A Lock-Free Algorithm for Concurrent Bags

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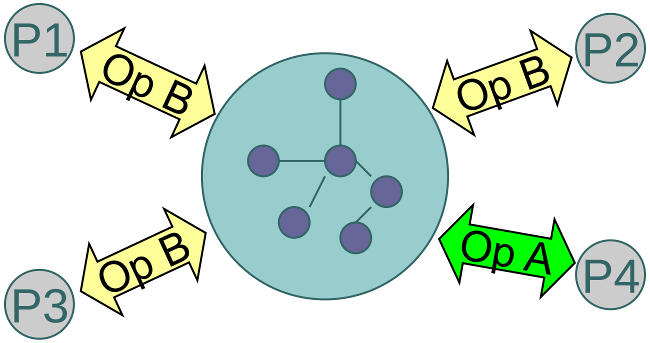
Outline

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

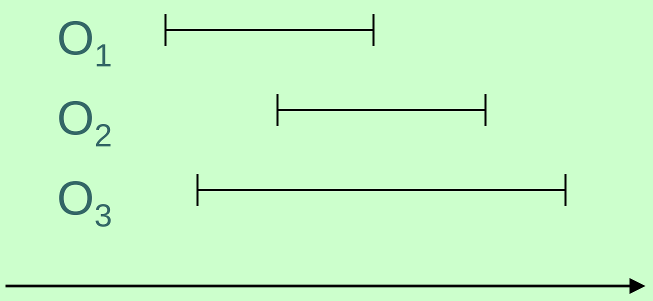
Synchronization on a shared object



- Lock-free synchronization
  - Allows 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.



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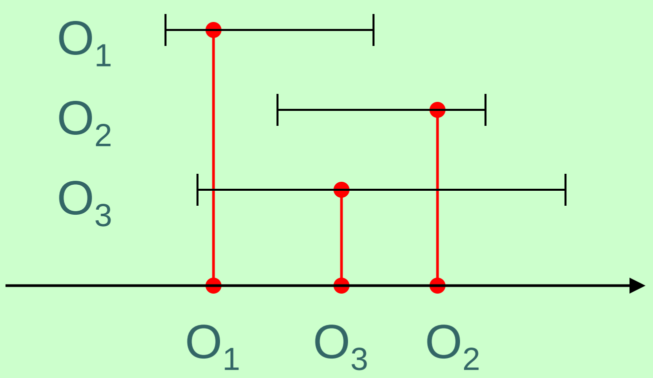
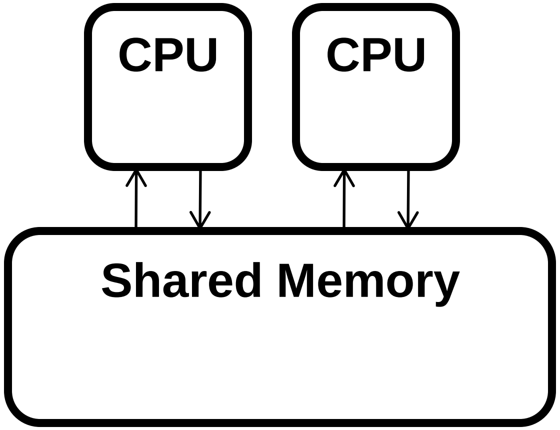


System Model

- Processes can read/write single memory words
  - Model: Sequential consistency
- 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



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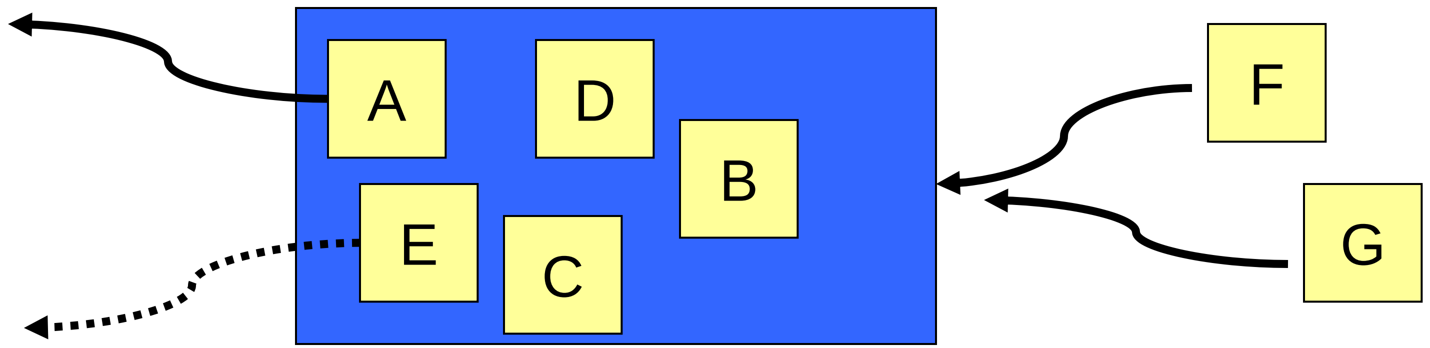
The Problem: Concurrent bag shared data object

- Basic operations: **Add()** and **TryRemoveAny()**
- Elements in the bag are *unordered*



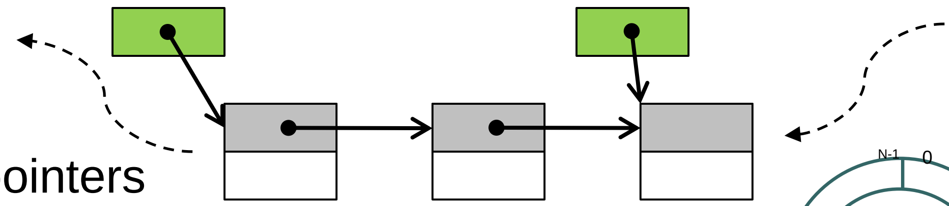
- Desired Properties
  - Linearizable and lock-free
    - Linearizable means: Add(A) -> TryRemoveAny() returns A;
      if TryRemoveAny() returns EMPTY then the bag really was empty
  - Dynamic size (maximum only limited by available memory)
  - Bounded memory usage (in terms of live contents)
  - Fast on current systems

The Problem: Concurrent bag shared data object

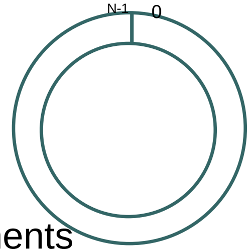
- Motivation
  - Useful for communication/work distribution, e.g.
    - Implementation of Parallel foreach / forall
    - Between (unordered) pipeline stages
  - Abstract data type available in some languages
    - Bag / Producer-Consumer Collection
    - .NET C#
    - …
  - A concurrent bag can be implemented with other data structures, e.g. queue, stack, …
    - But “better” service comes at a price

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

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

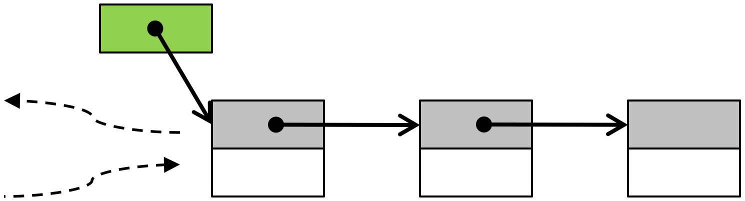


- [Tsigas & Zhang, 2001]
  - Static circular array of elements
    - Two different NULL values for distinguishing initially empty from dequeued elements
  - Global shared head and tail indices, lazily updated



- [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
  - Uses stronger memory management than M&S (SLFRC or Beware&Cleanup)

Related Work:
Lock-free Multi-P/C Stacks and Pools



- L-F stacks
  - [Michael, 2004]
    - Linked-list, one element/node
    - Global shared head pointer
  - [Michael, 2004] +
    Elimination [Hendler, Shavit & Yerushalami, 2004]
    - Same as the above + elimination of concurrent pairs of push and pop.
- L-F pool
  - [Afek, Korland, Natanzon & Shavit, 2010]
    - Tree of balancers with elimination + queues.

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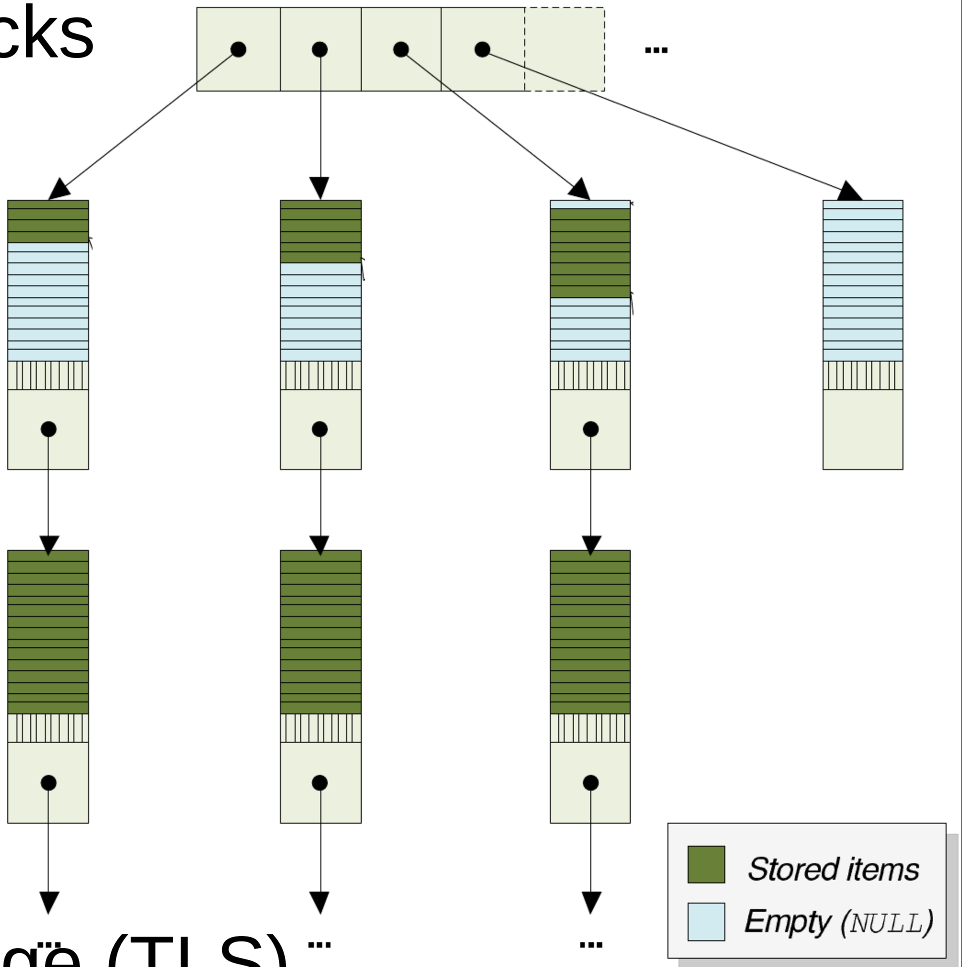
The Algorithm
Basic Idea

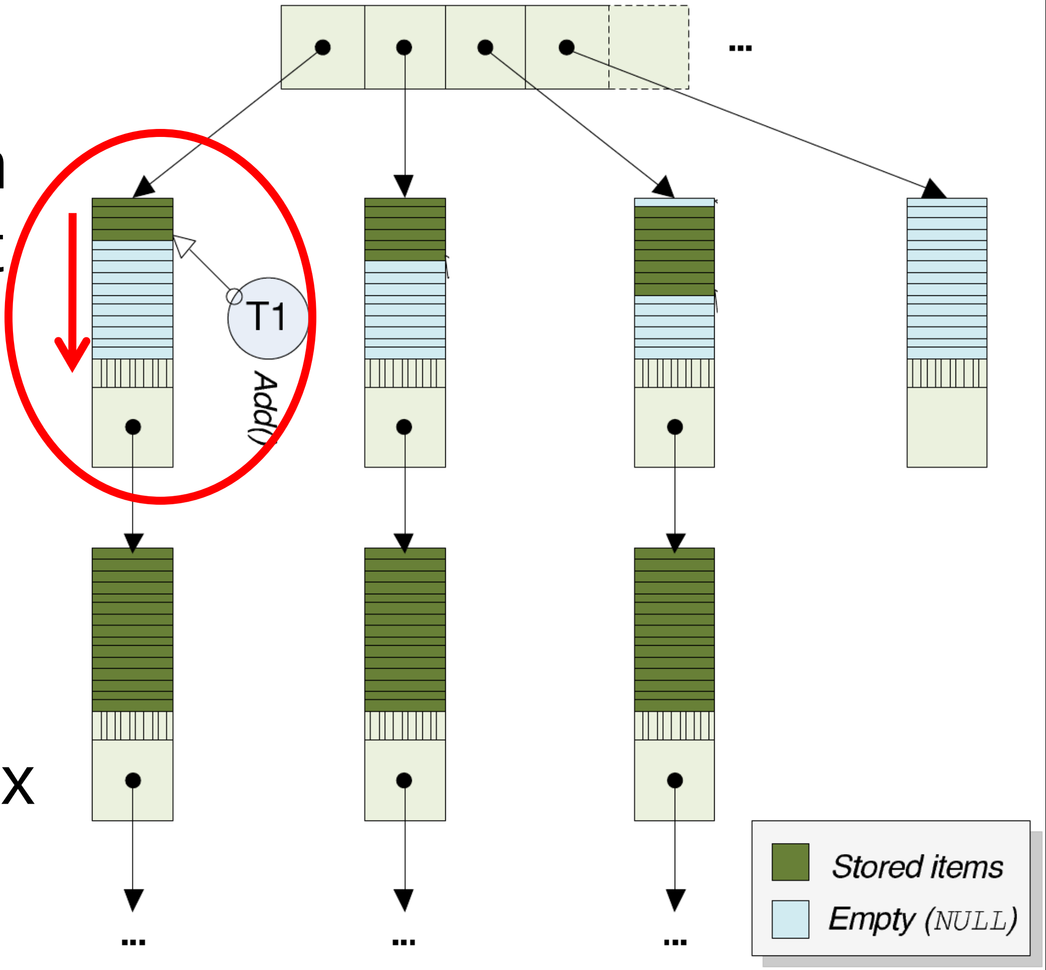
- Linked-lists of array blocks
  - One list per thread
    - Always used by Add()
    - TryRemoveAny() looks there first
  - Add()s by different threads do not contend
  - A TryRemoveAny() has a large number of blocks to choose from
    - Low risk for contention



- Static thread-local storage (TLS)
  - Used to avoid reading/writing shared state

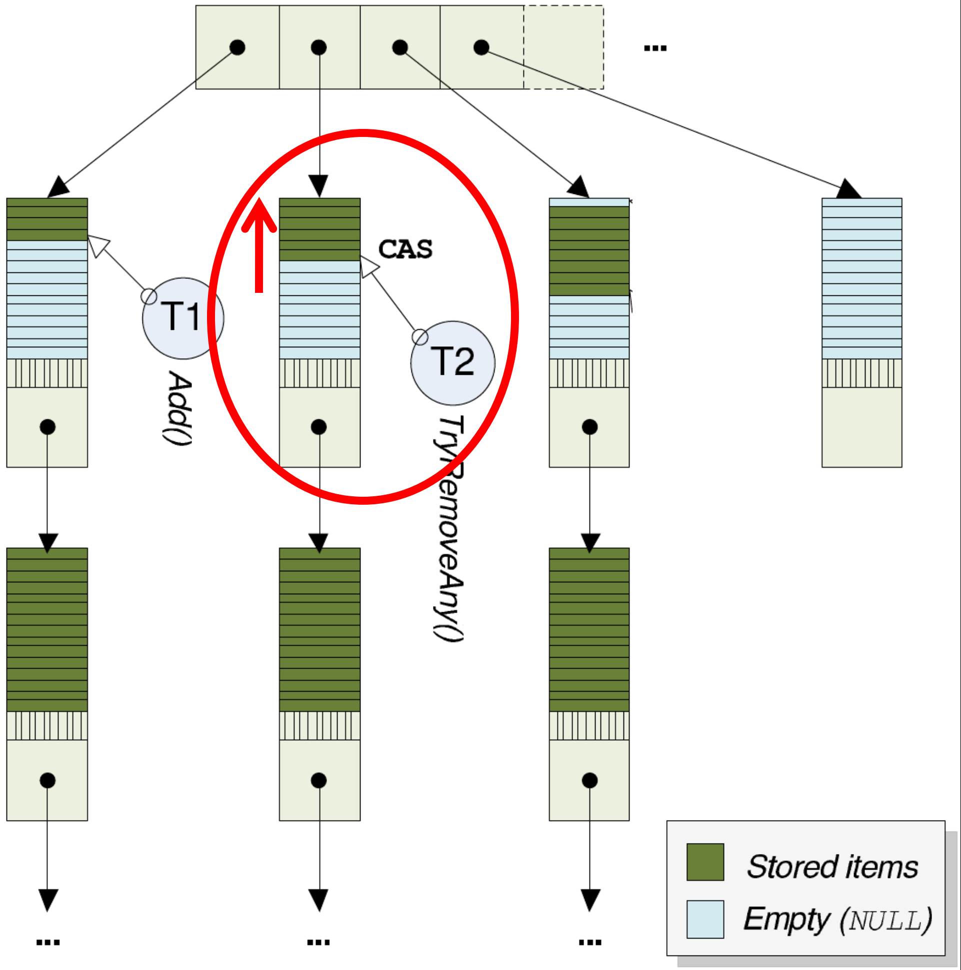
The Algorithm
Basic Idea

- Add()
  - Item is inserted in an empty slot in the first array block in the thread's list
  - A new first block is added when all slots have been used
  - The current slot index is stored in TLS



The Algorithm
Basic Idea

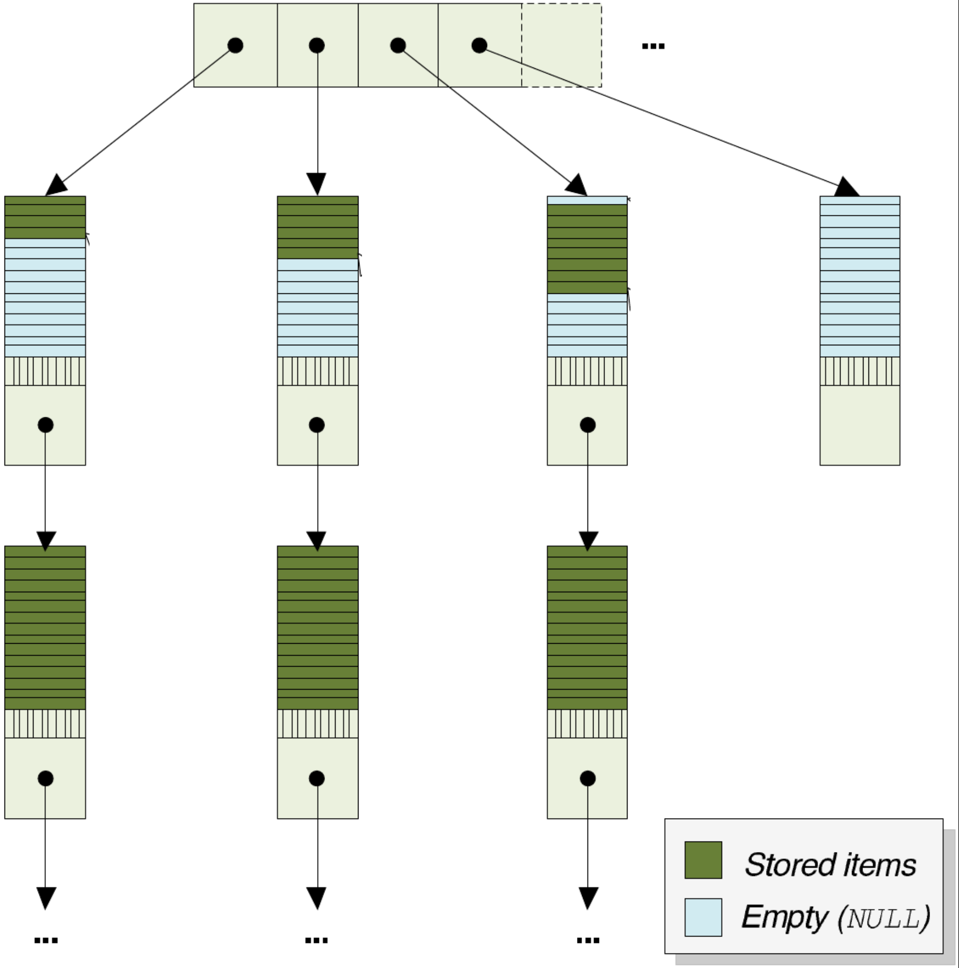
- TryRemoveAny()
  - The thread first scans the first block in its list (from the current index in TLS)
  - When an item is found it is removed via CAS
  - If the block is empty it is removed from the list



The Algorithm

Issues

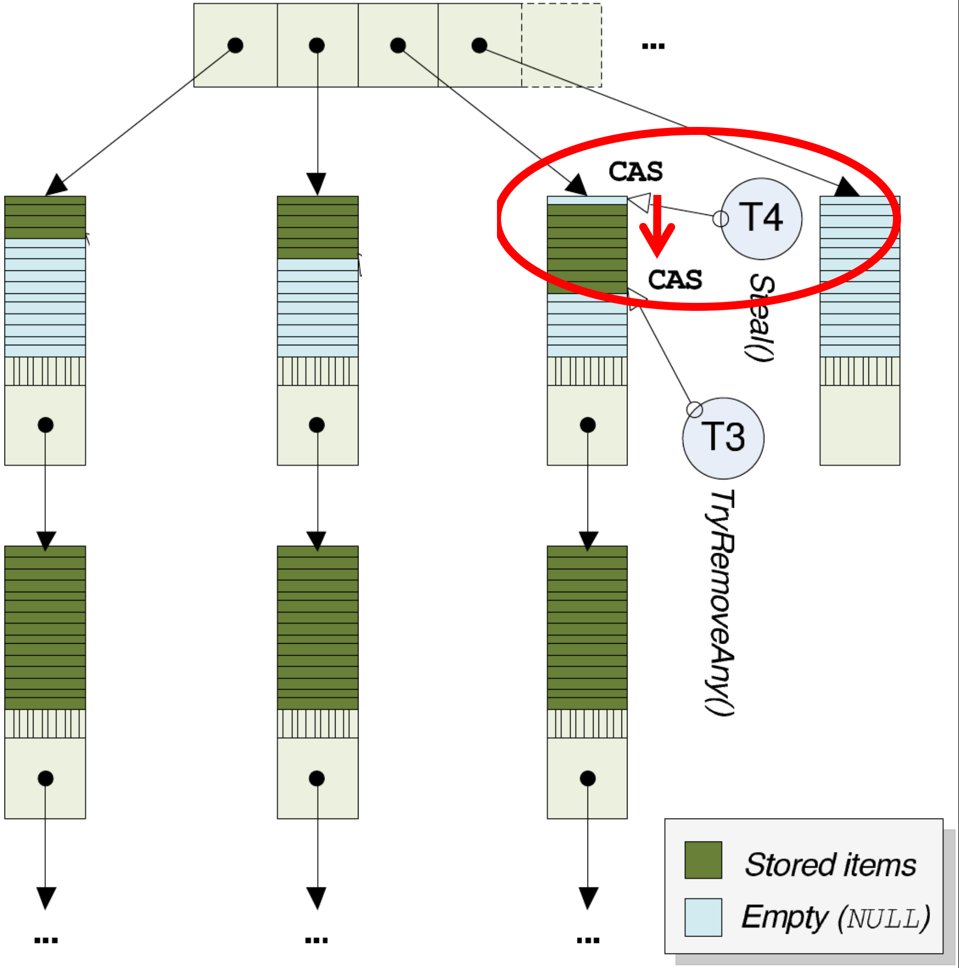
- Finding items when own list is empty
- Detecting that the bag is empty
- Managing the linked lists



The Algorithm

Finding items when the own list is empty

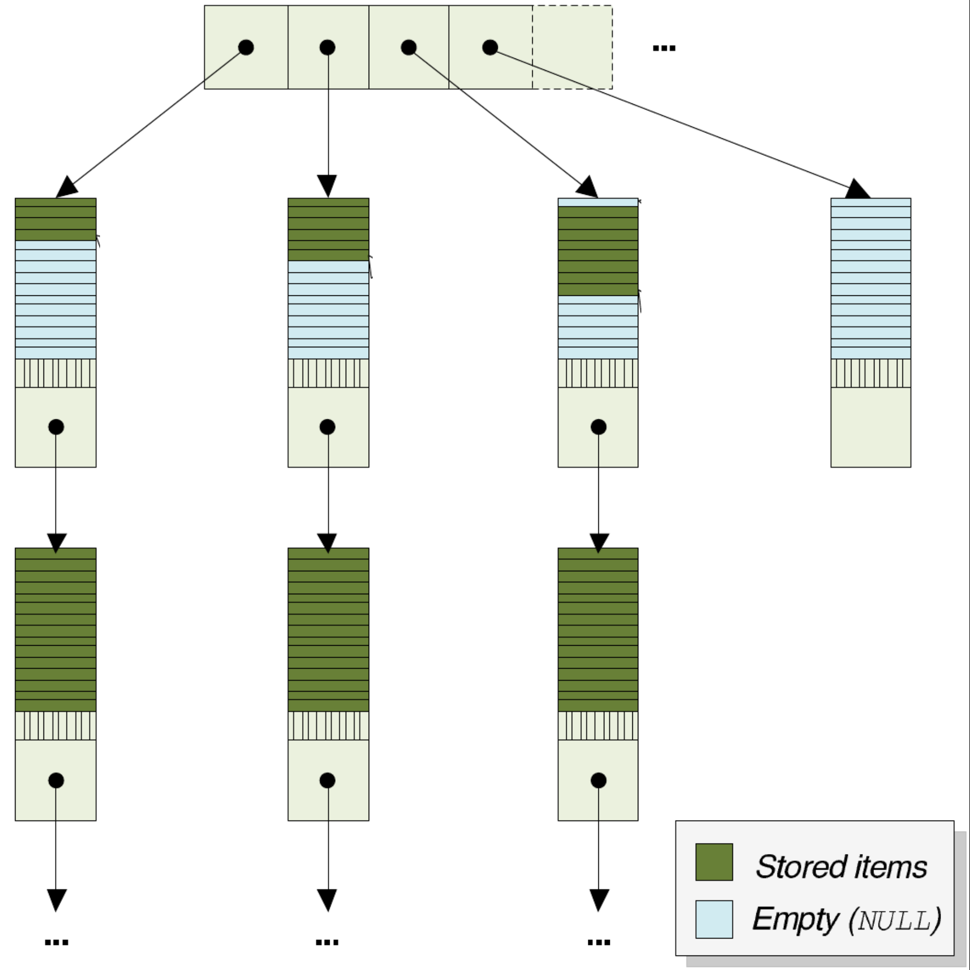
- Steal items from blocks belonging to other threads
  - Hence, CAS needed to remove items
- Never leave a block until it is empty
  - Help removing empty blocks



The Algorithm

Detecting that the bag is empty

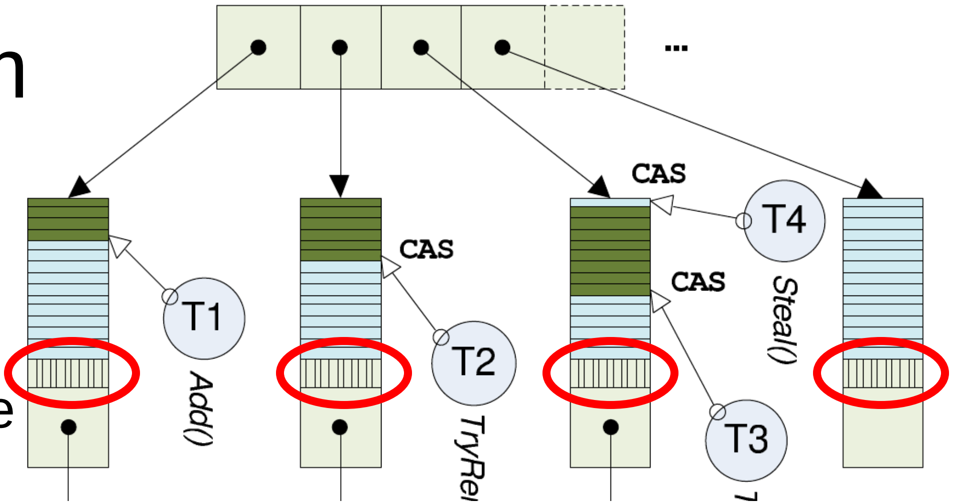
- No single place to look
- Scan all blocks of all threads
  - Items may be added concurrently
  - Items may be removed concurrently



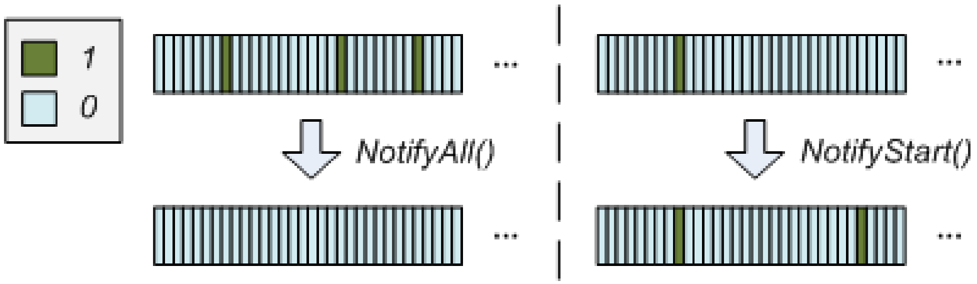
The Algorithm

Notification mechanism

- Per-block bit field
  - One bit for each thread
  - All bits cleared by Add()
  - Thieves set their bit before scanning the block



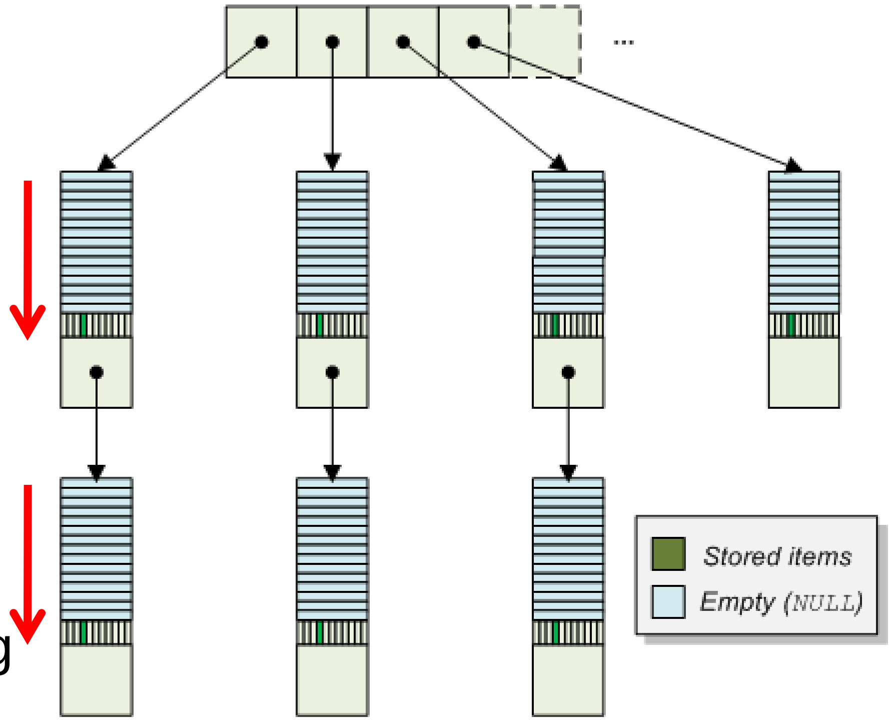
If the bit is still set for all blocks when the thief rescans the bag is empty?



The Algorithm

Notification mechanism

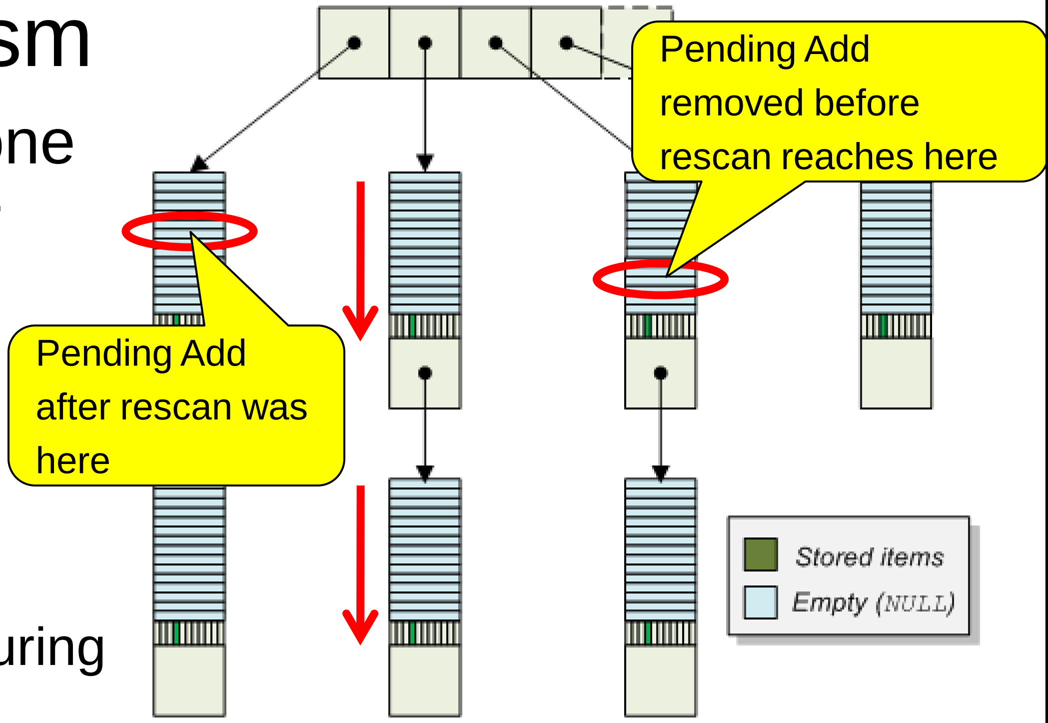
- No, there can still be one pending Add per other thread
  - Cleared the notify bits before the thief started scanning
  - Items can show up and disappear (removed) during the scan



The Algorithm

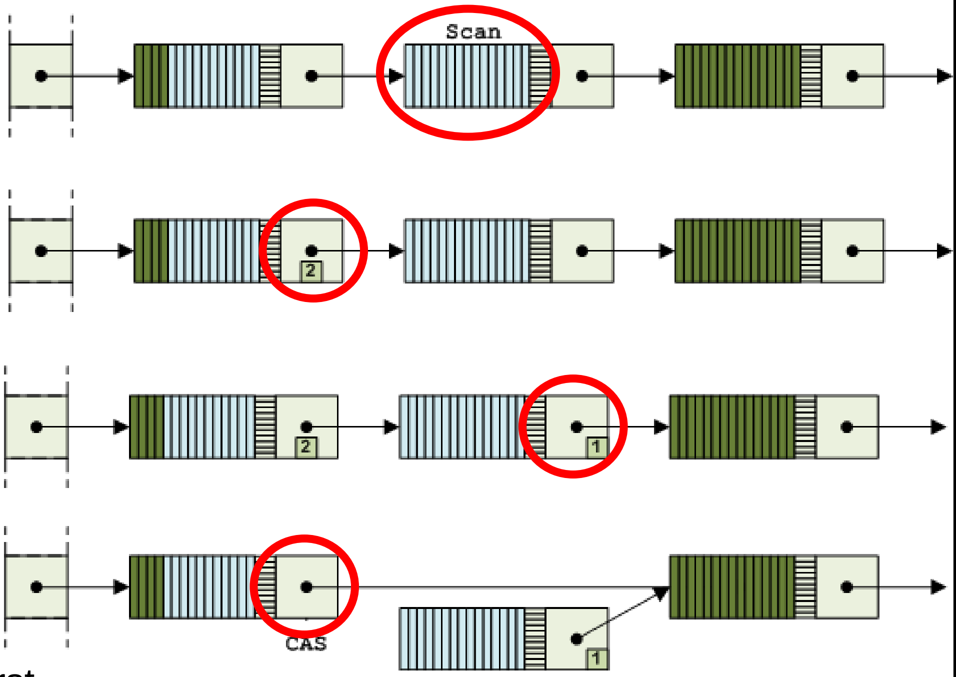
Notification mechanism

- No, there can still be one pending Add per other thread
  - Cleared the notify bits before the thief started scanning
  - Items can show up and disappear (removed) during the scan
- Rescan everything *#threads+1* times
  - if found empty in all scans it truly was empty



The Algorithm
Managing the linked lists

- Removing blocks
  - When the block is scanned and found empty it is marked logically deleted, with mark1
    - By owner
      - No problem
    - By thief
      - Must not be the first block in the linked-list since owner may add items there
      - Mark the preceding block with mark2 first
        - The block cannot be the first
        - Prevents the block from becoming the first block



  - Seeing mark1 or mark2 invokes helping
- Memory management
  - (Modified) Hazard pointers scheme [Michael, 2002]

The Algorithm
Managing the linked lists

- Properties
  - Only the owner can remove the first block
  - The last block of each linked-list cannot be removed
  - Thieves can remove any other block found empty
- So
  - After an linked list has been scanned by TryRemoveAny() there can be at most 2 empty blocks in it
  - Hence, a thread finding the bag empty will have no more than *2*#threads* blocks to traverse once it has helped any pending removals (at most 1 per thread)

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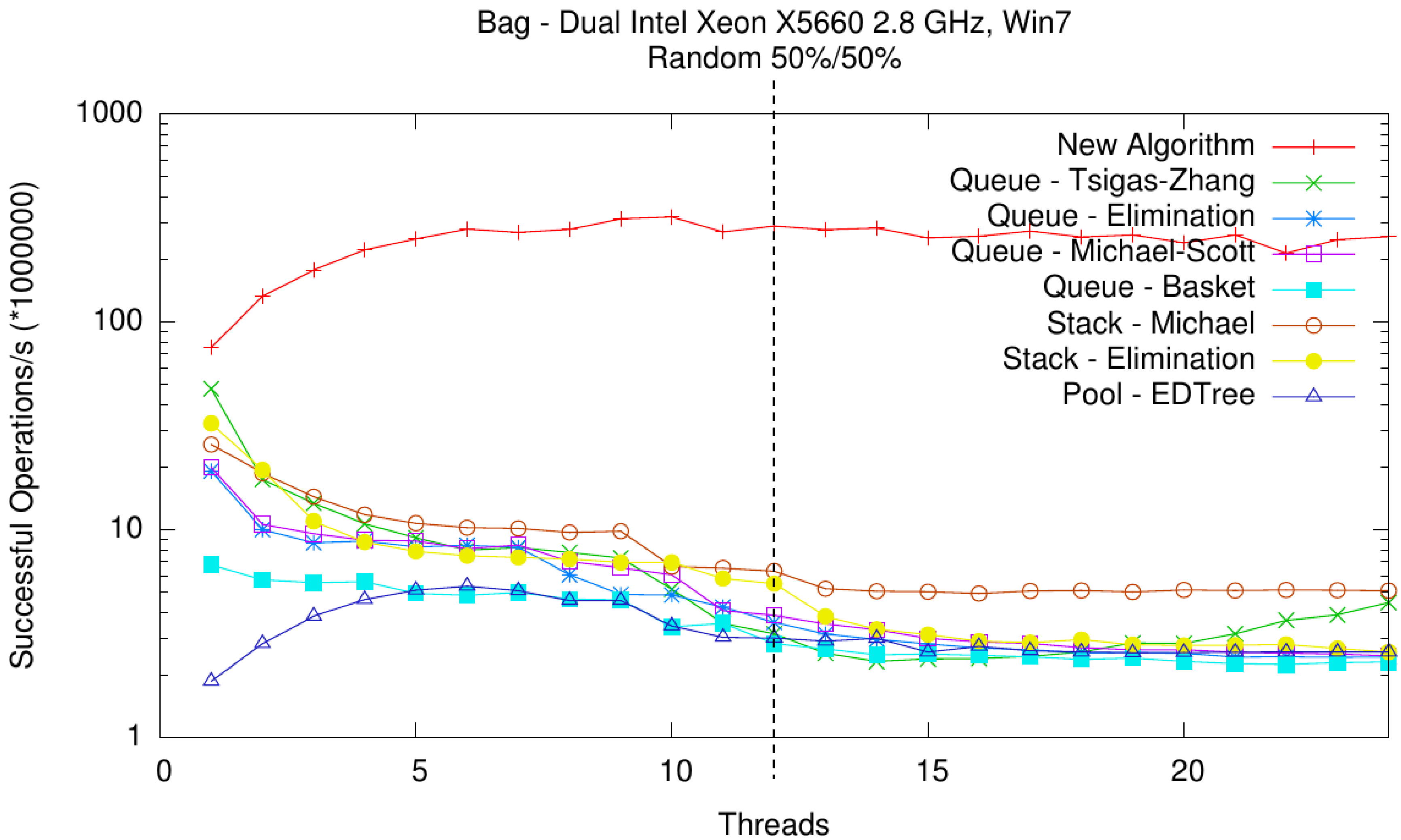
Experimental evaluation

- Micro benchmark
  - Threads execute Add and TryRemoveAny operations on a shared bag
    - High contention
  - Test Configurations
    1. Random *50% / 50%*, initial size *0*
    2. *1* Producer / *N-1* Consumers, initial size *0*
    3. *N-1* Producers / *1* Consumer, initial size *0*
    4. *N/2* Producers / *N/2* Consumers, initial size *0*
  - Measured throughput in items/sec
    - #TryRemoveAny not returning EMPTY
- Application
  - Parallel computation of Mandelbrot set
  - Producer/Consumer pattern

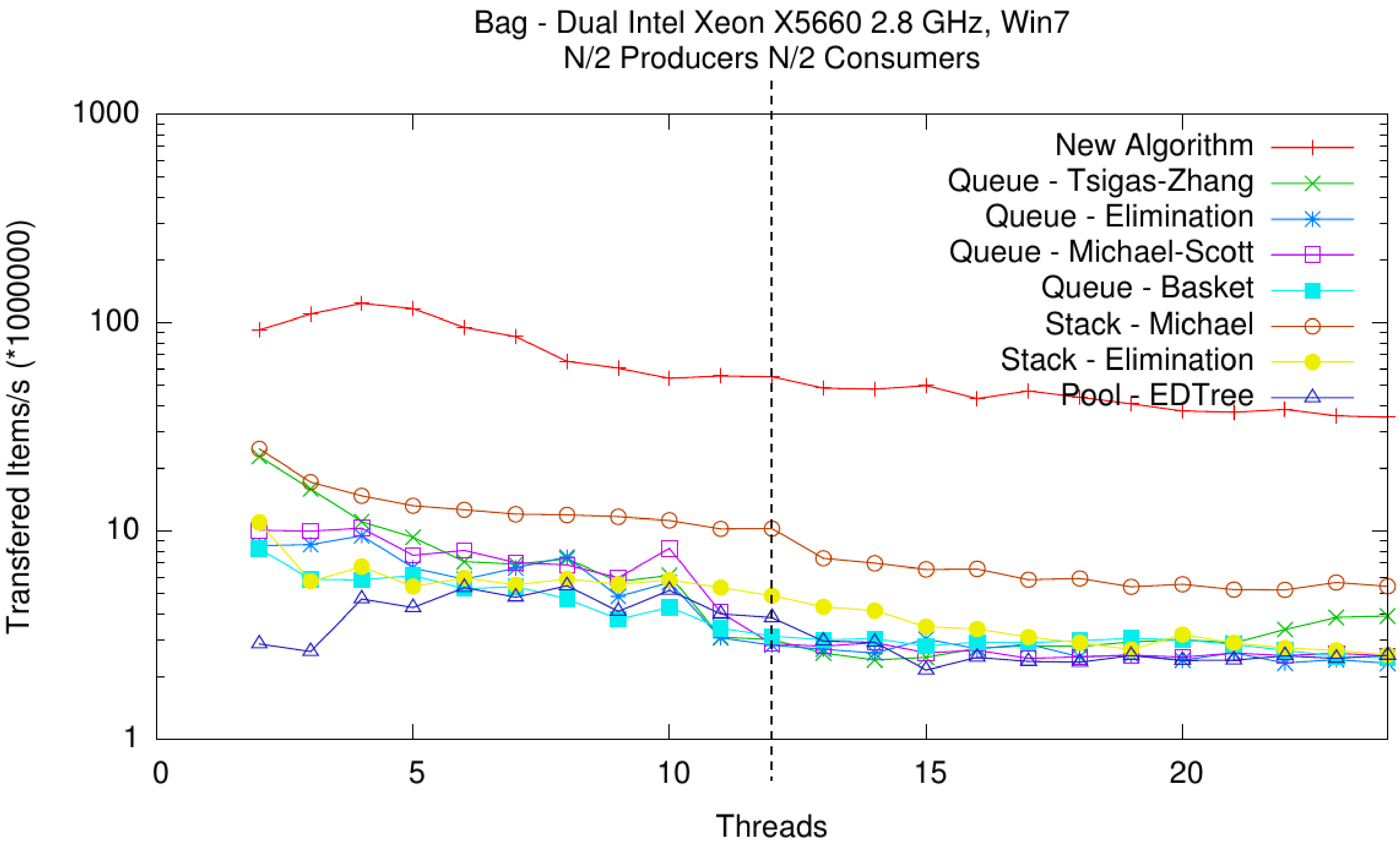
Experimental evaluation

- Algorithms
  - L-F queue [Michael & Scott, 1996]
  - L-F queue [Michael & Scott, 1996] + Elimination [Moir, Nussbaum, Shalev & Shavit, 2005]
  - L-F queue [Tsigas & Zhang, 2001]
  - L-F queue [Hoffman, Shalev & Shavit, 2007]
  - L-F stack [Michael, 2004]
  - L-F stack [Michael, 2004] + Elimination [Hendler, Shavit & Yerushalami, 2010]
  - L-F pool [Afek, Korland, Natanzon & Shavit, 2010]
  - The new L-F bag [Gidenstam, Sundell, Papatriantafilou & Tsigas, 2011]
- PC Platform
  - CPU: 2x Intel Xeon X5660 @ 2.8 GHz
  - 6 cores per CPU with 2 hardware threads each => **12 cores, 24 hw threads**
  - RAM: 12 GB DDR3 @ 1333 MHz
  - Windows 7 64-bit

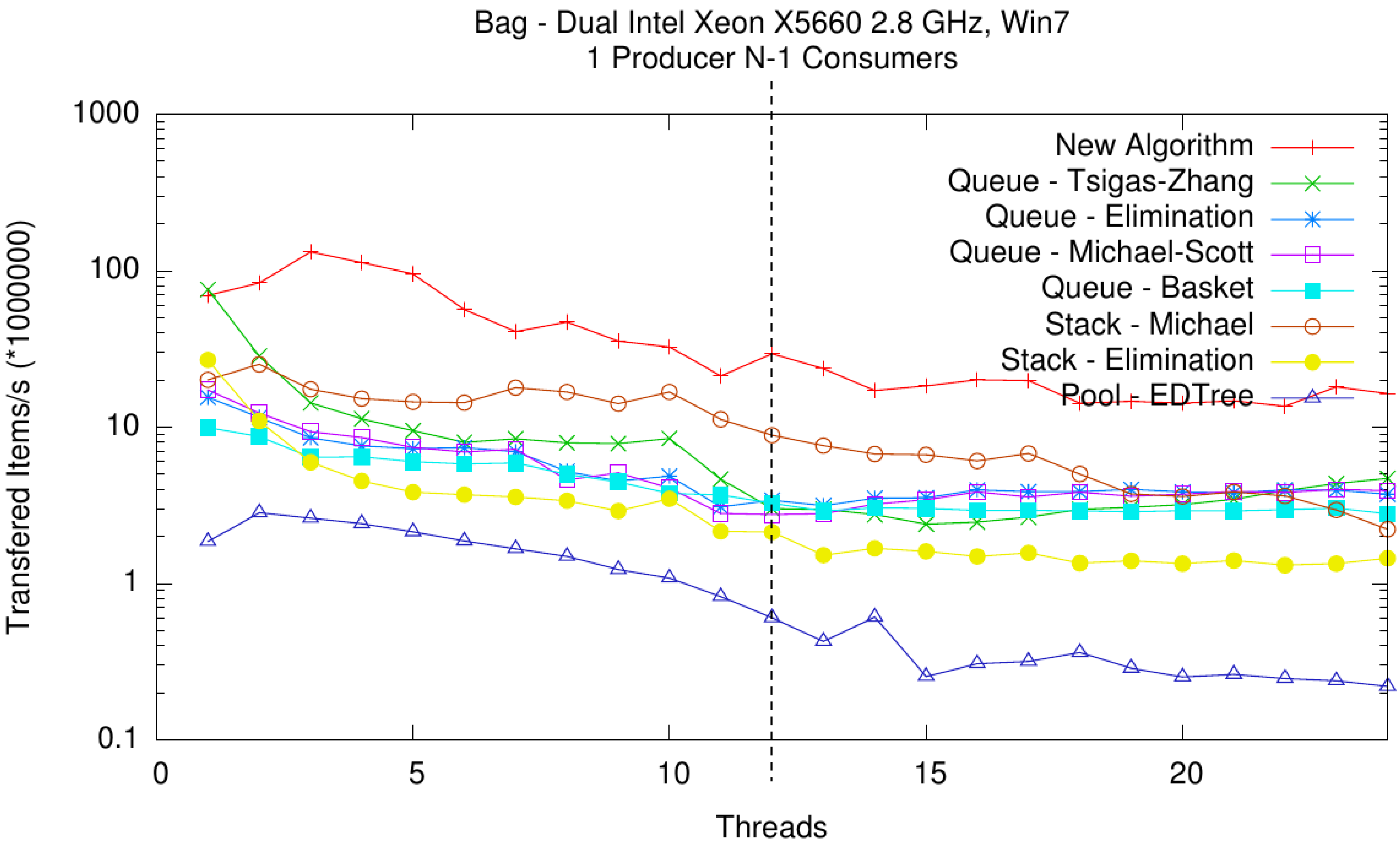
Experimental evaluation (i)



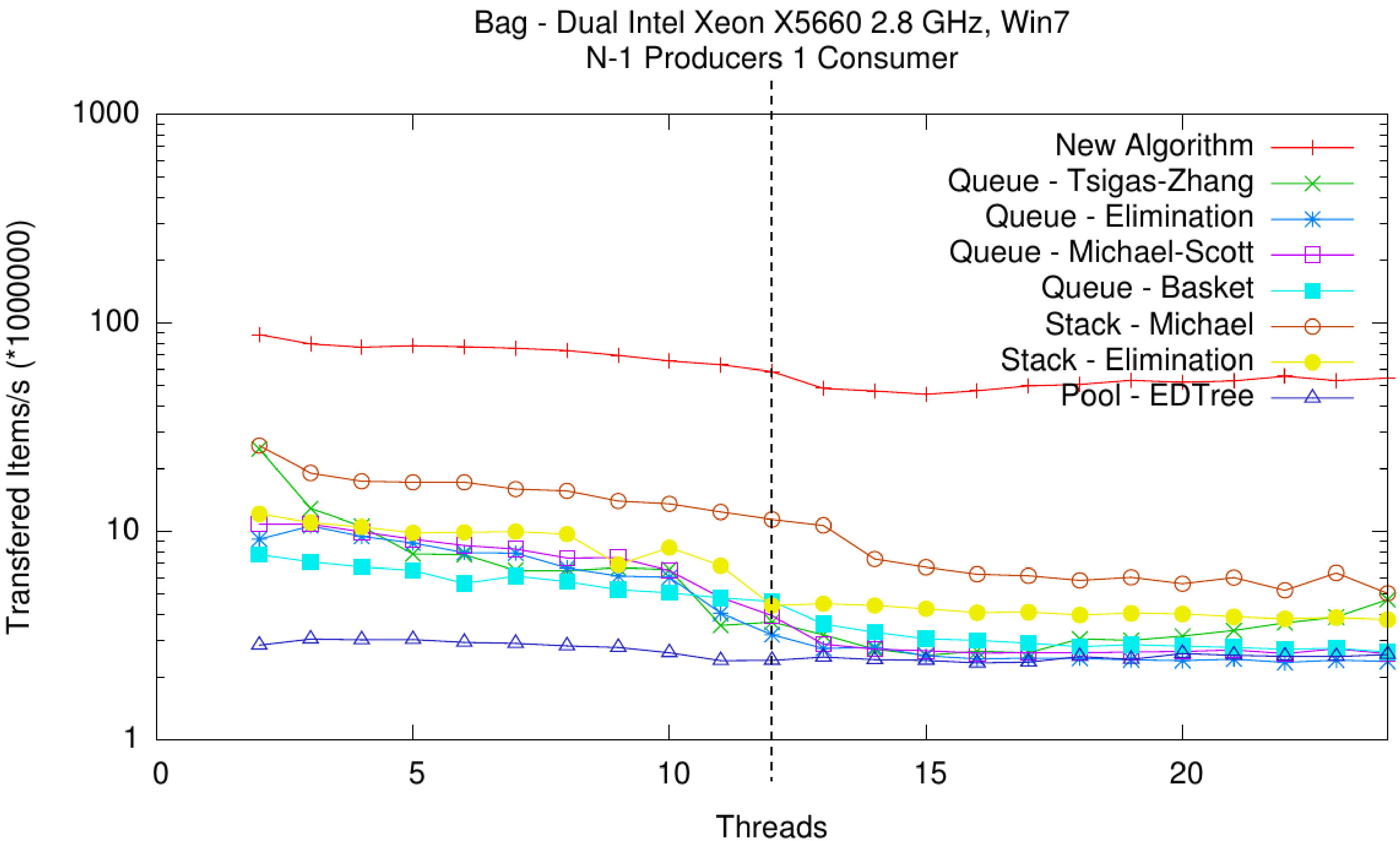
Experimental evaluation (ii)



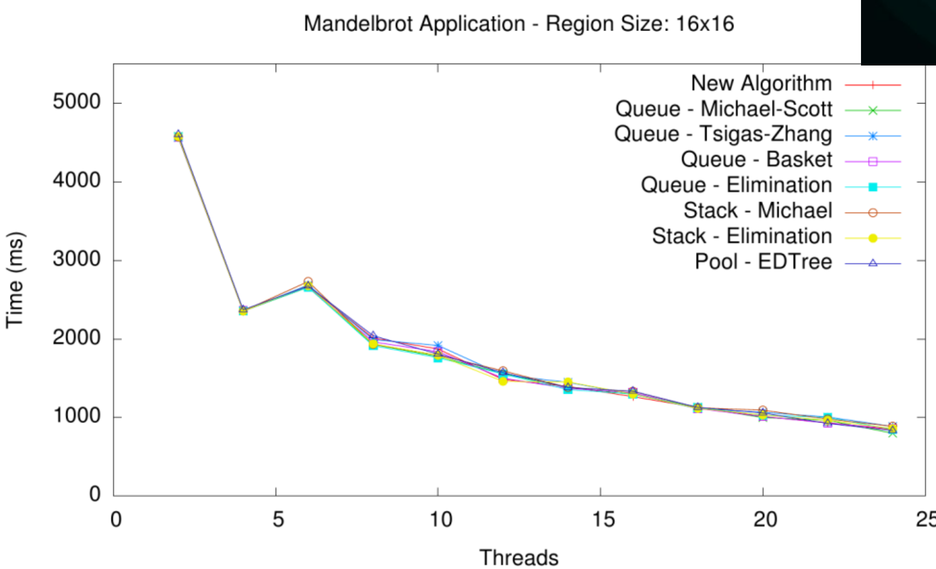
Experimental evaluation (iii)

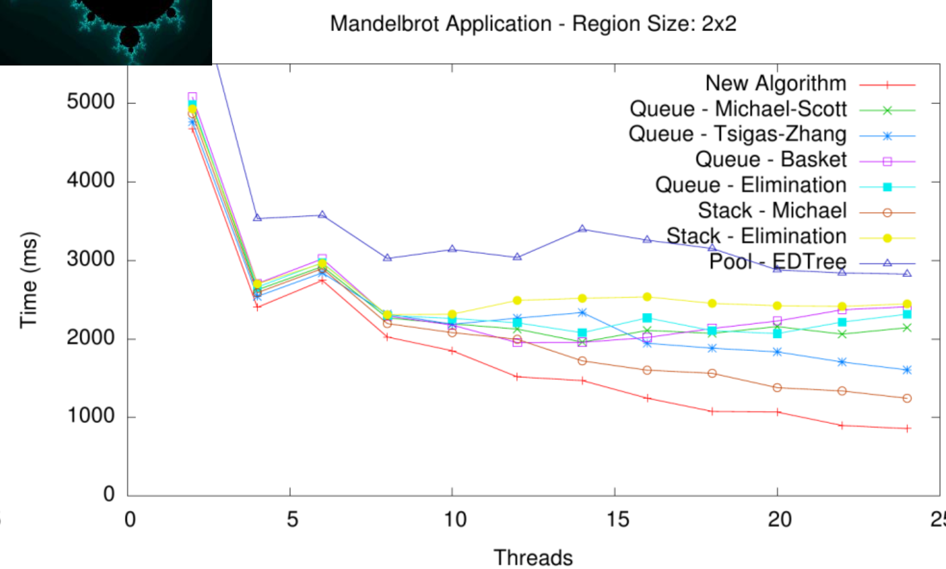


Experimental evaluation (iv)



Experimental evaluation (v)
Parallel application for the Mandelbrot set





- 16x16 chunks: Large work units
  => Low contention on the shared data structure (bag)
- 2x2 chunks: Small work units
  => High contention. The bag implementation matters

Conclusions

- Lock free and linearizable algorithm for a concurrent bag producer/consumer collection data structure
  - Distributed design, promoting access-parallelism.
  - Exploiting thread-local static storage.
  - Dynamic in size via lock-free memory management.
  - Only requires atomic primitives available in contemporary systems.

Thank you for listening!

Questions?