Read-Copy-Update for HelenOS

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Department of Distributed and Dependable Systems

D3S

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CHARLES UNIVERSITY IN PRAGUE

faculty of mathematics and physics

HelenOS

Introduction

- **HelenOS**
  - Microkernel multiserver operating system
  - Relying on asynchronous IPC mechanism
    - Major motivation for scalable concurrent algorithms and data structures
- **Martin Děcký**
  - Researcher in computer science (operating systems)
  - Not an expert on concurrent algorithms
    - But very lucky to be able to cooperate with hugely talented people in this area

In a Nutshell

Asynchronous IPC

=

Communicating parties may access the communication facilities concurrently

In a Nutshell

Asynchronous IPC

=

Communicating parties may access the communication facilities concurrently

→ **The state of the shared communication facilities needs to be protected by explicit synchronization means**

In a Nutshell

Asynchronous IPC

=

Communicating parties have to access the communication facilities concurrently

In a Nutshell

HelenOS

Asynchronous IPC

=

Communicating parties have to access the communication facilities concurrently

← In order to counterweight the overhead of the communication by doing other useful work while waiting for a reply

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In a Nutshell

HelenOS

Asynchronous IPC

→

Communication facilities have to use concurrency-friendly (non-blocking) synchronization means

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In a Nutshell

Asynchronous IPC

→

Communication facilities have to use concurrency-friendly (non-blocking) synchronization means

← In order to avoid limiting the achievable degree of concurrency

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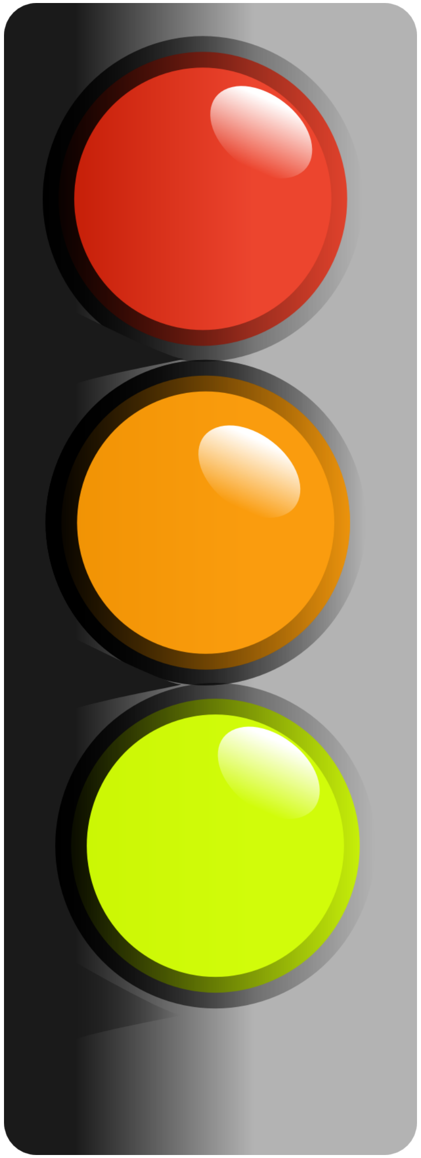
Basic Synchronization Taxonomy

- **For accessing shared data structures**
- **Mutual exclusion synchronization**
  - Temporal separation of scheduling entities
  - Typical means
    - *Disabling preemption*, *Dekker's algorithm*, *direct use of atomic test-and-set operations*, etc.
  - Typical mechanisms
    - *Locks*, *semaphores*, *condition variables*, etc.
    - [+] Relatively intuitive semantics, well-known characteristics
    - [-] Overhead, restriction of concurrency, deadlocks

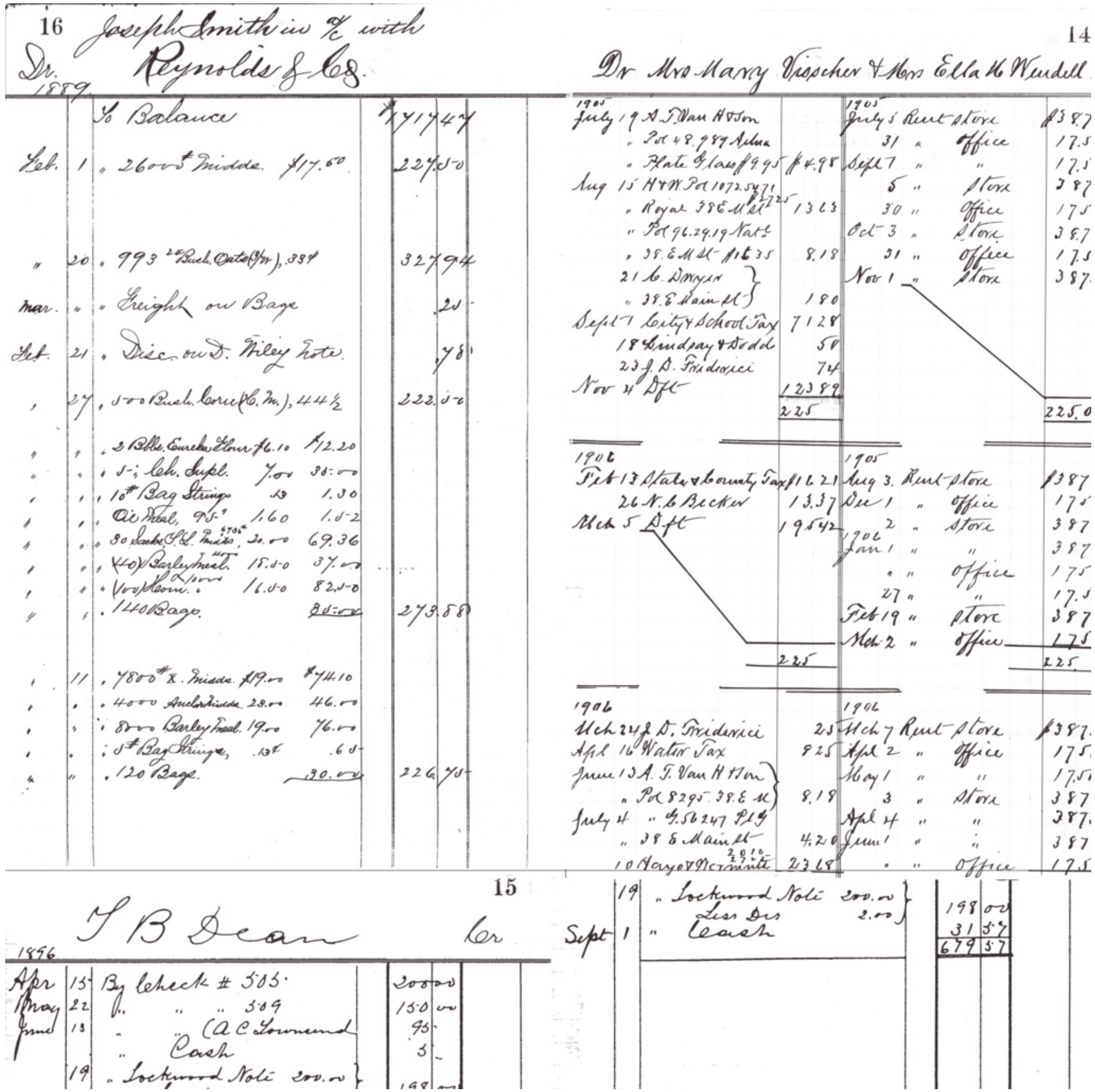
Mutual Exclusion Synchronization



Basic Synchronization Taxonomy

- **Non-blocking synchronization**
  - Replace temporal separation by sophisticated means that guarantee logical consistency
  - Typical means
    - *Atomic writes, direct use of atomic read-modify-write operations*, etc.
  - Typical mechanisms
    - *Transactional memory, hazard pointers*, *Read-Copy-Update*, etc.
  - [+] Reasonable (almost no) overhead and restriction of concurrency in favorable cases, guarantee of progress
  - [-] Less intuitive semantics, sometimes non-trivial characteristics, non-favorable cases, livelocks

Non-blocking Synchronization



Non-blocking Synchronization

- **Wait-freedom**
  - Guaranteed system-wide progress and starvation-freedom (all operations are finitely bounded)
  - Wait-freedom algorithms always exist [1], but the performance of general methods is usually inferior to blocking algorithms
  - Wait-free queue by Kogan & Petrank [2]
- **Lock-freedom**
  - Guaranteed system-wide progress, but individual threads can starve
  - Four phases: Data operation, assisting obstruction, aborting obstruction, waiting
- **Obstruction-freedom**
  - Guaranteed single thread progress if isolated for a bounded time (obstructing threads need to be suspended)

From Means to Mechanism

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Synchronization means

Individual instance of usage

→

Synchronization mechanism

Generic reusable pattern

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From Means to Mechanism

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Synchronization means

Individual instance of usage

E.g. non-blocking list implementation using atomic pointer writes

Synchronization mechanism

Generic reusable pattern

E.g. non-blocking list implementation using Read-Copy-Update

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What Is Read-Copy-Update

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- **Non-blocking synchronization mechanism**
  - Targeting synchronization of read-mostly pointer-based data structures with immutable values
    - Favorable case: R/W ratio of ~ 10:1 (but even 1:1 is achievable)
    - Unlimited number of readers without blocking (not waiting for other readers or writers)
    - Little overhead on the reader side (smaller than taking an uncontended lock)
    - Readers have to tolerate “stale” data and late updates
    - Readers have to observe “safe” access patterns
    - Synchronization among writers out of scope of the mechanism
    - Optional provisions for asynchronous reclamation

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What Is Read-Copy-Update (2)

- **Read-side critical section**
  - Delimited by **read_lock()** and **read_unlock()** operations (non-blocking)
    - Protected data can be referenced only inside the critical section
  - Safe **access()** methods for reading pointers
    - Avoiding unsafe compiler optimizations (reloading the pointer)
    - Not necessary for reading values
  - **Quiescent state** (a thread outside a critical section)
  - **Grace period** (all threads pass through a quiescent state)

What Is Read-Copy-Update (3)

HelenOS

- **Synchronous write-side update**
  - Atomically unlinking an old element
  - Calling a **synchronize()** operation
    - Blocks until a grace period elapses (all readers pass a quiescent state, no longer referencing the unlinked data)
    - Possibility to reclaim or free the unlinked data
  - Inserting a new element using safe **assign()** operation
    - Avoiding unsafe compiler optimizations and store reordering on weakly ordered architectures

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Synchronous Update Example

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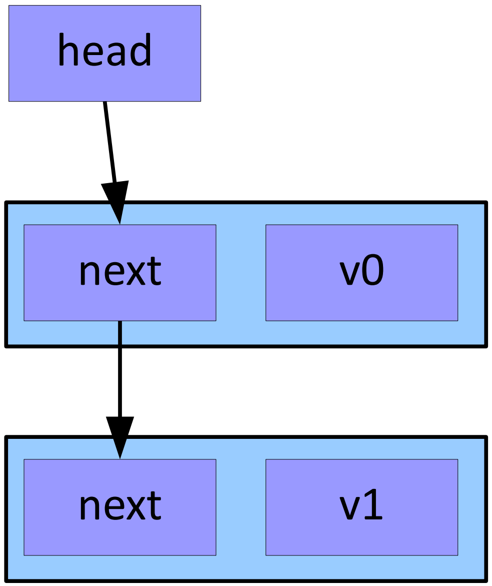
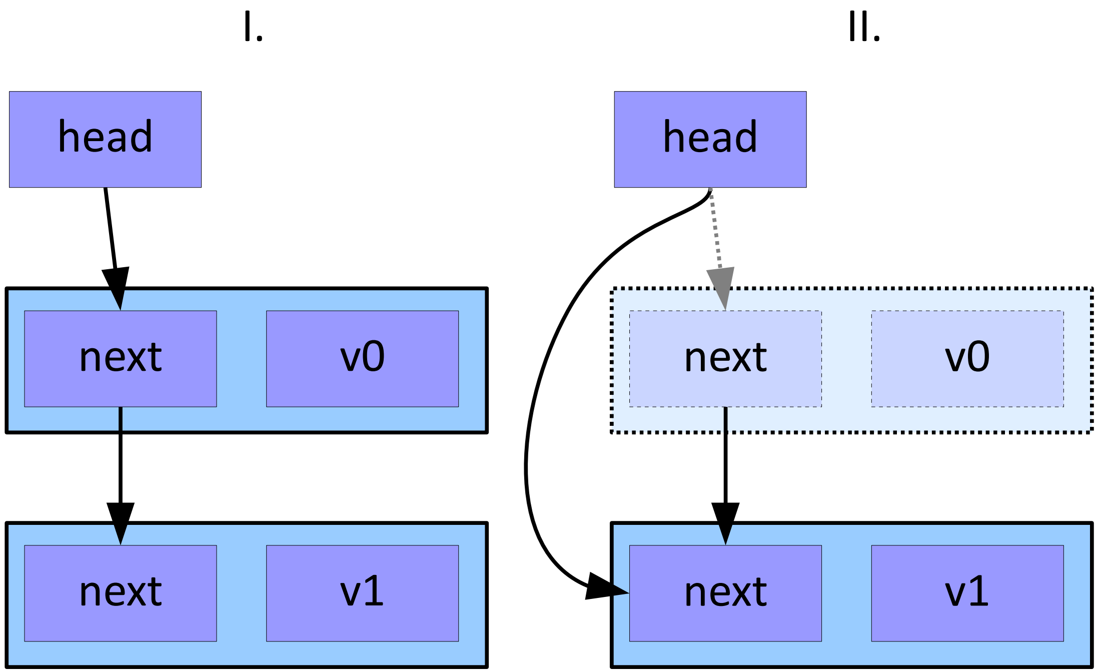


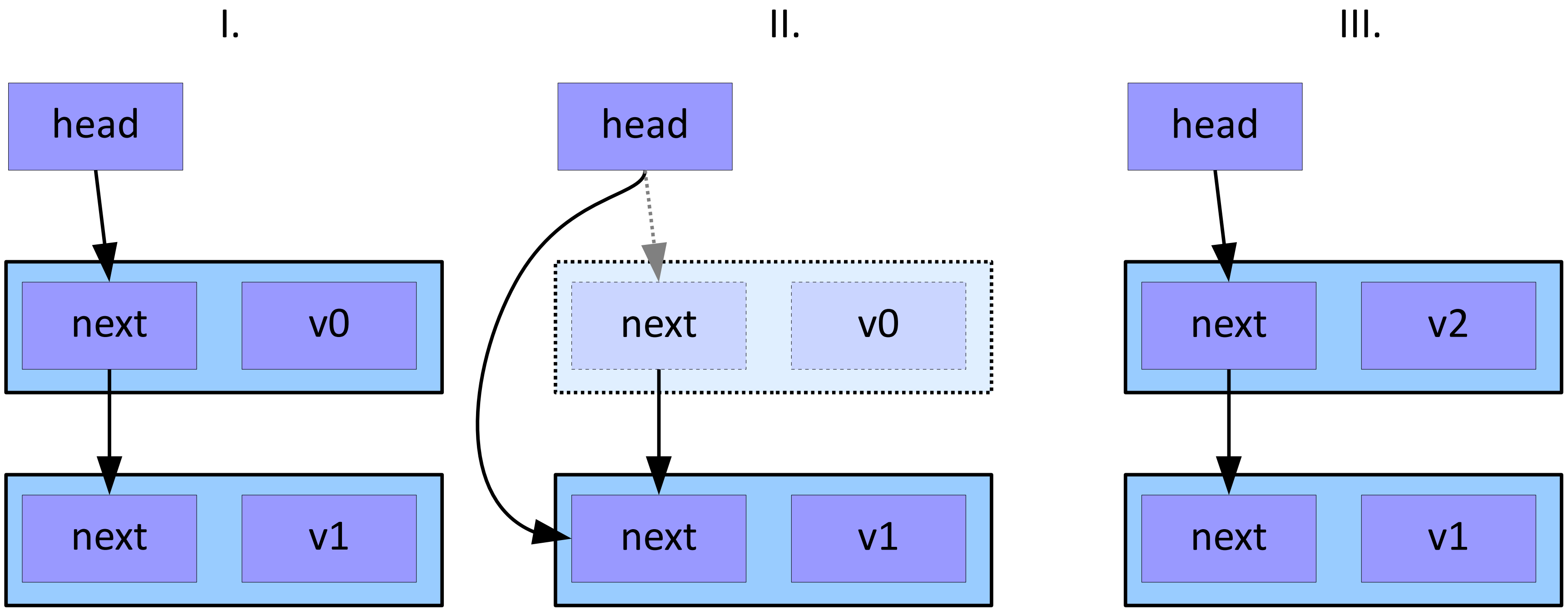
Atomic pointer update to remove the element with v0 from the list

Synchronous Update Example



Blocking on **synchronize()**
During the grace period preexisting readers can still access the “stale” element with v0

Synchronous Update Example



No reader can reference the element with v0 anymore – it can be reclaimed
New element with v2 can be atomically inserted

What Is Read-Copy-Update (4)

- **Asynchronous write-side update**
  - Using a **call()** operation
    - Non-blocking operation registering a callback
    - Callback is executed after a grace period elapses
  - Using a **barrier()** operation
    - Waiting for all queued asynchronous callbacks

Grace Period Detection

HelenOS

- **Cornerstone of any RCU algorithm**
  - Implicit trade-off between precision and overhead
    - Any extension of a grace period is also a grace period
    - Long (imprecise) grace periods
      - Blocking synchronous writers for a longer time
      - Increasing memory usage due to unreclaimed elements
    - Short (precise) grace periods
      - Increasing overhead on the reader side (need for memory barriers, atomic operations, other heavy-weight operations, etc.)
  - Usual compromise
    - Identifying *naturally occurring quiescent states* for the given RCU algorithm
      - Context switches, exceptions (timer ticks), etc.

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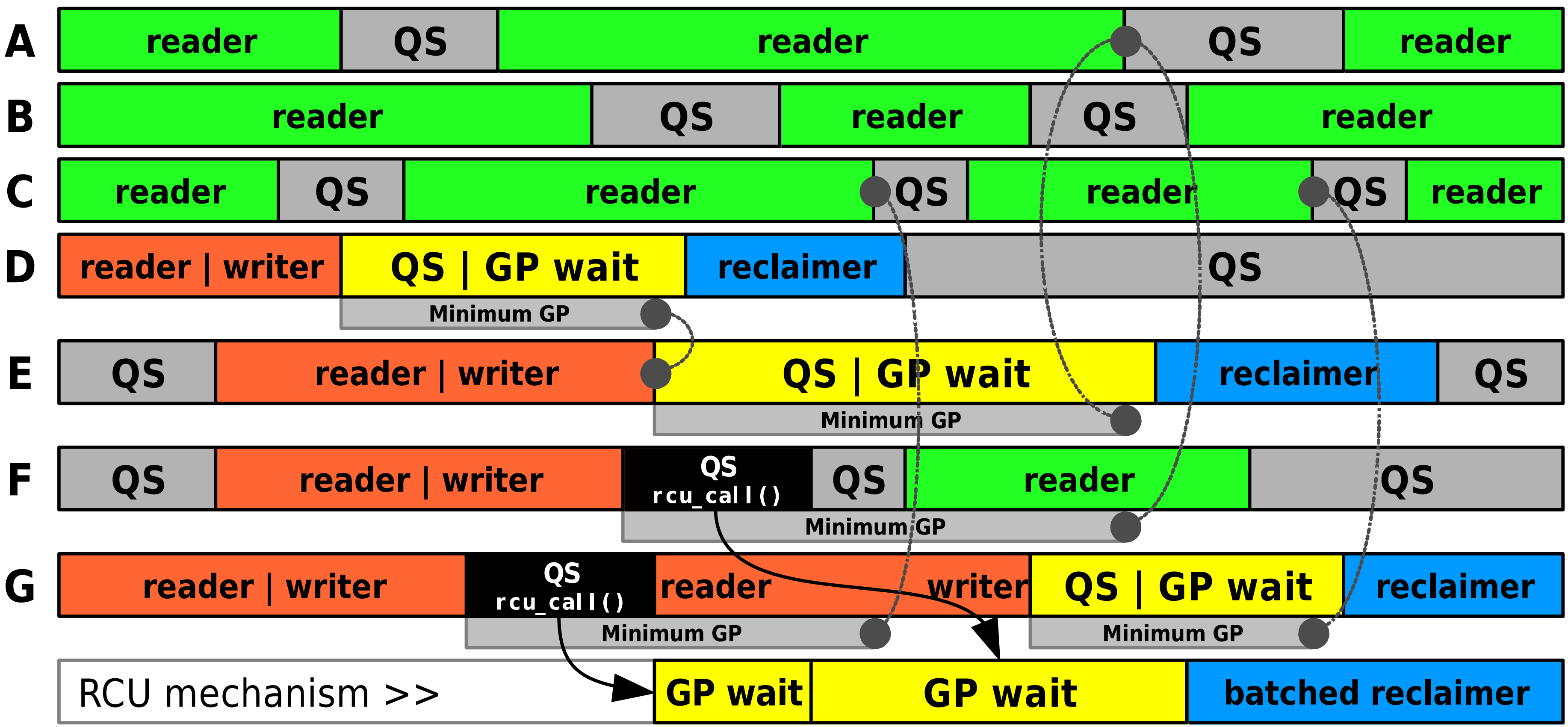
The Big Picture ...



Motivation for RCU in HelenOS

- **Foundation for a scalable concurrent data structure**
- **Developing a microkernel-specific RCU algorithm**
  - Specific requirements, constraints and use cases
  - Last well-known RCU implementation for a microkernel in 2003 (K42)

Credits

- **AP-RCU**
  - Non-intrusive, portable RCU algorithm
  - Developed and implemented by Andrej Podzimek for UTS (OpenSolaris) [3] [4]
- **AH-RCU**
  - Inspired by AP-RCU and several other RCU algorithms
  - Developed and implemented by Adam Hraška for SPARTAN (HelenOS) [7]
  - Foundation for the Concurrent Hash Table in HelenOS [8]
  - Additional variants (preemptible AP-RCU, user space RCU)

HelenOS requirements

- **The RCU algorithm must not impose design concepts of legacy systems on HelenOS**
  - E.g. a specific way how the timer interrupt handler is implemented
- **The kernel space RCU algorithm must support**
  - Read-side critical sections in interrupt and exception handlers
  - Asynchronous reclaimation (**call()**) in interrupt and exception handlers
  - Read-side critical sections with preemption enabled (not affecting scheduling latency)

HelenOS requirements (2)

- **Concurrent Hash Table implementation**
  - Growing and shrinking
  - Interrupt and non-maskable interrupt tolerant
    - Suitable for a global page hash table
  - Concurrent reads with low overhead
  - Concurrent inserts and deletes

AH-RCU

- **Basic characteristics**
  - Kernel space algorithm
  - Read-side critical sections are preemptible (without loss of performance)
    - Multiple read-side critical sections within a time slice
    - Expensive operations when a thread was preempted do not make much harm
  - Support for asynchronous reclamation in interrupt and exception handlers
  - No reliance on periodic timer

AH-RCU (2)

- **Grace period detection**
  - Test if all CPUs passed a quiescent state
    - Sending an interprocessor interrupt (IPI) to each CPU
      - If the interrupt handler detects a nesting count of 0, it issues a memory barrier (representing a natural quiescent state)
    - Avoid sending IPI if context switch is detected
  - Detect any preempted readers holding up the current grace period
    - Sleep and wait for the last preempted reader holding up the grace period to wake the detector thread

AH-RCU (3)

- **Advantages**
  - Low overhead and preemptible read-side critical section, suitable for exception handlers
  - No regular sampling
- **Disadvantages**
  - Polling CPUs using interprocessor interrupts might be disruptive in large systems

HelenOS Concurrent Hash Table

- **Basic characteristics**
  - Inspired by Triplett's relativistic hash table [5] and Michael's lock-free lists [6]
    - Hash collisions resolved using separate RCU-protected bucket lists
    - Buckets organized as lock-free lists without hazard pointers
      - RCU still protects against accessing invalid pointers and the ABA problem
    - Concurrent lookups and concurrent modifications
      - Tolerance for nested concurrent modifications from interrupt and exception handlers
  - Growing and shrinking using background resizing by a factor of 2
    - Concurrent with lookups and updates
    - Requires four grace periods
  - Deferred element freeing using RCU **call()**

Enough talk!

Enough talk!
Show me the (pseudo)code!

AP-RCU Reader Side

read_lock():

```
disable_preemption()
check_qs()
cpu.nesting_cnt++
```

read_unlock():

```
cpu.nesting_cnt--
check_qs()
enable_preemption()
```

check_qs():

```
if (cpu.nesting_cnt == 0) {
    if (cpu.last_seen_gp != cur_gp) {
        gp = cur_gp
        memory_barrier()
        cpu.last_seen_gp = gp
    }
}
```

AP-RCU Reader Side

read_lock():

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disable_preemption()
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read_unlock():

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check_qs():

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        memory_barrier()
        cpu.last_seen_gp = gp
    }
}
```

The first reader to notice the start of a new grace period on each CPU announces its quiescent state.
Once all CPUs announce a quiescent state or perform a context switch (a naturally occurring quiescent state due to disabled preemption), the grace period ends.

Note: Writer forces a context switch on CPUs where no read-side critical section was not observed for a while.

Note: Except **memory_barrier()** only inexpensive operations.

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Preemptible AP-RCU Reader Side

```
read_lock():
    disable_preemption()
    if (thread.nesting_cnt == 0)
        record_qs()
    thread.nesting_cnt++
    enable_preemption()

read_unlock():
    disable_preemption()
    if (thread.nesting_cnt-- == 0) {
        record_qs()
        if ((thread.was_preempted) ||
           (cpu.is_delaying_gp))
            signal_unlock()
    }
    enable_preemption()
```

```
record_qs():
    if (cpu.last_seen_gp != cur_gp) {
        gp = cur_gp
        memory_barrier()
        cpu_last_seen_gp = gp
    }

signal_unlock():
    if (atomic_exchange(cpu.is_delaying_gp, false)
       == true)
        remaining_readers_semaphore.up()
    if (atomic_exchange(thread.was_preempted, false)
       == true) {
        preempt_mutex.lock()
        preempted_list.remove(thread)
        if ((is_empty(cpu.cur_preempted)) &&
           (preempted_blocking_gp))
            remaining_readers_semaphore.up()
        preempt_mutex.unlock()
    }
```

AH-RCU Reader Side


```
read_lock():
    thread.nesting_cnt++
    compiler_barrier()

read_unlock():
    compiler_barrier()
    thread.nesting_cnt--
    if (thread.nesting_cnt == was_preempted)
        preempted_unlock()

preempted_unlock():
    // avoid race between thread and interrupt handler
    if  (atomic_exchange(thread.nesting_cnt, 0) == was_preempted) {
        preempt_lock.lock()
        preempted_list.remove(thread)
        if ((is_empty(cpu.cur_preempted)) && (detection_waiting))
            detection_semaphore.up()        // notify the detector thread about the grace period
        preempt_lock.unlock()
    }
```

Note: Except **preempted_unlock()** only inexpensive operations.

AP-RCU Writer Side

synchronize():

```
	memory_barrier()
	mutex.lock()

	cur_gp++                                        // start a new grace period
	reader_cpus = []                                // gather CPUs potentially in read-side CS
	foreach cpu in cpus {
		if ((!cpu.idle) && (cpu.last_seen_gp != cur_gp)) {
			cpu.last_ctx_switch_cnt = cpu.ctx_switch_cnt
			reader_cpus += cpu
		}
	}

	wait(10ms)                                      // longest acceptable grace period duration (tunable)

	foreach cpu in reader_cpus {                    // enforce a quiescent state
		if ((!cpu.idle) && (cpu.last_seen_gp != cur_gp) &&
		   (cpu.last_ctx_switch_cnt == cpu.ctx_switch_cnt))
			cpu.ctx_switch_force_wait()
	}

	mutex.unlock()
```

AH-RCU Writer Side

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```
detector_thread:
    forever {
        wait_for_callbacks()

        // run callbacks added before the current grace period
        execute_callbacks()

        // push callbacks registered since last processing to the queue
        advance_callbacks()

        wait_for_gp_end()
    }
```

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AH-RCU Writer Side (2)

```
wait_for_gp_end():
    gp_mutex.lock()
    if (completed_gp != cur_gp) {      // a grace period is already in progress
        wait_for_gp_end_signal()
        goto out
    } else {                           // start a new grace period
        preempt_lock.lock()
        cur_gp++
        preempt_lock.unlock()
    }
    gp_mutex.unlock()

    wait_for_readers()

    gp_mutex.lock()
    completed_gp = cur_gp

    out:
        gp_mutex.unlock()
```

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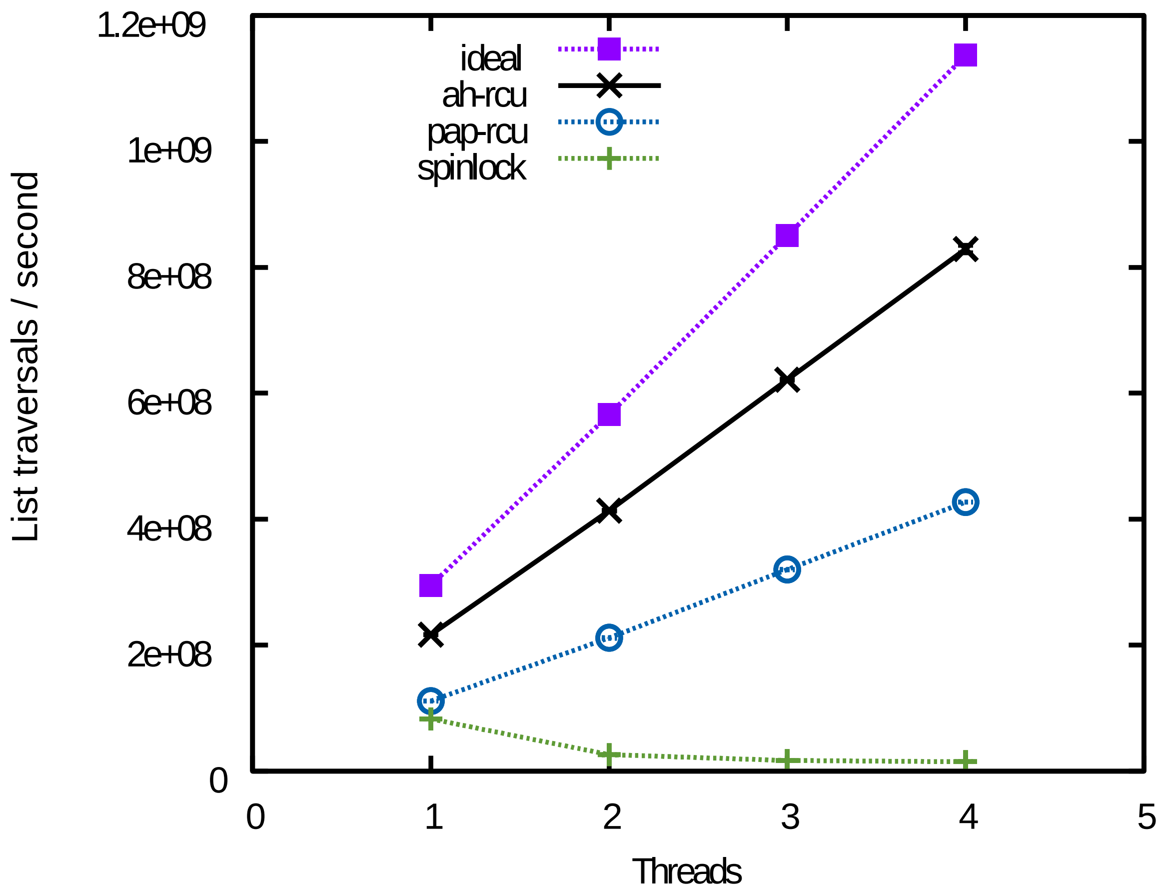
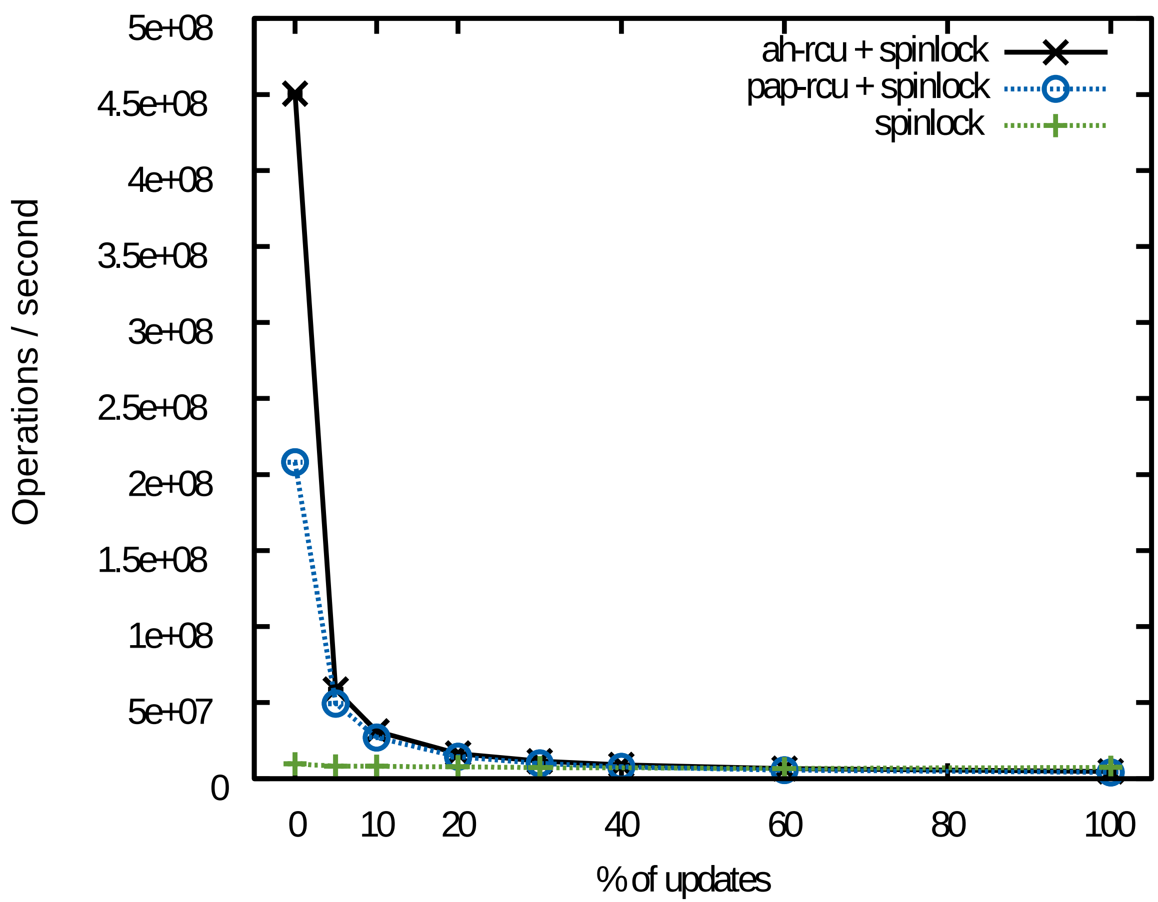
Evaluation

Read-side critical section scalability: Traversal of a five-element list
The list is protected as a whole, it is only read, never modified.



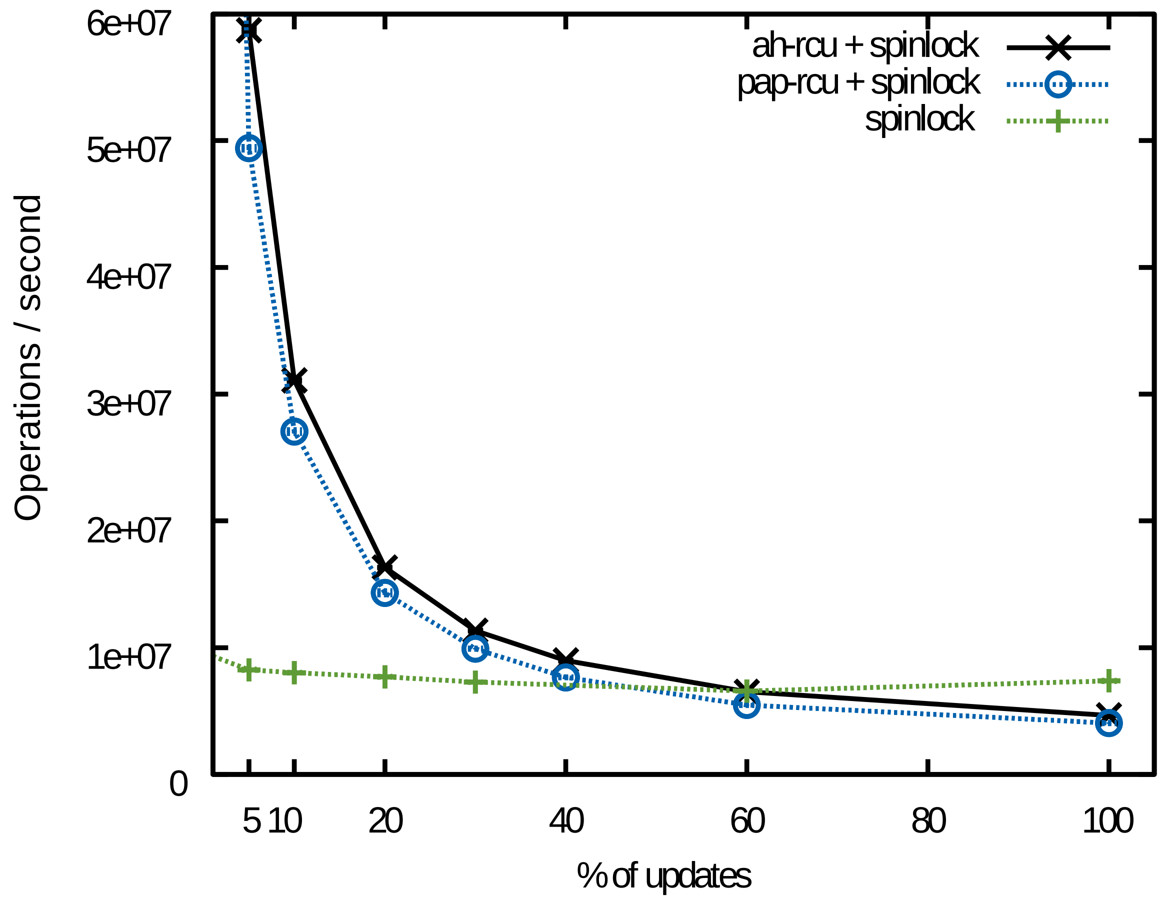
Evaluation (2)

Write-side overhead: Different ratios of updates vs. lookups
Five-element list, four threads running in parallel. Updates are always synchronized by a spinlock.



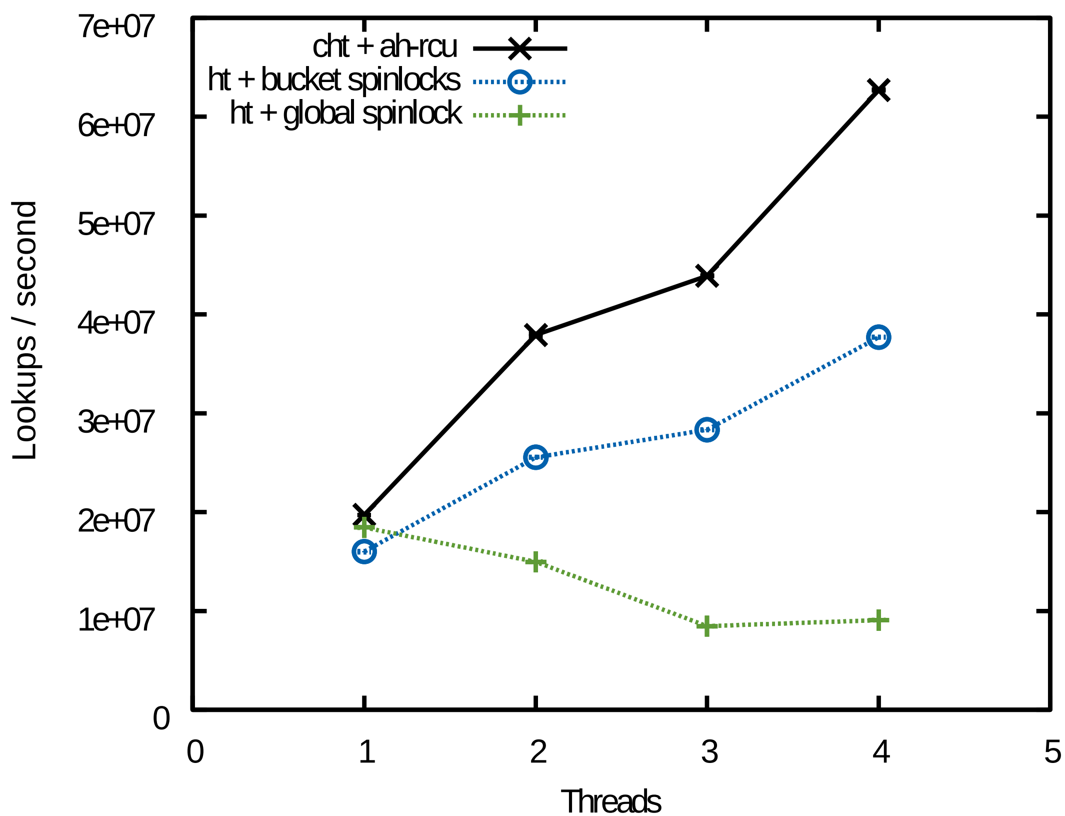
Evaluation (3)

Read-side scalability vs. write-side overhead: Crossover point
Data points from previous figure with low fraction of updates are discarded.



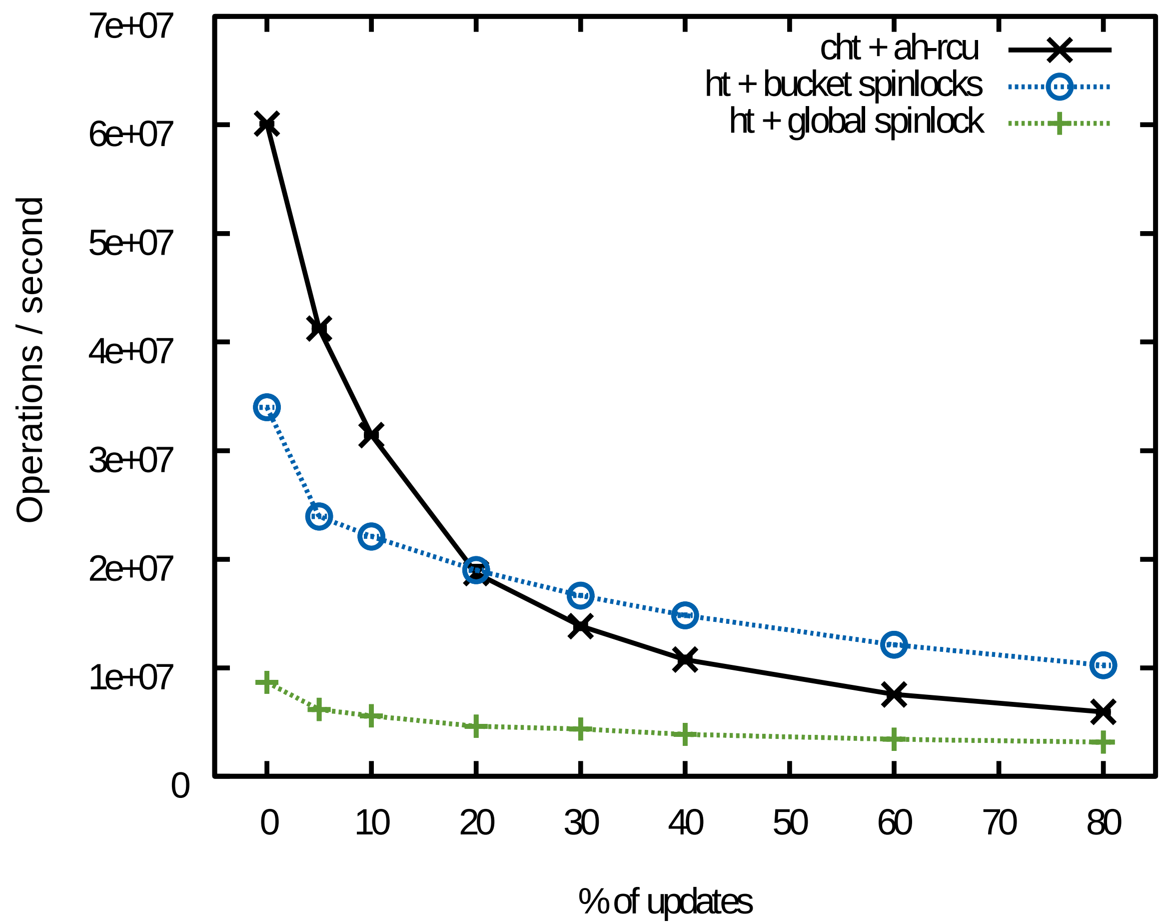
Evaluation (4)

Concurrent hash table lookup scalability
128 buckets, average load factor of 4 elements per bucket, 50 % of lookups for hitting keys, 50 % of lookups for missing keys (each thread used a separate list). The resize condition was checked, but never executed.



Evaluation (5)

Concurrent hash table update overhead: Different ratios of concurrent updates vs. lookups
Four threads running in parallel.



Conclusion

HelenOS

- **Novel scalable algorithms**
  - Preemptible AP-RCU for HelenOS
  - Preemptible AH-RCU for HelenOS
  - Resizeable Concurrent Hash Table for HelenOS
    - Suitable as a basic data structure for asynchronous HelenOS IPC
    - Suitable for other kernel uses (e.g. global page table)
- **Thorough evaluation**
  - Promising behavior

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Q&A

HelenOS

www.helenos.org

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References

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[2] Kogan A., Petrank E.: *Wait-free queues with multiple enqueuers and dequeuers*, in Proceedings of 16th ACM Symposium on Principles and Practice of Parallel Programming, ACM, 2011

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