Resizable, Scalable, Concurrent Hash Tables via Relativistic Programming

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Synchronization = Waiting

- Concurrent programs require synchronization
- Synchronization requires some threads to wait on others
- Concurrent programs spend a lot of time waiting

Locking

- One thread accesses shared data
- The rest wait for the lock

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- Straightforward to get right
- Minimal concurrency

Fine-grained Locking

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- Disjoint-access parallelism
- Reduce waiting, allow multiple threads to proceed

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- Disjoint-access parallelism
- Reduce waiting, allow multiple threads to proceed
- Many expensive synchronization instructions
- Wait on memory
- Wait on the bus
- Wait on cache coherence

Reader-writer locking

- Don't make readers wait on other readers
- Readers still wait on writers and vice versa

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- Readers still wait on writers and vice versa
- Same expensive synchronization instructions
- Dwarfs the actual reader critical section
- No actual reader parallelism; readers get serialized

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- So, no waiting, right?

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- So, no waiting, right?
- Expensive synchronization instructions
- All but one thread must retry
- Useless parallelism: waiting while doing busywork
- At best equivalent to fine-grained locking

Transactional memory

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- (Often implemented using locks for performance)

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- Theoretically equivalent performance to NBS
- In practice, somewhat more expensive
- Fancy generic abstraction wrappers around waiting

How do we stop waiting?

- Reader-writer locking had the right idea
- But readers needed synchronization to wait on writers
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- Readers should not wait at all
- Joint-access parallelism: Can we allow concurrent readers and writers on the same data at the same time?
- What does "at the same time" mean, anyway?

Modern computers

- Shared address space
- Distributed memory
- Expensive illusion of coherent shared memory

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- “At the same time” gets rather fuzzy
- Shared address spaces make communication simple
- Incredibly optimized communication via cache coherence
- When we have to communicate, let’s take advantage of that!
- (and not just to accelerate message passing)

Relativistic Programming

- By analogy with relativity: no absolute reference frame
- No global order for non-causally-related events
- Readers do no waiting at all, for readers or writers
- Minimize expensive communication and synchronization
- Writers do all the waiting, when necessary
- Reads linearly scalable

What if readers see partial writes?

- Writers must not disrupt concurrent readers
- Data structures must stay consistent after every write
- Writers order their writes by waiting
- No impact to concurrent readers

Outline

- Synchronization = Waiting
- Introduction to Relativistic Programming
- Relativistic synchronization primitives
- Relativistic data structures
- Hash-table algorithm
- Results
- Future work

Relativistic synchronization primitives

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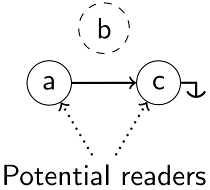
  - No waiting: Notification, not permission
- Pointer publication
  - Ensures ordering between initialization and publication
- Updaters can wait for readers
  - Existing readers only, not new readers

Example: Relativistic linked list insertion



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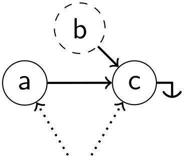

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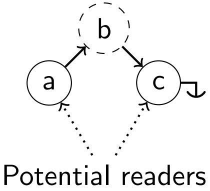

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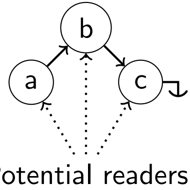

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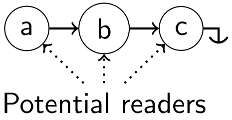
- Readers can immediately begin observing the new node

Example: Relativistic linked list removal



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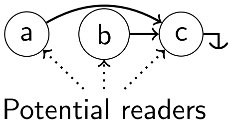

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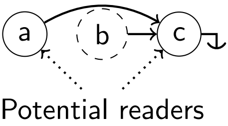

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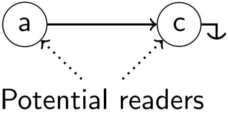

- Initial state of the list; writer wants to remove node b
- Sets a's next pointer to c, removing b from the list for all future readers
- Wait for existing readers to finish
- Once no readers can hold references to b, the writer can safely reclaim it.

Relativistic data structures

- Linked lists
- Radix trees
- Tries
- Balanced trees
- Hash tables

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- What about resizing?
- Necessary to maintain constant-time performance and reasonable memory usage
- Must keep the table consistent at all times

Existing approaches to resizing

- Don't: allocate a fixed-size table and never resize it
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- Herbert Xu's resizable relativistic hash tables
  - Extra linked-list pointers in every node
  - High memory usage

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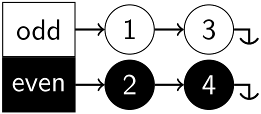
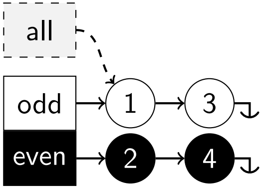
- A reader traversing a hash bucket must always observe all elements in that bucket
- ... but if it observes more, no harm done
- *Imprecise* hash buckets contain elements from other buckets

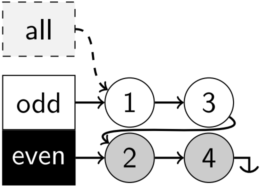
Shrinking: Initial state



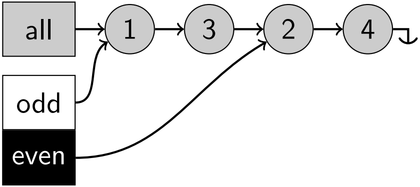
Shrinking: Initialize new buckets



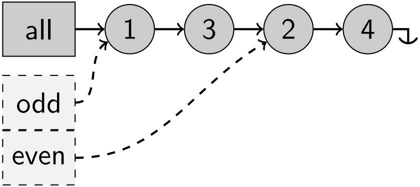
Shrinking: Link old chains



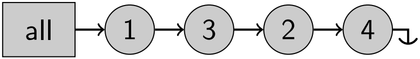
Shrinking: Publish new buckets



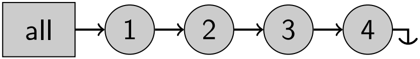
Shrinking: Wait for readers



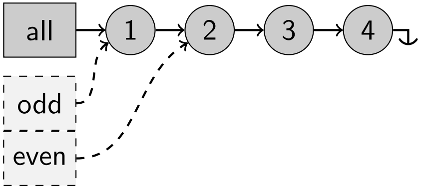
Shrinking: Reclaim



Expanding: Initial state



Expanding: Initialize new buckets



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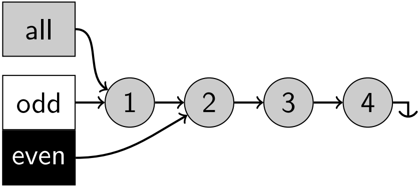

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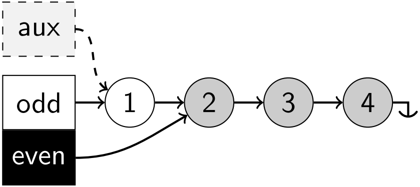
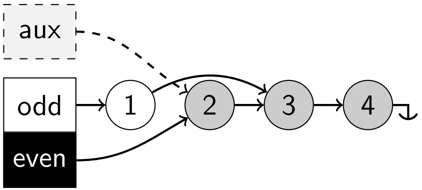
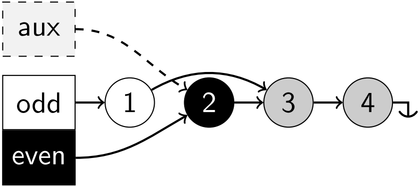


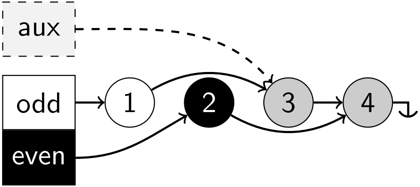
Expanding: Unzip one step



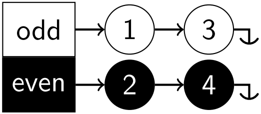
Expanding: Wait for readers



Expanding: Unzip again



Expanding: Final state



Benchmarking methodology

- Implemented a microbenchmark as a Linux kernel module
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- Used Linux's Read-Copy Update (RCU) implementation
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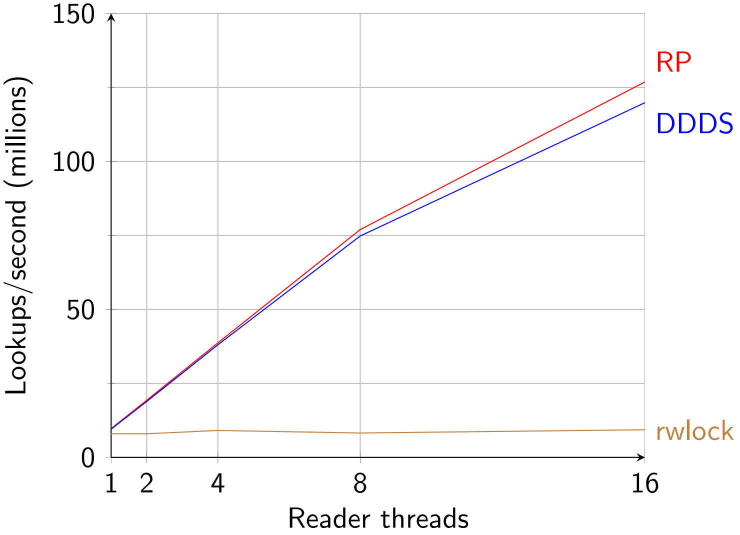
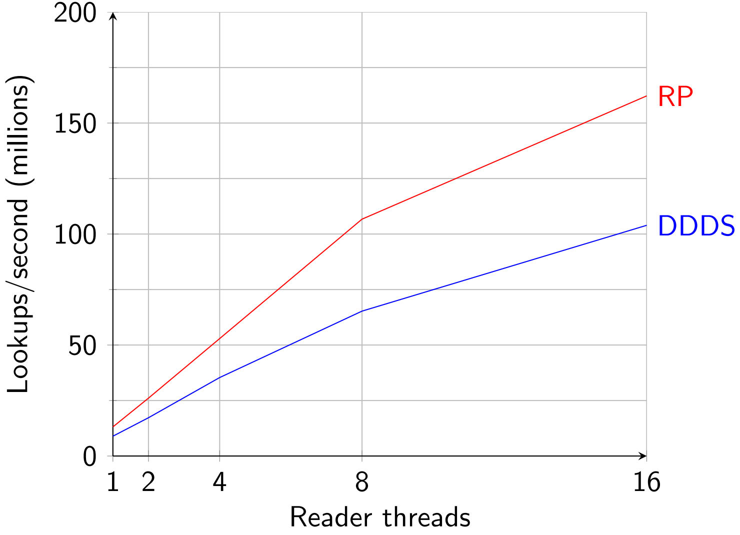
- Lookups with no resize as a baseline
- Lookups with continuous resizing as a worst-case scenario
- Compared: our algorithm, DDDS, rwlock

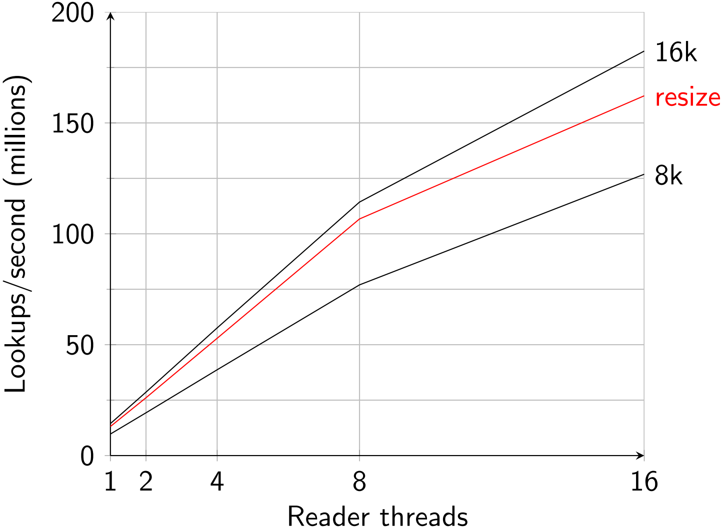
Results: fixed-size table baseline



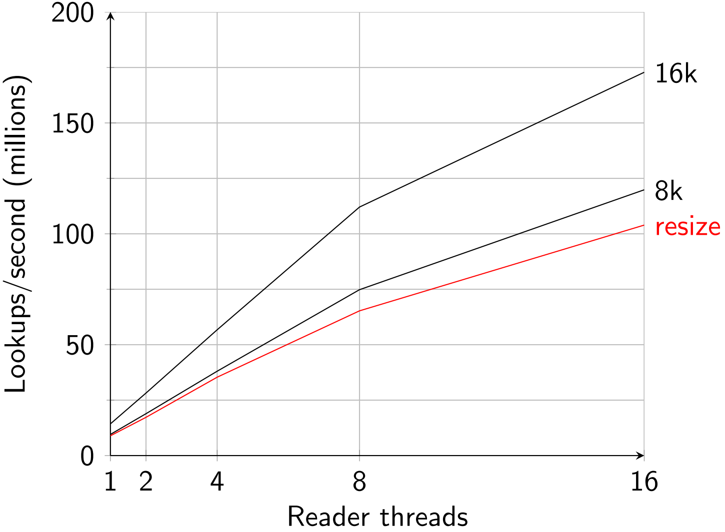
Results - continuous resizing



Results - our resize versus fixed



Results - DDDS resize versus fixed



Hang on a minute...

- This is USENIX!
- We don't settle for microbenchmarks here
- We care about real-world implementations

memcached

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- Used for caching
- Performance-critical

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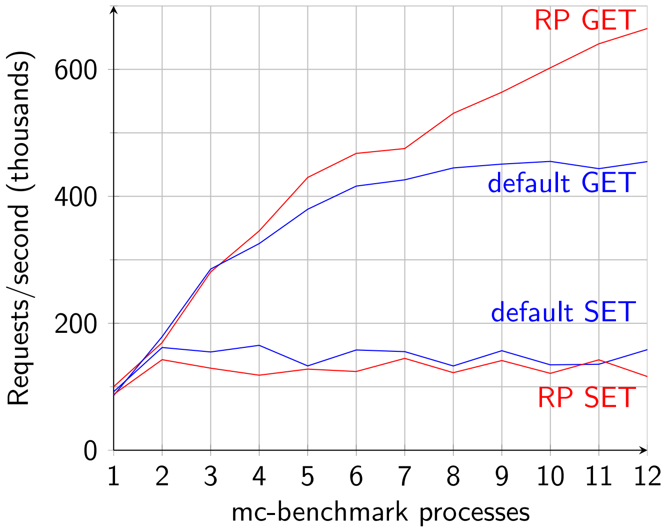
- . . . and it uses a global table lock

memcached with relativistic hash tables

- Uses the userspace RCU implementation, urcu
- Adds a fast path for GET requests using relativistic lookups
- Copies value while still in a relativistic reader
- Falls back to the slow path for expiry, eviction
- Writers use safe relativistic memory reclamation

memcached results



Future work: Relativistic data structures

- New relativistic algorithms currently require careful construction
- We have a general methodology for algorithm construction
  - Write an algorithm assuming our memory model
  - Use this methodology to mechanically place barriers and wait-for-readers operations

Summary

- Relativistic programming allows linearly scalable readers
- Relativistic hash tables support resizing now
  - Now suitable for general-purpose usage
- Real-world code scales better with relativistic programming

Questions?