Efficient Multi-word Compare and Swap

CS6868:Concurrent Programming – Course Project

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Overview

1. What is MCAS?
   - Why Should We Care?
   - MCAS – The Formal Bit
2. The Impossibility Result
3. How the k+1 CAS Algorithm Works
   - Two Phases, One CAS to Rule Them All
   - But Wait – How Do Reads Work?
   - The Scoreboard
   - Recap
4. Detailed Algorithm & Persistent Memory
   - Listing 1: Data Structures
   - Listing 2: `readInternal`
   - Listing 3: Main Algorithm
5. Experimental Evaluation & Conclusion
   - Performance Overview
   - Doubly Linked List Benchmark

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What is MCAS? – From One Word to Many

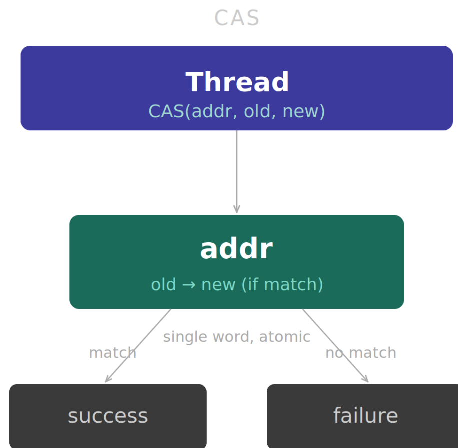
Compare-and-Swap

CAS atomically swaps **one** memory word.

`CAS(addr, old, new)`

Single word, atomic

That's all hardware gives us!



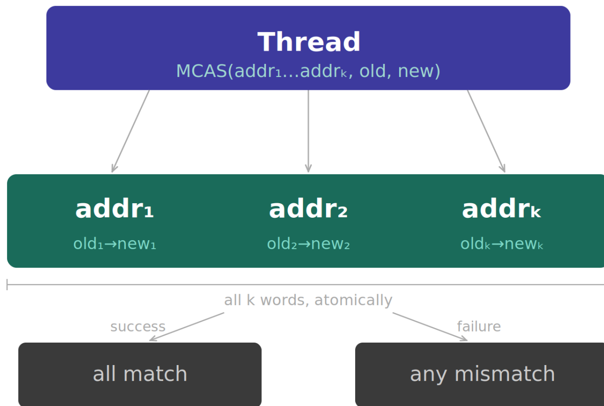
What is MCAS? – From One Word to Many

Multi-word CAS (Guerraoui et al., 2020)

MCAS does the same for k words at once!

`MCAS(addr`$_1$`..addr`$_k$`, old`$_1$`..old`$_k$`, new`$_1$`..new`$_k$`)`

k **words, still atomic!**



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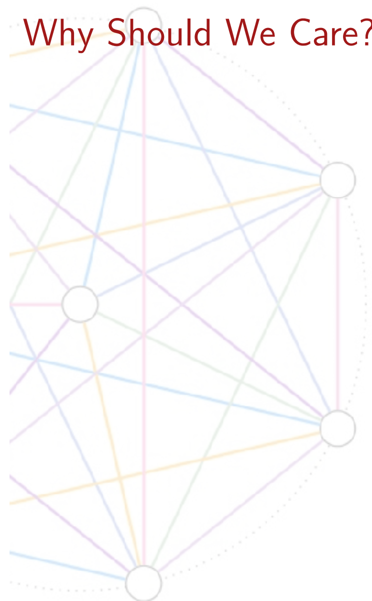

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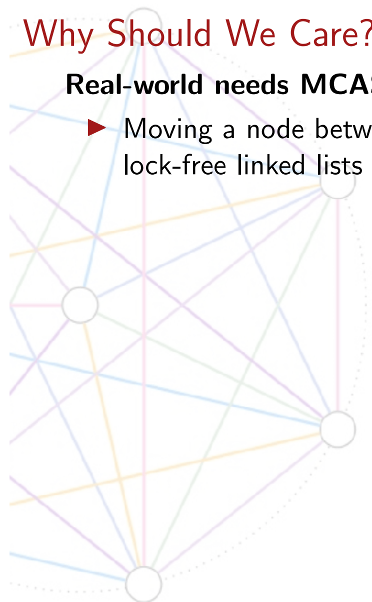

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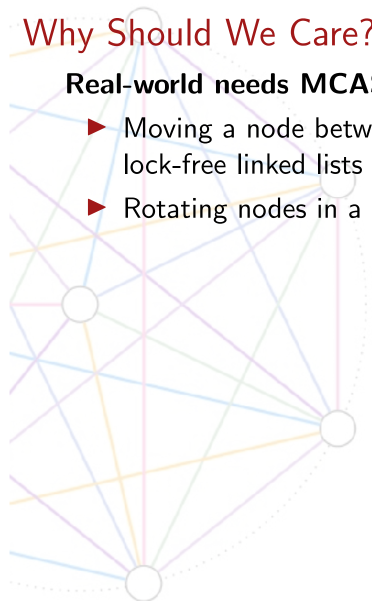

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STM? Too slow!

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This paper? **Just k+1.**

Nearly half the work. Mic drop.

MCAS – The Formal Bit

Theorem 1.1: Multi-word Compare-and-Swap (MCAS) (Guerraoui et al., 2020)

- **Input:** Array of k tuples $\langle \text{addr}_i, \text{old}_i, \text{new}_i \rangle$
- **Atomically:**
  - If $\forall i : *\texttt{addr}_i = \text{old}_i \Rightarrow$ write all new values, return $\textsc{Success}$
  - Otherwise $\Rightarrow$ change nothing, return $\textsc{Failure}$

MCAS – The Formal Bit

Theorem 1.2: Multi-word Compare-and-Swap (MCAS) (Guerraoui et al., 2020)

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Each op looks instantaneous

Lock-free (Herlihy, 1991)
Progress even if threads crash

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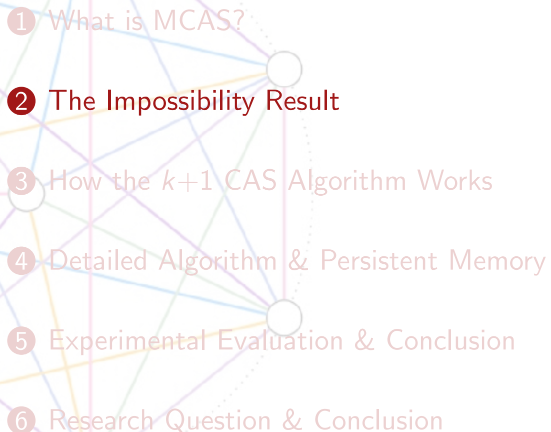
Progress even if threads crash

Addresses sorted in a total order (prevents deadlocks). Each operation uses a **descriptor** to track its state.

Overview



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The Impossibility Result – You Can't Cheat Physics

Theorem (Guerraoui et al.):

Any lock-free, DAP k-CAS needs $\geq k$ CAS operations.

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Intuition: build a "star" of $k+1$ conflicting calls – c_0 shares a target with each c_i, but the c_i's are pairwise disjoint.

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Punchline: k is the floor. This paper hits $k+1$. **Gap of just 1!**

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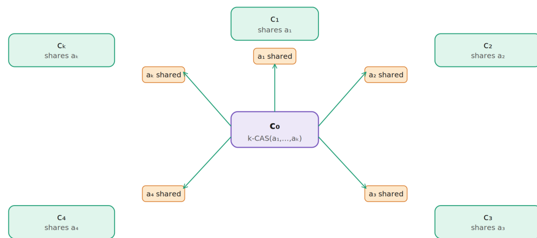

Star configuration: c_0 is the hub, $c_1 \ldots c_k$ are the spokes.

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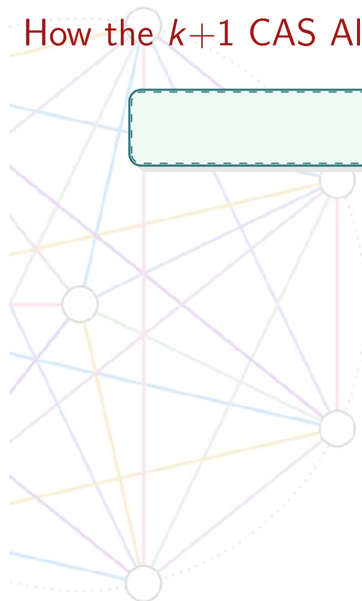
How the k+1 CAS Algorithm Works – The Big Idea



What if we just... didn't unlock?

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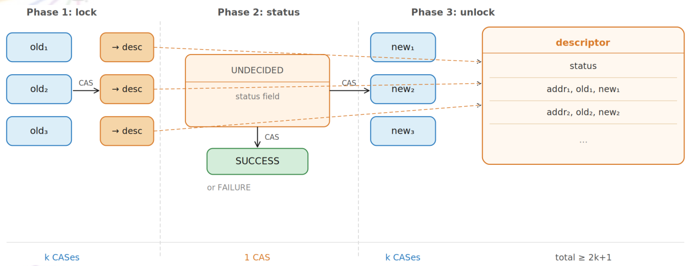


How the $k+1$ CAS Algorithm Works – The Big Idea

What if we just... didn't unlock?

Phase 1: lock
old$_1$ → desc
old$_2$ CAS → desc
old$_3$ → desc
k CASes

Phase 2: status
UNDECIDED
status field
CAS
SUCCESS
or FAILURE
1 CAS

Phase 3: unlock
CAS
new$_1$
new$_2$
new$_3$
k CASes

descriptor
status
addr$_1$, old$_1$, new$_1$
addr$_2$, old$_2$, new$_2$
...
total ≥ 2k+1

Prior work: $2k+1$ CAS

lock(k) + status(1) + unlock(k)

This paper: $k+1$ CAS

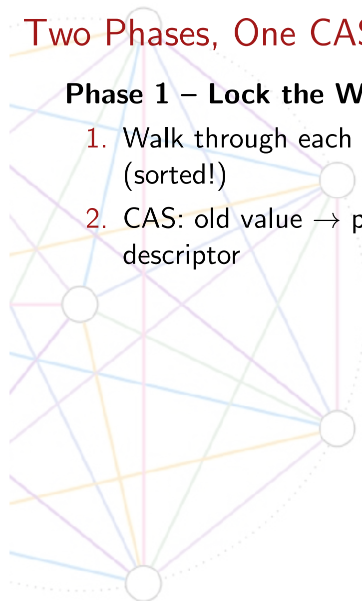
lock(k) + status(1) + ~~unlock~~

Descriptors cleaned up lazily!

Two Phases, One CAS to Rule Them All

Phase 1 – Lock the Words

Two Phases, One CAS to Rule Them All



Phase 1 – Lock the Words

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2. CAS: old value $\rightarrow$ pointer to our descriptor

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   This CAS is the linearization point!

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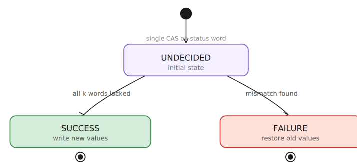

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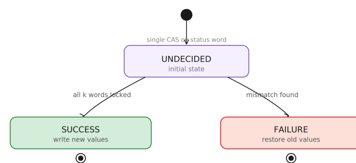
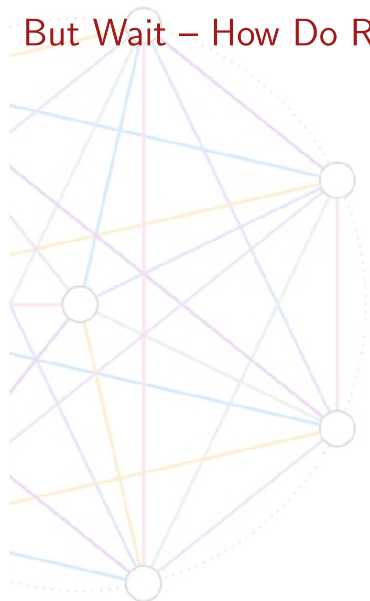


No Phase 3!

Old algorithms unlock each word (k more CAS ops). This paper leaves descriptors in place and cleans up later via epoch-based garbage collection.

But Wait – How Do Reads Work?



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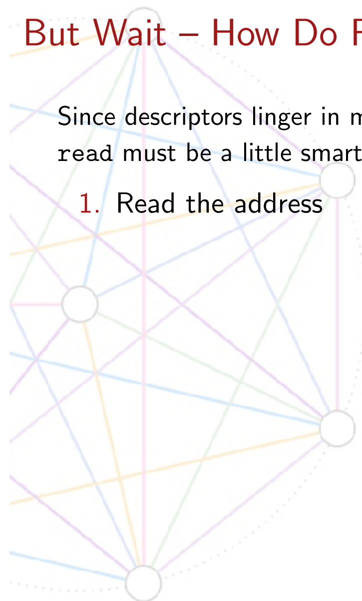

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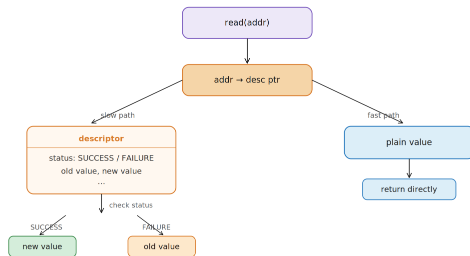

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algorithm	CAS per k-CAS	read cost
Harris et al. (RDCSS)	≥ 3k+1	O(1), no indirection
PMCAS (persistent)	5k+1 + 2k+1 fences	O(1), no indirection
This work (volatile)	k+1	+1 level (desc present)
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$\Rightarrow$ less contention
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Read indirection
Extra pointer follow
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Tradeoff: MCAS throughput improves significantly; reads pay a small cost only when a descriptor is still in place.

Recap – What We Learned

CAS → MCAS
Atomically swap k words at once

→

Lower Bound
$\geq k$ CAS needed (star config)

→

k+1 CAS
Skip the unlock! Lazy cleanup.

→

Tradeoff
Faster MCAS
Reads: +1 deref

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TL;DR: By leaving descriptors in place instead of unlocking, we cut the critical path from $2k$+1 CAS down to just k+1 – provably near-optimal, lock-free, and linearizable. Not bad for a day's work!

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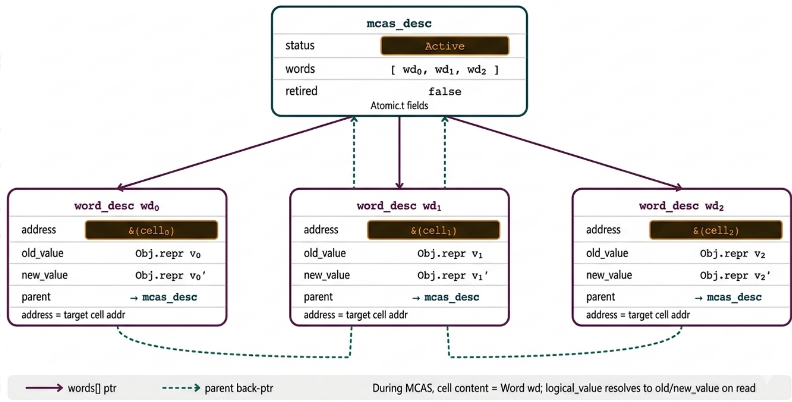
Detailed Algorithm & Persistent Memory – Descriptor Object Graph



The descriptor links words to their parent MCAS operation to facilitate helping (Guerraoui et al., 2020).

Listing 1: Data Structures

Algorithm 1 Data structures used by our algorithm (Guerraoui et al., 2020)

```
1:  struct WordDescriptor {
2:     void * address;
3:     uintptr_t old_val;
4:     uintptr_t new_val;
5:     MCASDescriptor * parent;
6:  }
7:  enum StatusType { ACTIVE, SUCCESSFUL, FAILED }
8:  struct MCASDescriptor {
9:     StatusType status;
10:    size_t N;
11:    WordDescriptor words[N];
12: }
```

Listing 2: readInternal

Algorithm 2 The `readInternal` auxiliary function (Guerraoui et al., 2020)

```
1:  function READINTERNAL(addr, self)
2:      retry_read: val = *addr
3:      if not ISDESCRIPTOR(val) then return <val, val>
4:      else                                              ▷ found a descriptor
5:          parent = val->parent
6:          if parent != self and parent->status == ACTIVE then
7:              HELP(parent); goto retry_read
8:          end if
9:          if parent->status == SUCCESSFUL then return <val, val->new_val>
10:         else return <val, val->old_val>
11:     end if
12: end function
```

Listing 3: Main Algorithm

Algorithm 3 Main algorithm (Guerraoui et al., 2020)

```
1:  function READ(address)
2:      <content, value> = READINTERNAL(address, NULL); return value
3:  end function
4:  function MCAS(self)
5:      for i = 0 to self->N - 1 do
6:          w = &self->words[i]; retry_acquire:
7:          <content, value> = READINTERNAL(w->address, self)
8:          if content == w then continue
9:          end if
10:         if value != w->old_val or self->status != ACTIVE then break
11:         end if
12:         if not CAS(w->address, content, w) then goto retry_acquire
13:         end if
14:     end for
15:     if i == self->N then CAS(&self->status, ACTIVE, SUCCESSFUL)
16:     else CAS(&self->status, ACTIVE, FAILED)
17:     return self->status == SUCCESSFUL
18: end function
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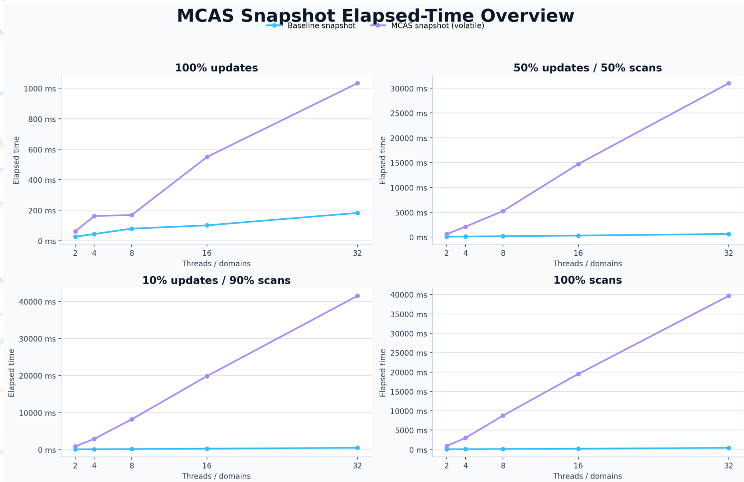
Performance Overview



General benchmark overview showing MCAS performance across different workloads.

Doubly Linked List Benchmark

MCAS Doubly-Linked-List Elapsed-Time Overview

Baseline Mutex DLL — MCAS Lock-Free DLL

90% updates / 10% search

67% updates / 33% search

100% search

Elapsed time — Threads / domains

Performance results for the Doubly Linked List implementation.

Linked List Benchmark

Performance results for the Singly Linked List implementation.

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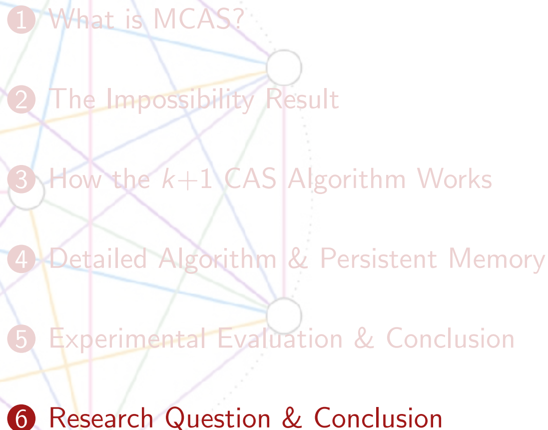

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Answer: MCAS provides useful expressive power, but for atomic snapshot specifically, that expressive gain comes with a **very large performance cost**.

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Answer: MCAS provides useful expressive power, but for atomic snapshot specifically, that expressive gain comes with a **very large performance cost**.

- **Expressiveness:** Gives a uniform way to express atomic multi-location changes, especially where several pointers or flags must move together.
- **Reusability:** The MCAS layer is a reusable abstraction (used in snapshot, linked lists, doubly linked lists).
- **Complexity vs Simplicity:** For atomic snapshot alone, the non-MCAS version is much simpler conceptually.

References I

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