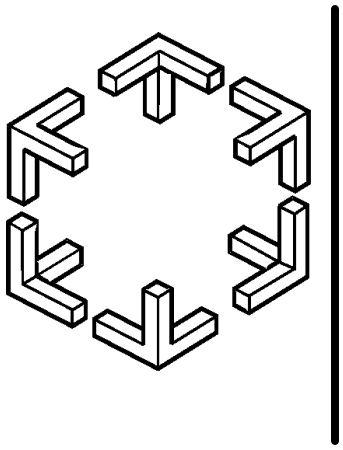

Efficient and Reliable Lock-Free Memory Reclamation Based on Reference Counting

Anders Gidenstam, Marina Papatriantafilou, Håkan Sundell and Philippas Tsigas

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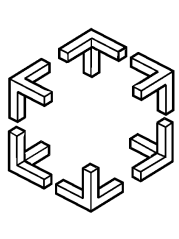
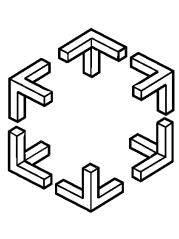
Chalmers University of Technology



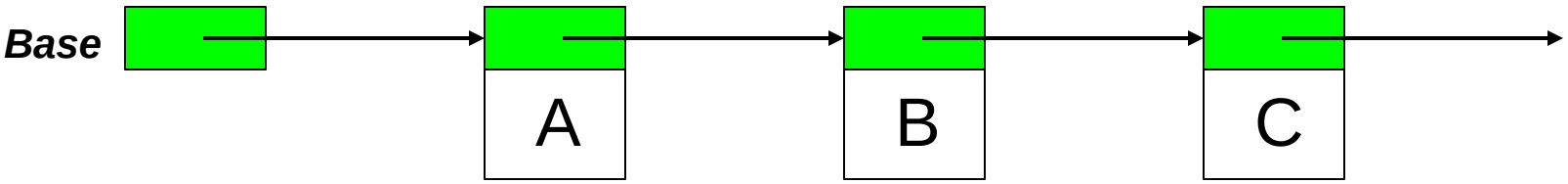
Outline

- Introduction
  - The Problem
  - Lock-free synchronization
- Our solution
  - Idea
  - Properties
- Experiments
- Conclusions

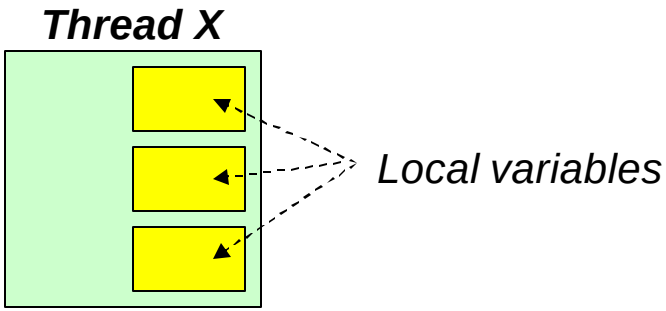


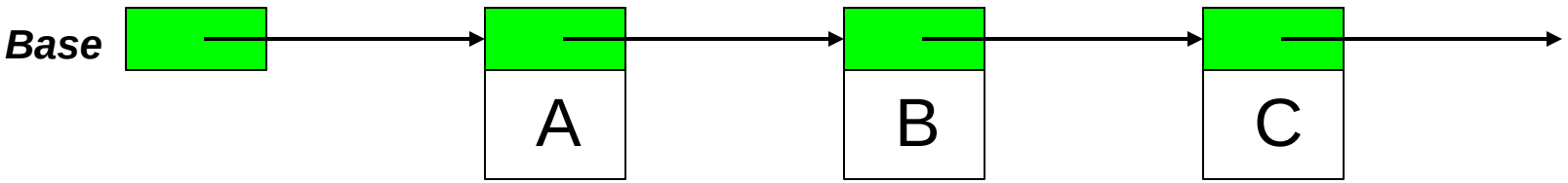
The Lock-Free Memory Reclamation Problem

- Concurrent shared data structure
  - Dynamic use of shared memory
  - Concurrent and overlapping operations by threads or processes

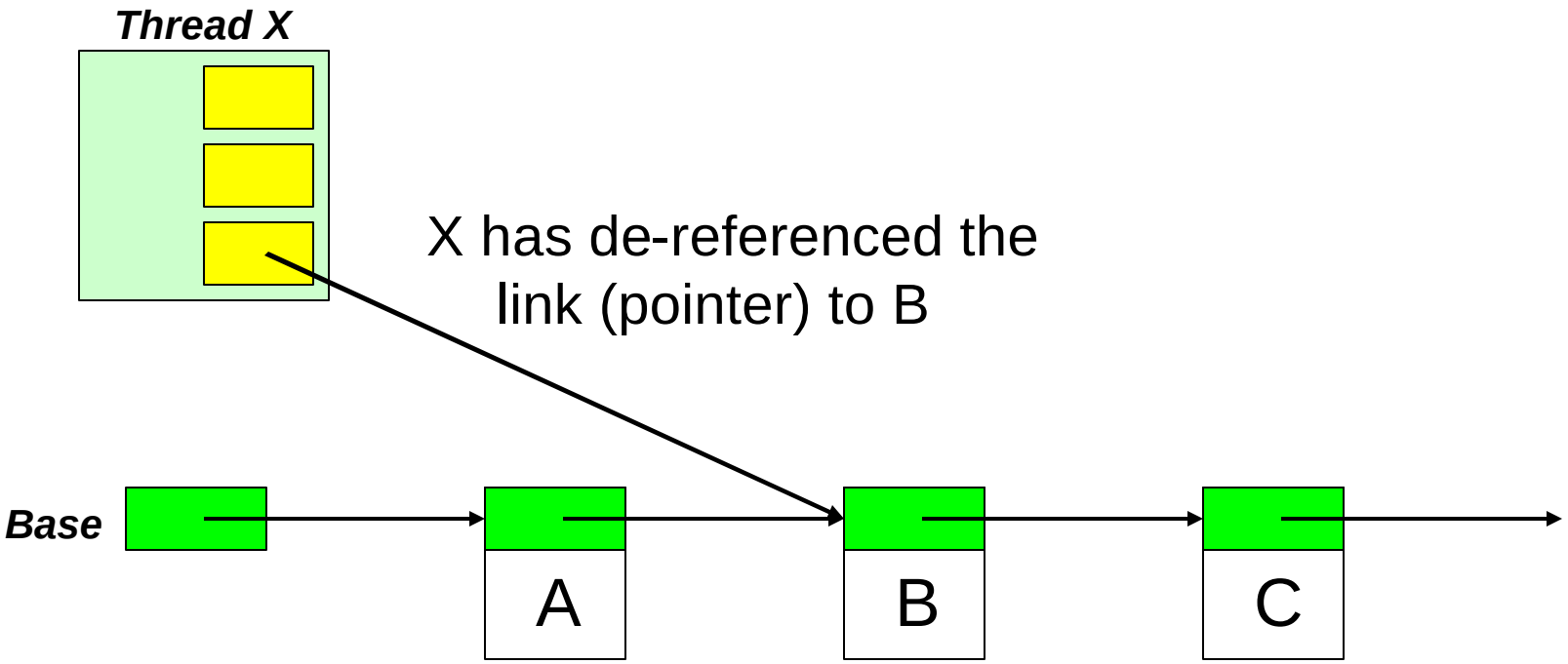


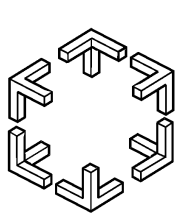
The Lock-Free Memory Reclamation Problem





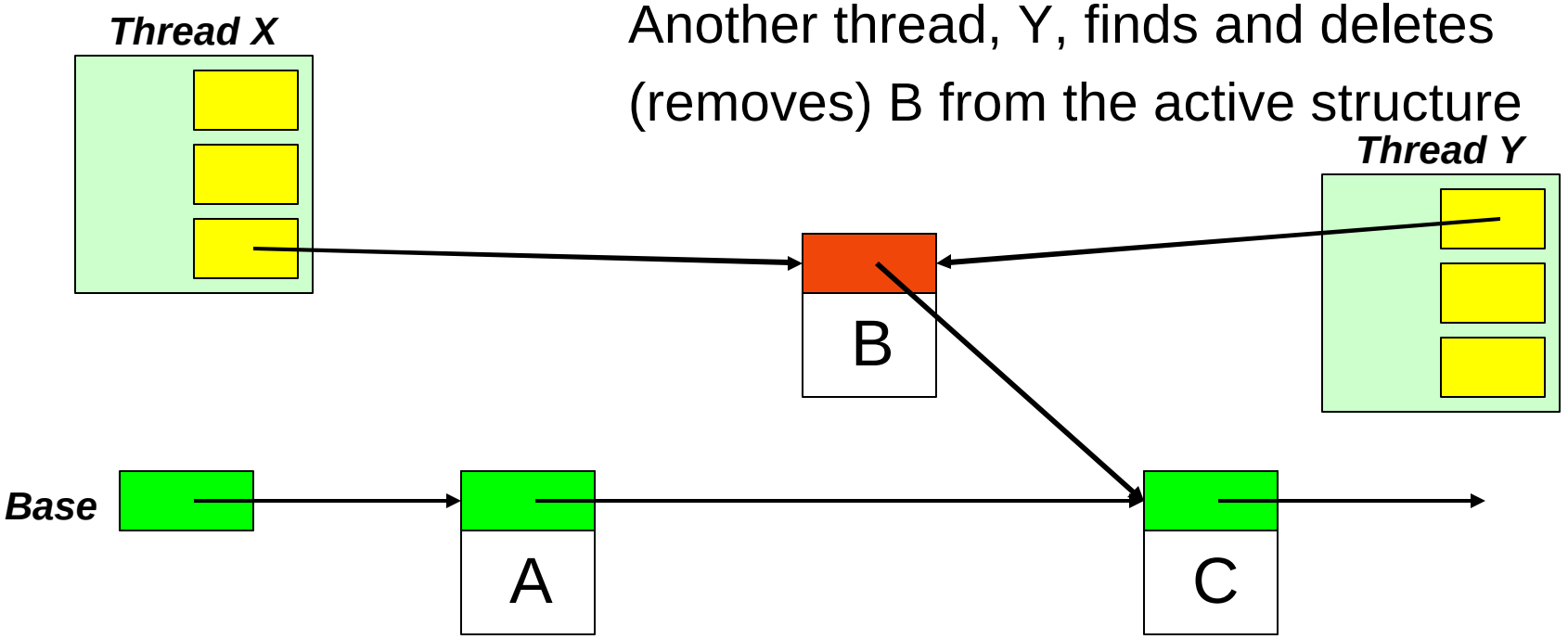
The Lock-Free Memory Reclamation Problem





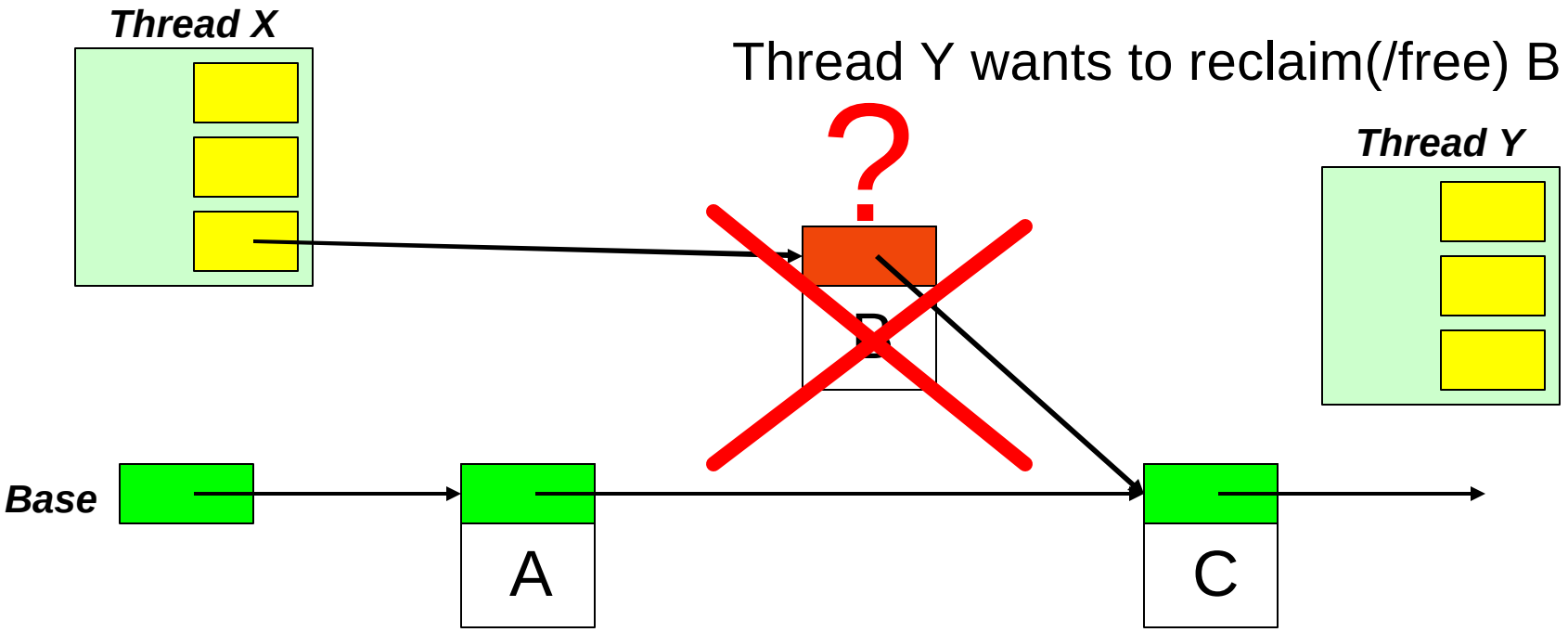
The Lock-Free Memory Reclamation Problem

Another thread, Y, finds and deletes (removes) B from the active structure



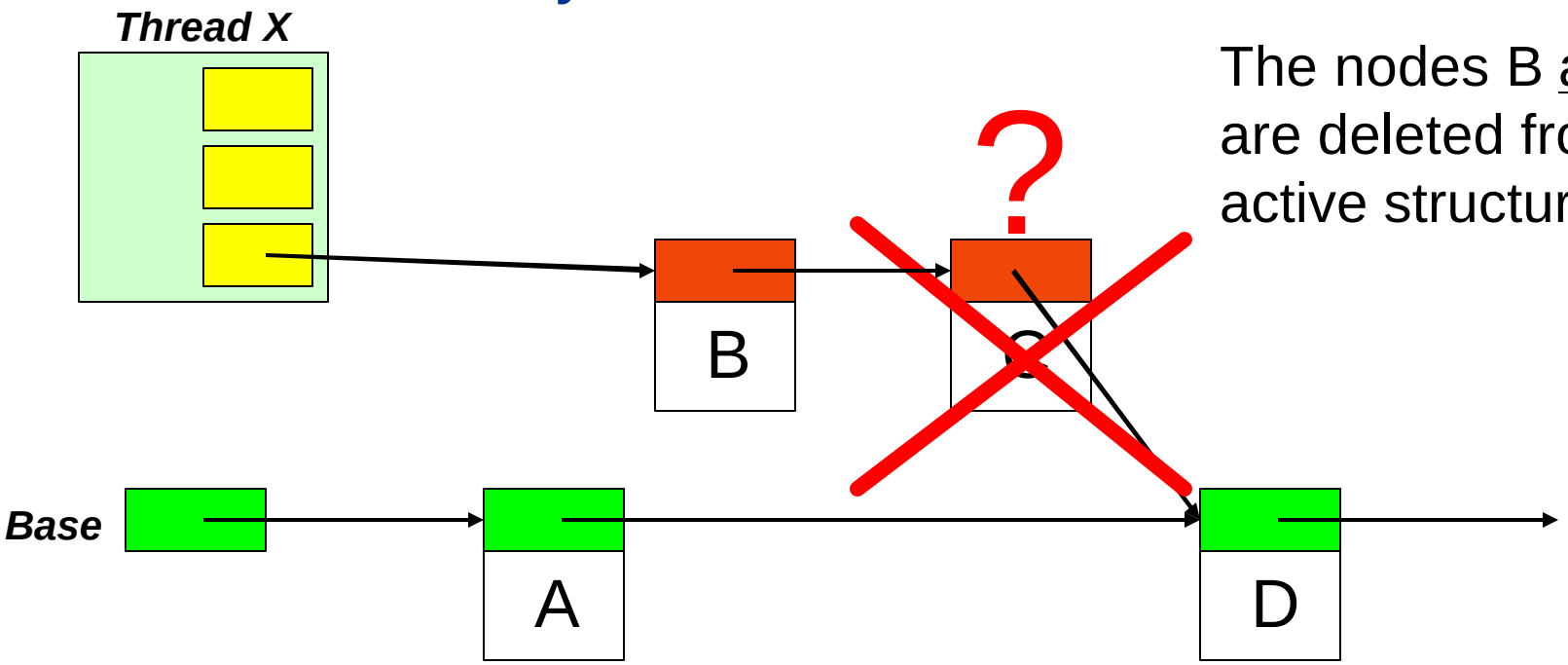
The Lock-Free Memory Reclamation Problem

Property I: A (de-)referenced node is not reclaimed

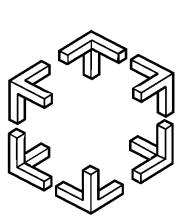


The Lock-Free Memory Reclamation Problem

Property II: Links in a (de-)referenced node should always be de-referencable.



The nodes B and C are deleted from the active structure.

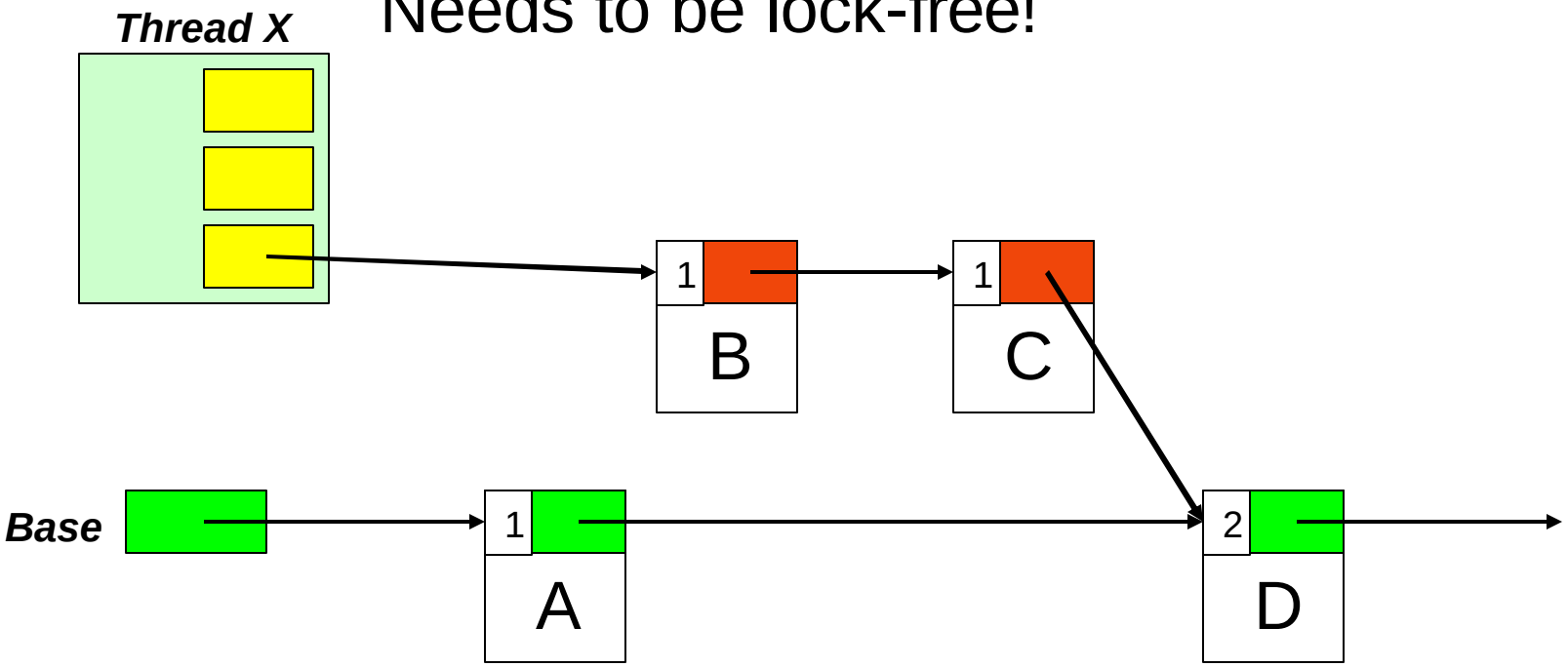


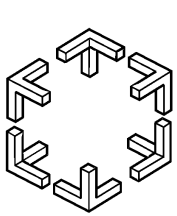
The Lock-Free Memory Reclamation Problem

Solutions?

- Garbage collection?
- Reference counting?

Needs to be lock-free!



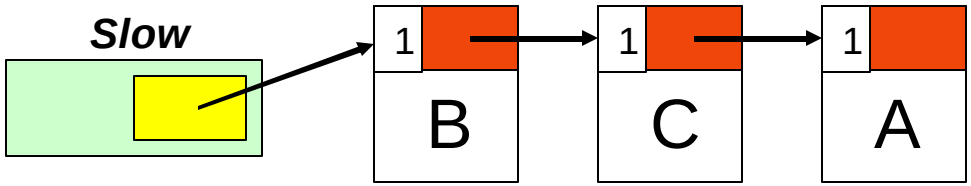


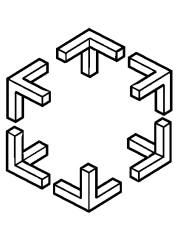
Lock-free synchronization

- A lock-free shared data structure
  - Allows concurrent operations without enforcing mutual exclusion (i.e. no locks)
  - Guarantees that at least one operation always makes progress
  - Avoids:
    - Blocking, deadlock and priority inversion
- Hardware synchronization primitives
  - Built into CPU and memory system
    - Typically: atomic read-modify-write instructions
  - Examples
    - Test-and-set, Compare-and-Swap, Load-Linked / Store-Conditional

Previous solutions

- Lock-free Reference Counting
  - Valois + Michael & Scott 1995
  - Detlefs et al. 2001
  - Herlihy et al. 2002
- Remaining issues
  - A slow thread might prevent reclamation
  - Cyclic garbage
  - Implementation practicality issues
    - Reference-count field MUST remain forever (Valois + Michael & Scott)
    - Needs double word CAS (Detlefs et al.)
    - Needs double width CAS (Herlihy, 2002)
    - Large overhead



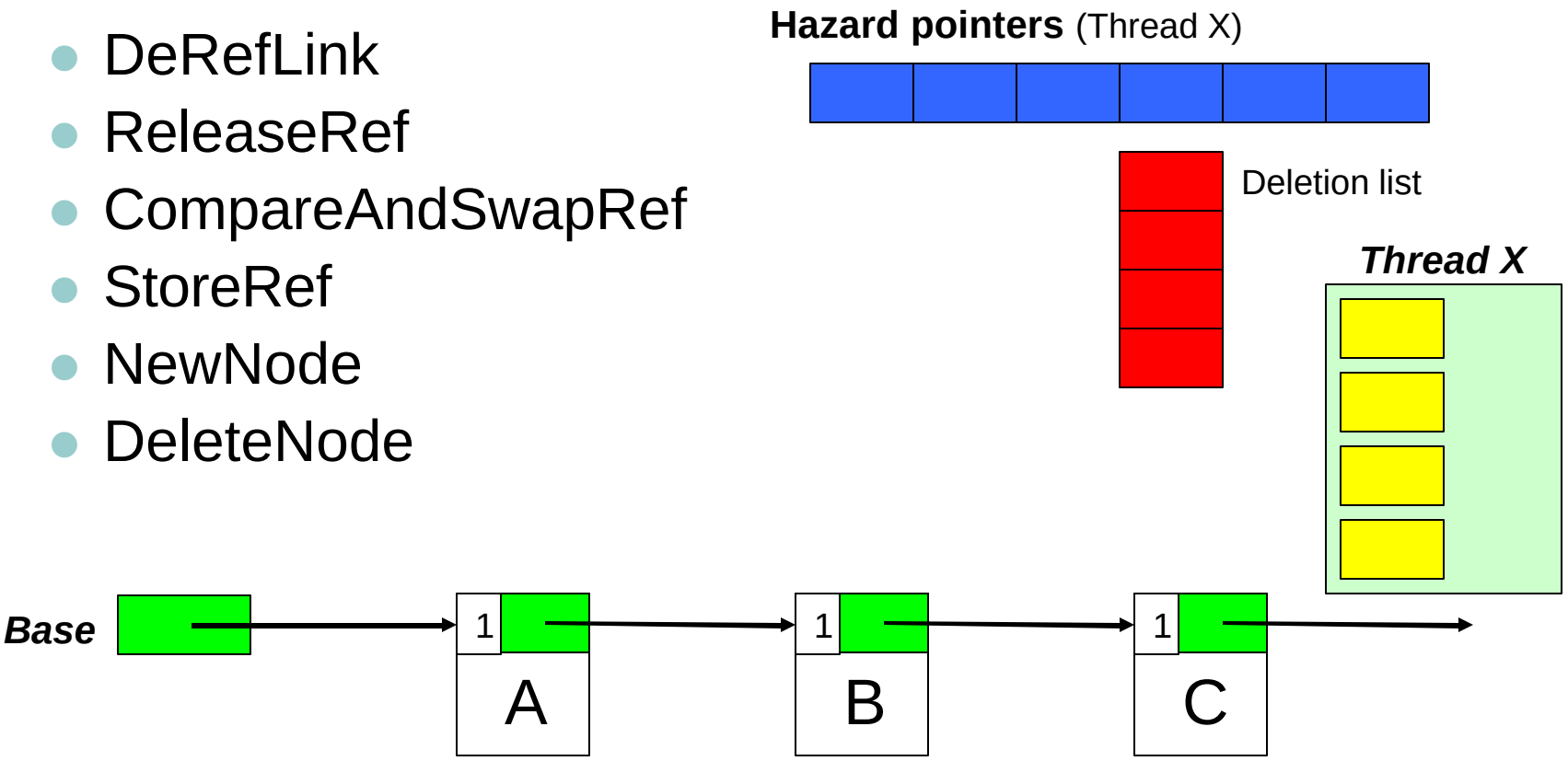


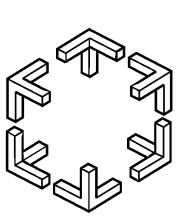
Our approach – The basic idea

- Combine the best of
  - Hazard pointers (Michael 2002)
    - Tracks references from threads
    - Fast de-reference
    - Upper bound on the amount of unreclaimed deleted nodes
    - Compatible with standard memory allocators
  - Reference counting
    - Tracks references from links in shared memory
      - Manages links within dynamic nodes
      - Safe to traverse links (also) in deleted nodes
- Practical
  - Uses only single-word Compare-And-Swap

The basic idea

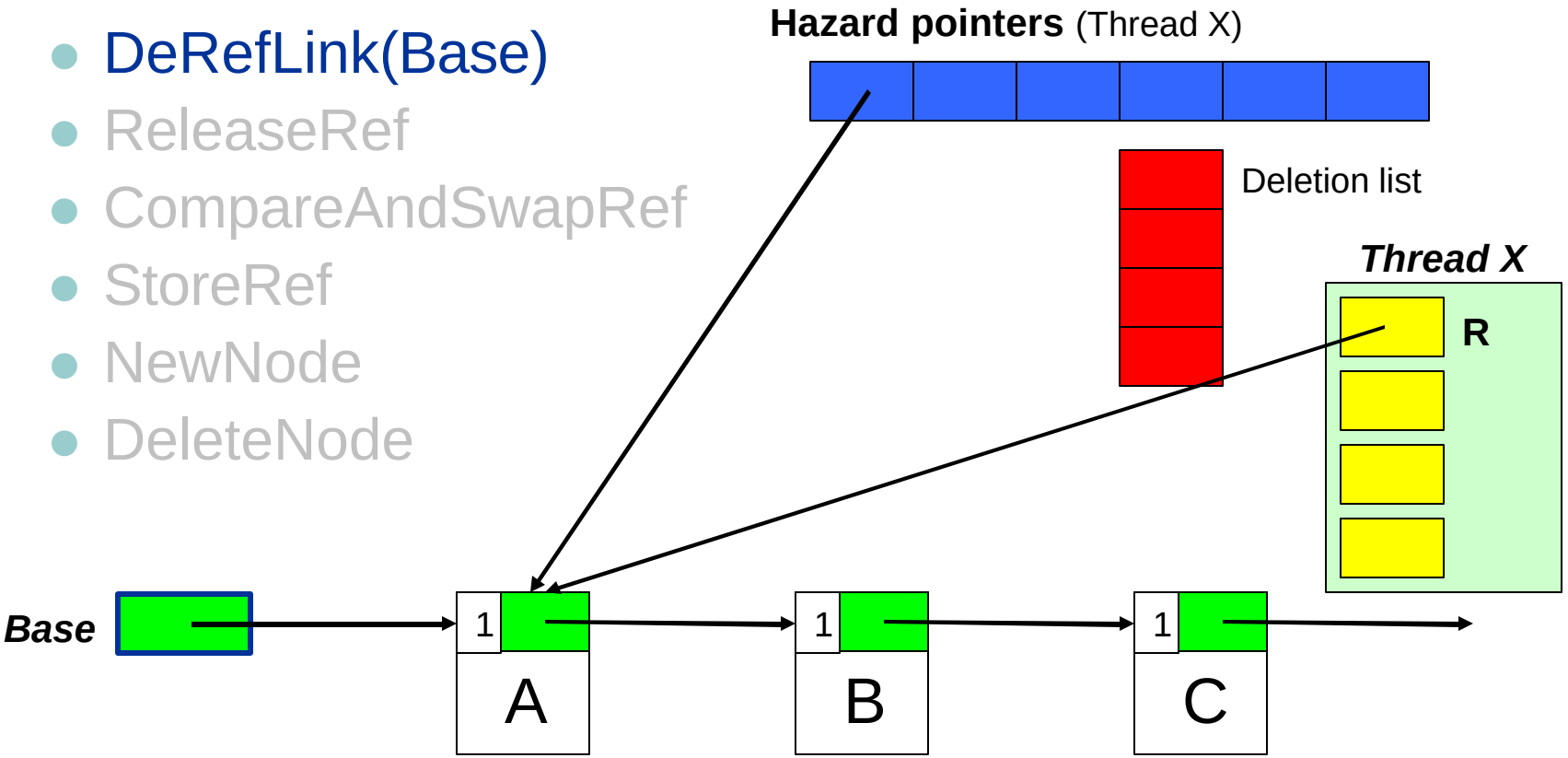
- API
  - DeRefLink
  - ReleaseRef
  - CompareAndSwapRef
  - StoreRef
  - NewNode
  - DeleteNode





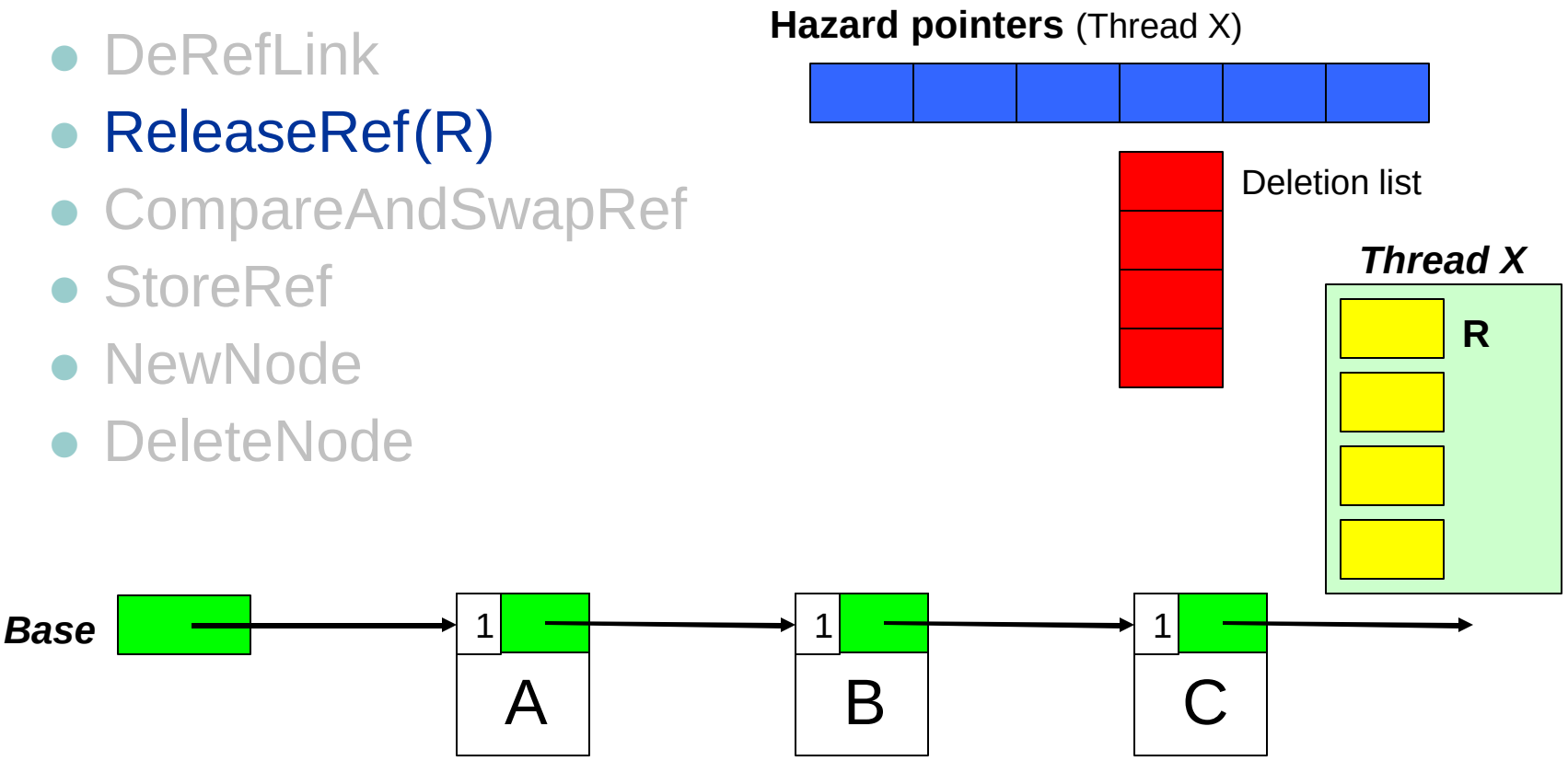
The basic idea

- API
  - DeRefLink(Base)
  - ReleaseRef
  - CompareAndSwapRef
  - StoreRef
  - NewNode
  - DeleteNode



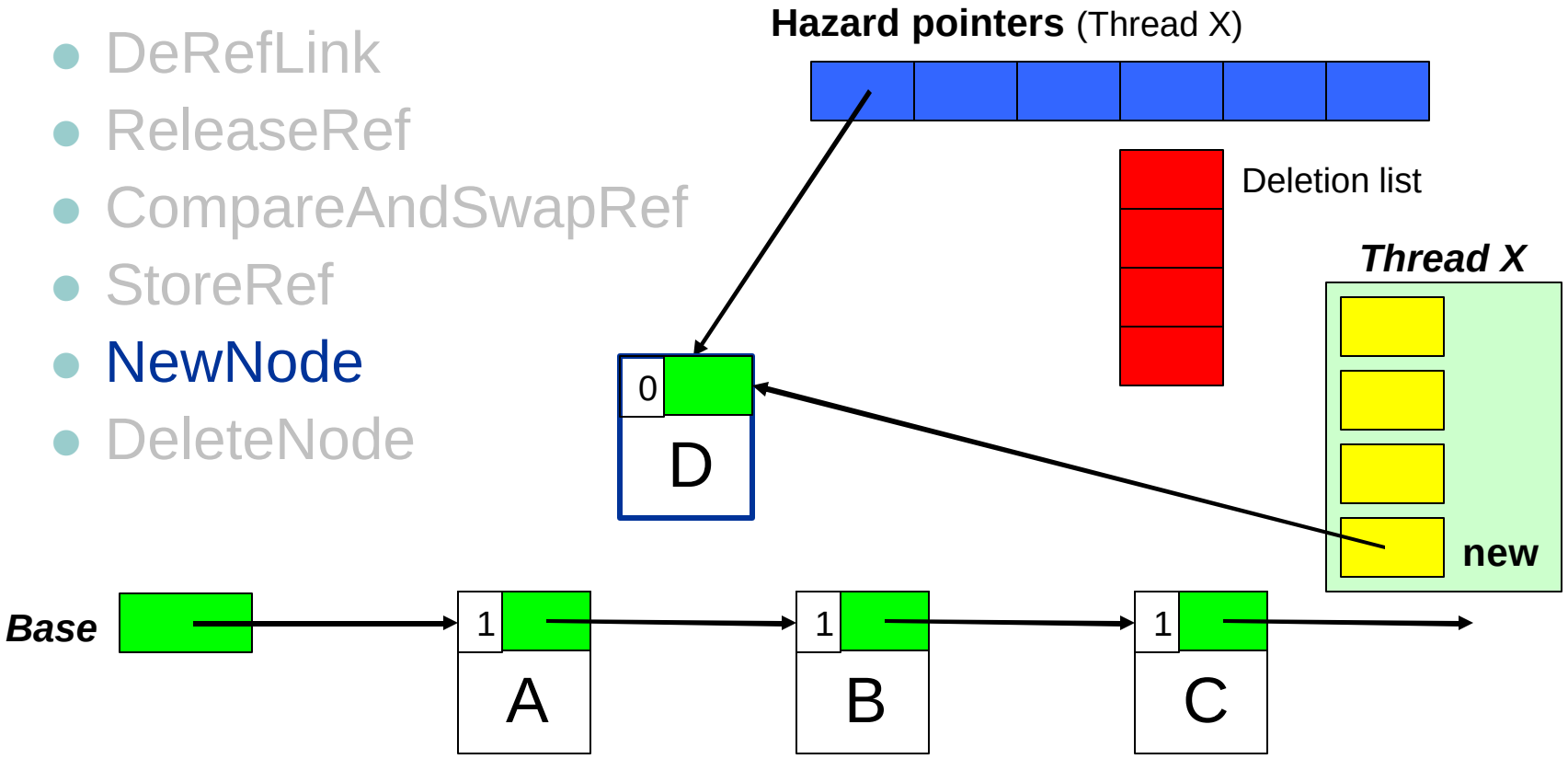
The basic idea

- API
  - DeRefLink
  - ReleaseRef(R)
  - CompareAndSwapRef
  - StoreRef
  - NewNode
  - DeleteNode



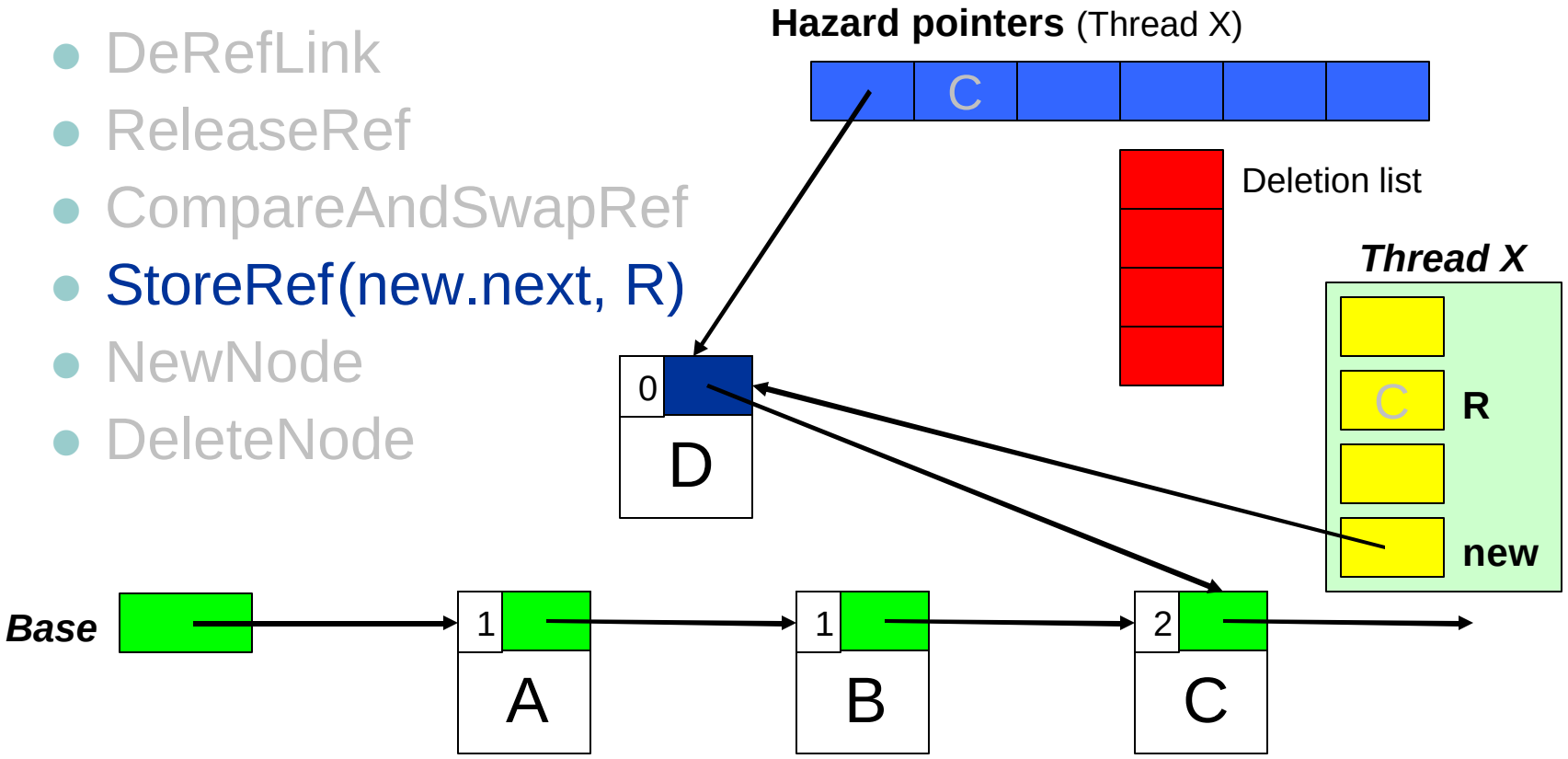
The basic idea

- API
  - DeRefLink
  - ReleaseRef
  - CompareAndSwapRef
  - StoreRef
  - NewNode
  - DeleteNode



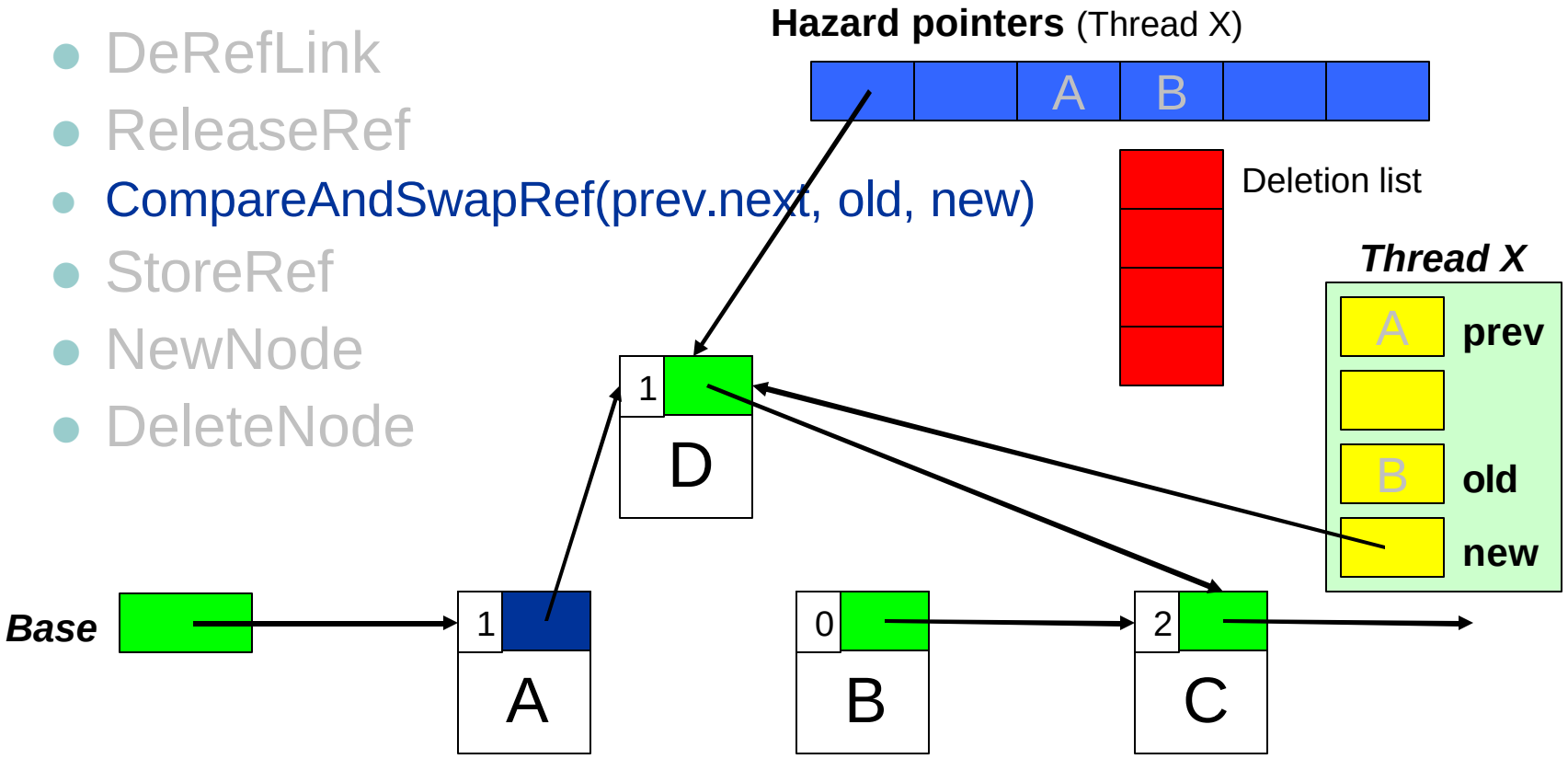
The basic idea

- API
  - DeRefLink
  - ReleaseRef
  - CompareAndSwapRef
  - StoreRef(new.next, R)
  - NewNode
  - DeleteNode



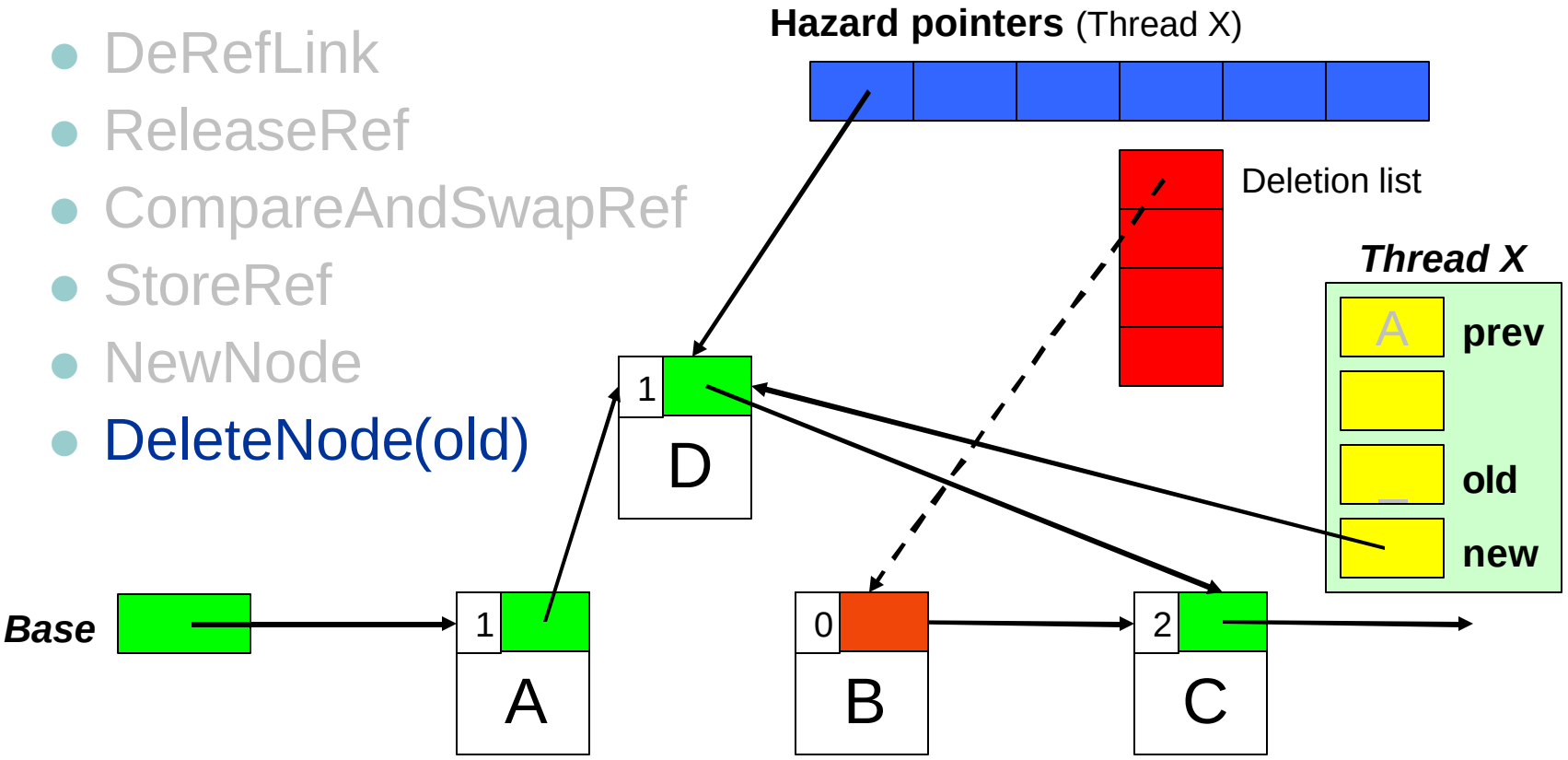
The basic idea

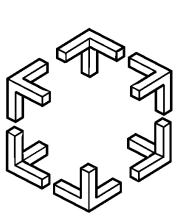
- API
  - DeRefLink
  - ReleaseRef
  - CompareAndSwapRef(prev.next, old, new)
  - StoreRef
  - NewNode
  - DeleteNode



The basic idea

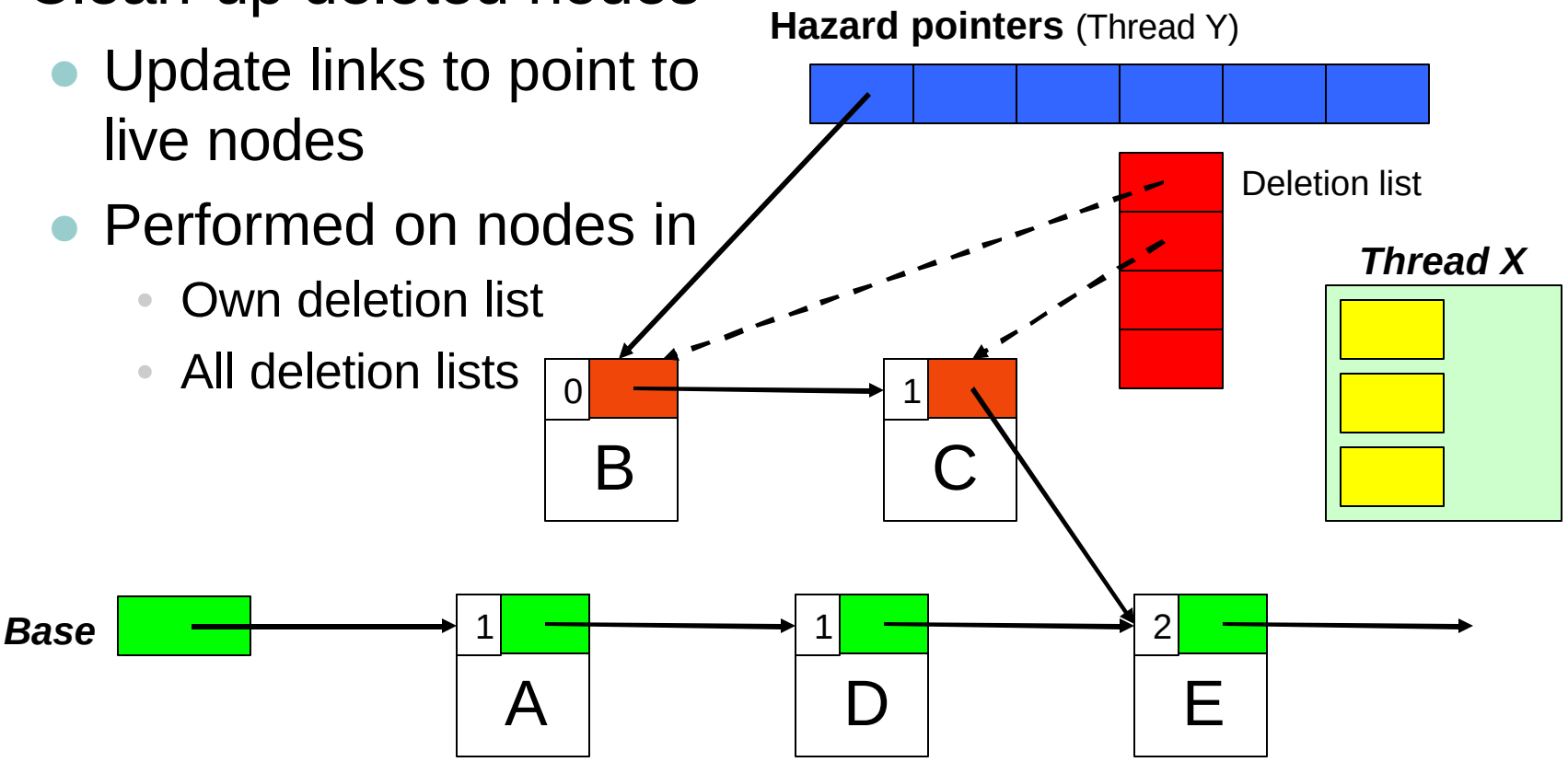
- API
  - DeRefLink
  - ReleaseRef
  - CompareAndSwapRef
  - StoreRef
  - NewNode
  - DeleteNode(old)

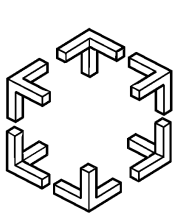




Breaking chains of garbage

- Clean-up deleted nodes
  - Update links to point to live nodes
  - Performed on nodes in
    - Own deletion list
    - All deletion lists





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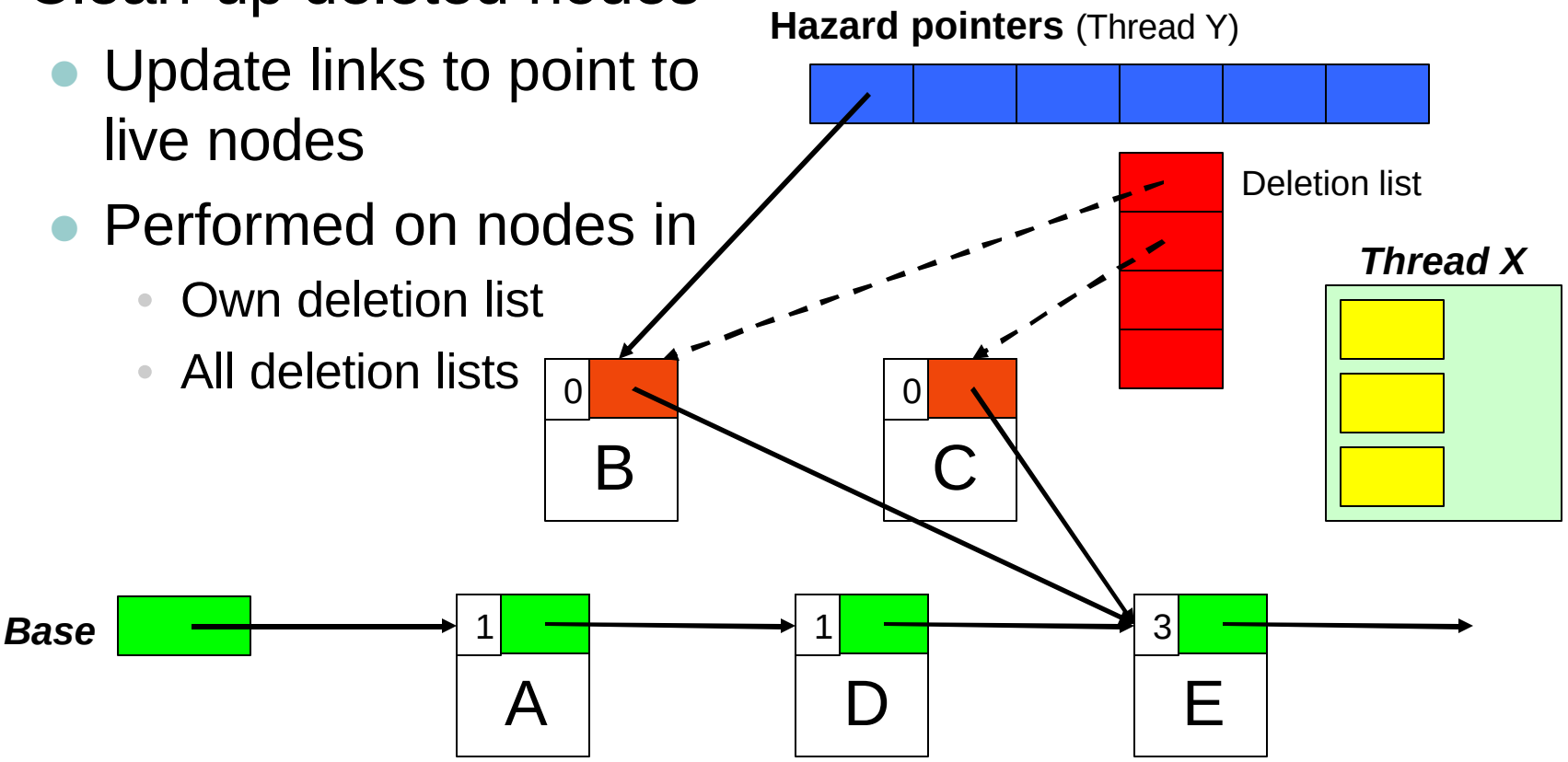
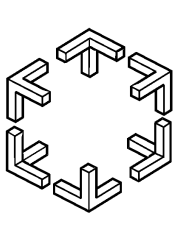
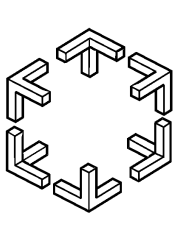




Bound on unreclaimed nodes

- A deleted node can be reclaimed when
  - The reference count is zero and
  - No hazard pointer is pointing to it and
  - There is no ongoing clean-up of this node

- With a rate relative to the number of threads of
  - Scanning hazard pointers
  - Cleaning up nodes as needed
- Then the maximum size of each deletion list depends on
  - The number of hazard pointers
  - The number of links per node
  - The number of threads



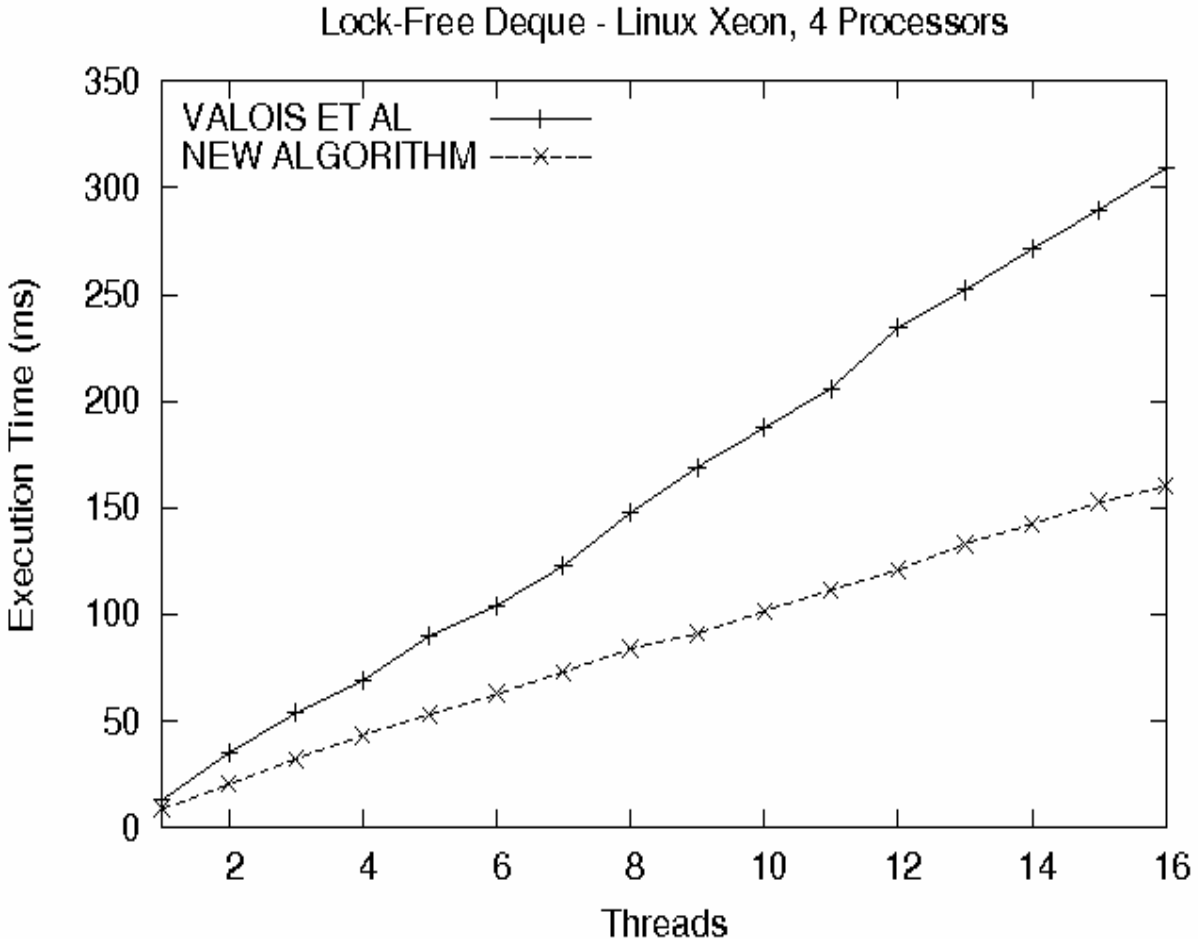
Experimental evaluation

- Lock-free deque (Sundell and Tsigas 2004)

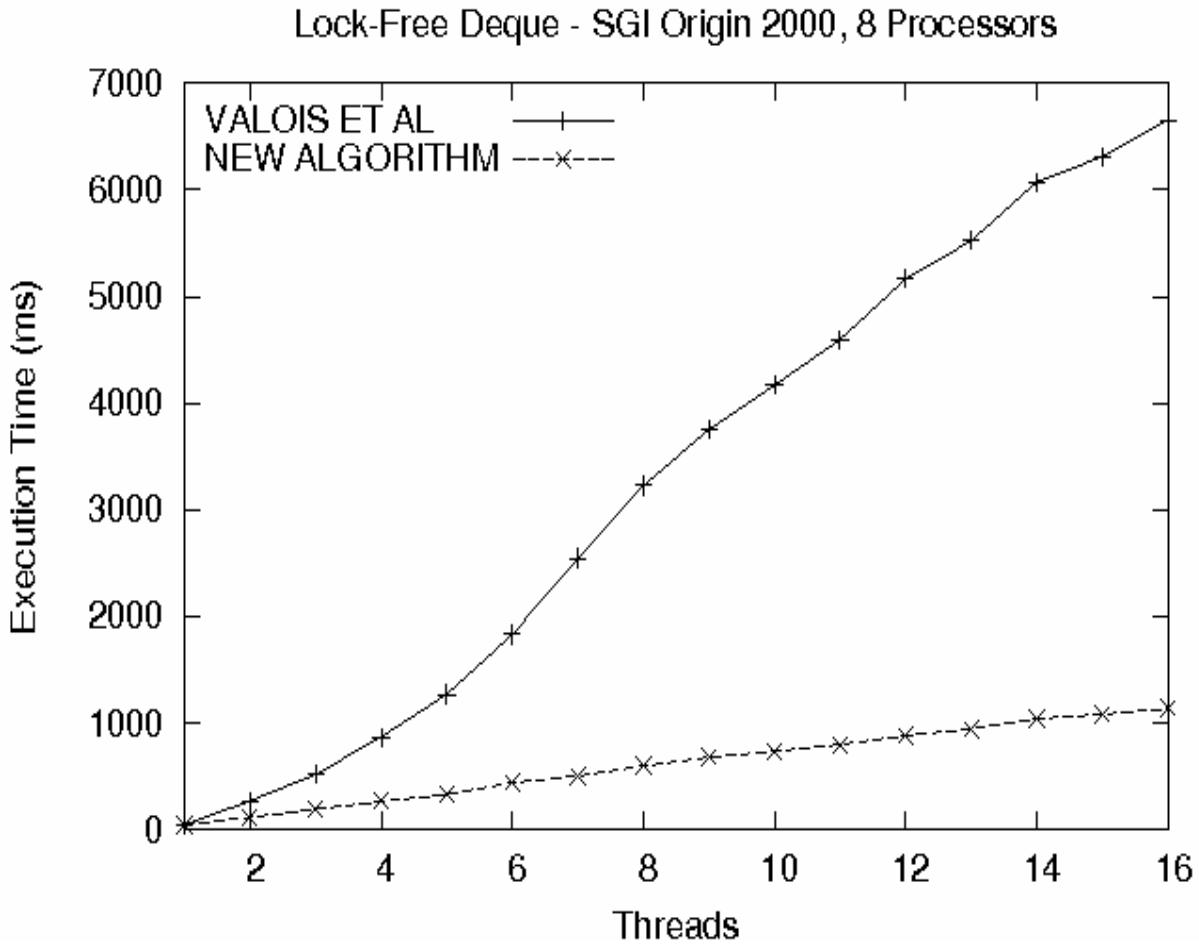
  (deque – double-ended queue)

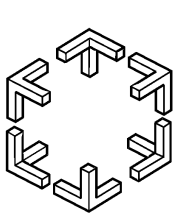
  - The algorithm needs traversal of deleted nodes
  - Time for 10000 random operations/thread
- Tested memory reclamation schemes
  - Reference counting, Valois et al.
  - The new algorithm
- Systems
  - 4 processor Xeon PC / Linux (UMA)
  - 8 processor SGI Origin 2000 / IRIX (NUMA)

Experimental evaluation



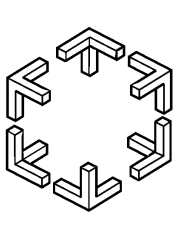
Experimental evaluation





Conclusions

- First lock-free memory reclamation scheme that
  - Only uses atomic primitives available in contemporary architectures
  - Guarantees safety of
    - Local and
    - Global references
  - Has an upper bound on the amount of deleted but unreclaimed nodes
  - Allows arbitrary reuse of reclaimed memory



Questions?

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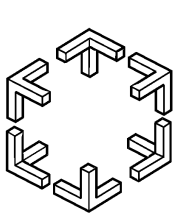
    Chalmers University of Technology,
    SE-412 96 Göteborg, Sweden
  - Email:

    andersg @ cs.chalmers.se
  - Web:

    http://www.cs.chalmers.se/~dcs
    http://www.cs.chalmers.se/~andersg
  - Implementation

    http://www.noble-library.org/



Conclusions

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  - Only uses atomic primitives available in contemporary architectures
  - Guarantees safety of
    - Local and
    - Global references
  - Has an upper bound on the amount of deleted but unreclaimed nodes
    (Bound: N * N * (k + L_max + a + 1))
  - Allows arbitrary reuse of reclaimed memory