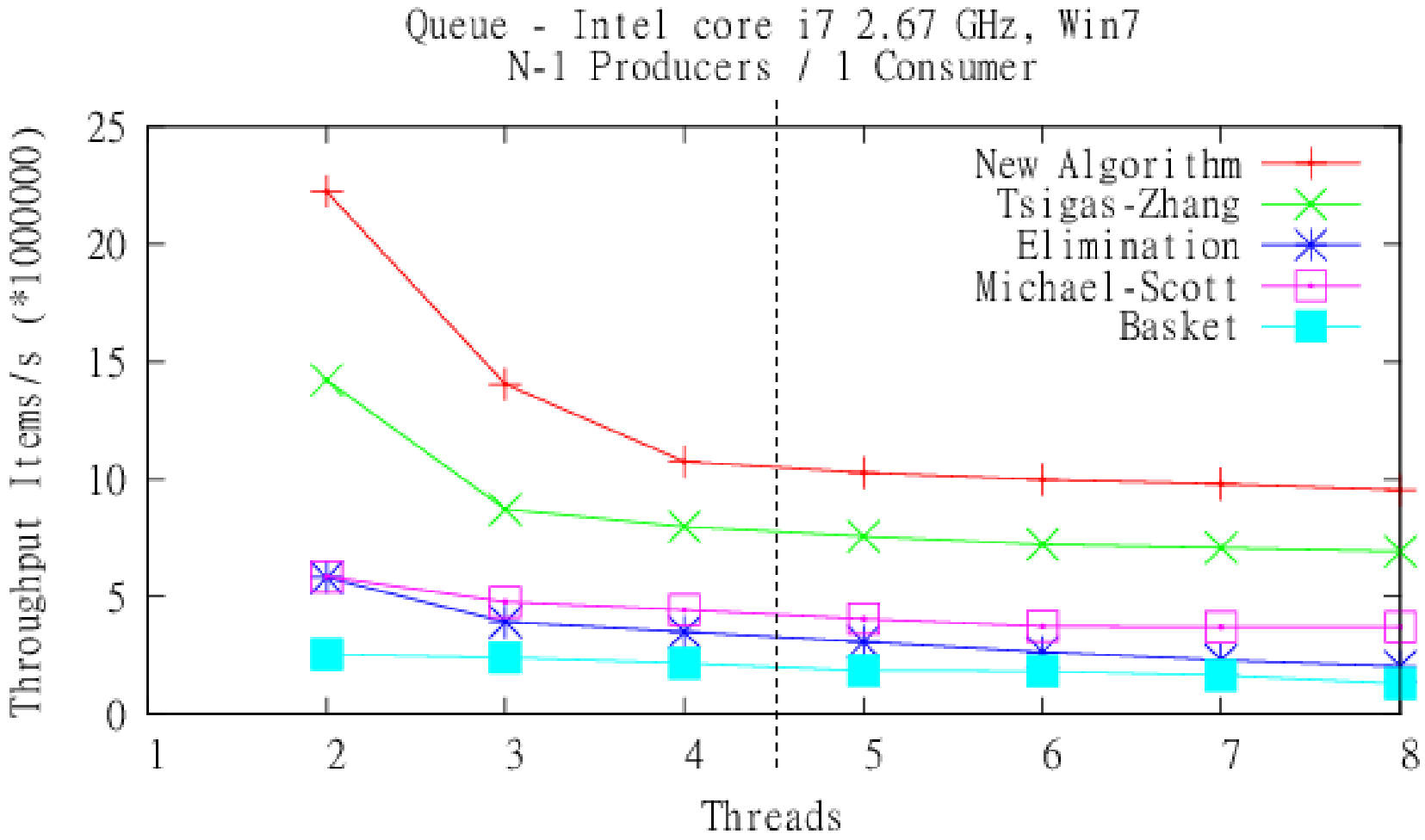


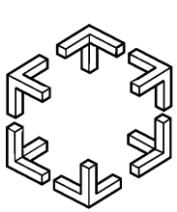
Experimental evaluation (iii)





Experimental evaluation (iv)

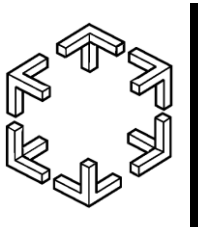




Conclusions

The Cache-Aware Lock-free Queue

- The first lock-free queue algorithm for multiple producers/consumers with all of the properties below
  - Designed to be cache-friendly
  - Designed for the weak memory consistency provided by contemporary hardware
  - Is disjoint-access parallel (except when near empty)
  - Use thread-local storage for reduced communication
  - Use a linked-list of array blocks for efficient dynamic size support



Thank you for listening!

Questions?