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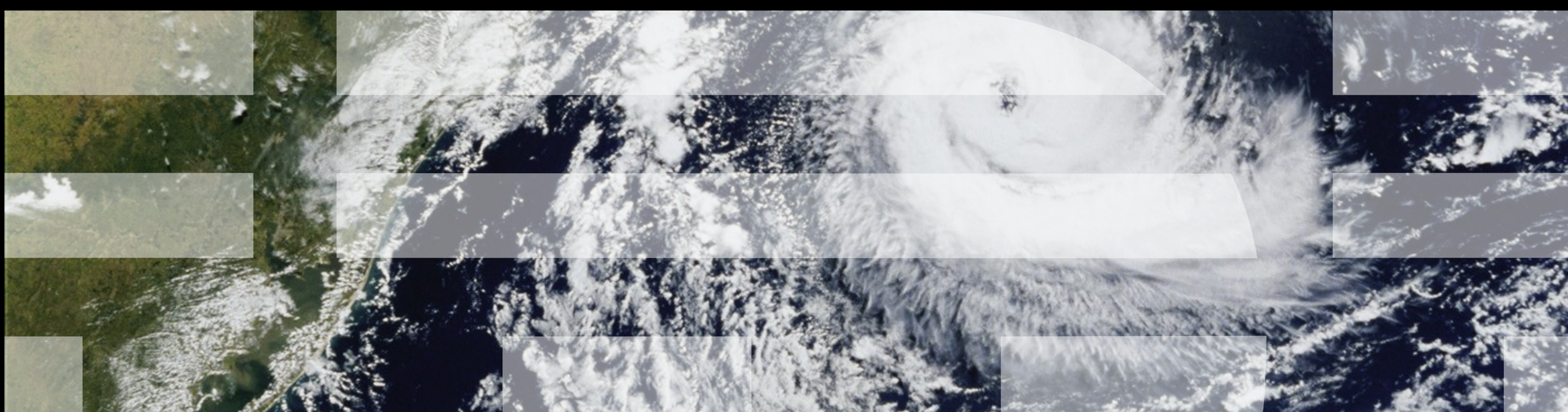
linux.conf.au, Auckland, New Zealand, January 16, 2015

# High-Performance and Scalable Updates: The Issaquah Challenge



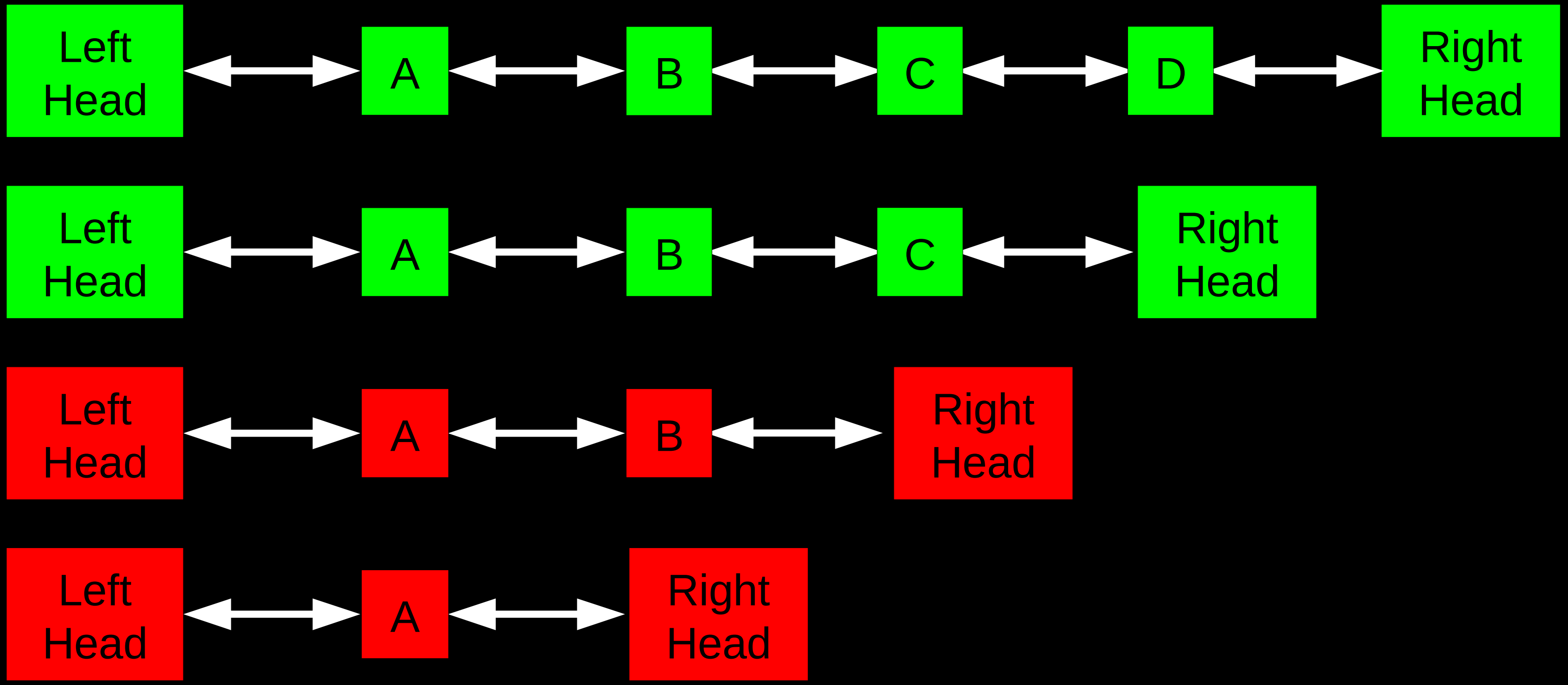
# Overview

- Before the Issaquah Challenge
- The Issaquah Challenge
- Aren't parallel updates a solved problem?
- Special case for parallel updates
  - Per-CPU/thread processing
  - Read-only traversal to location being updated
  - Existence-based updates
- The Issaquah Challenge: One Solution

# Before the Issaquah Challenge

# Before the Issaquah Challenge: Double-Ended Queue

- Can you create a trivial lock-based deque allowing concurrent pushes and pops at both ends?
  - Coordination required if the deque contains only one or two elements
  - But coordination is not required for three or more elements



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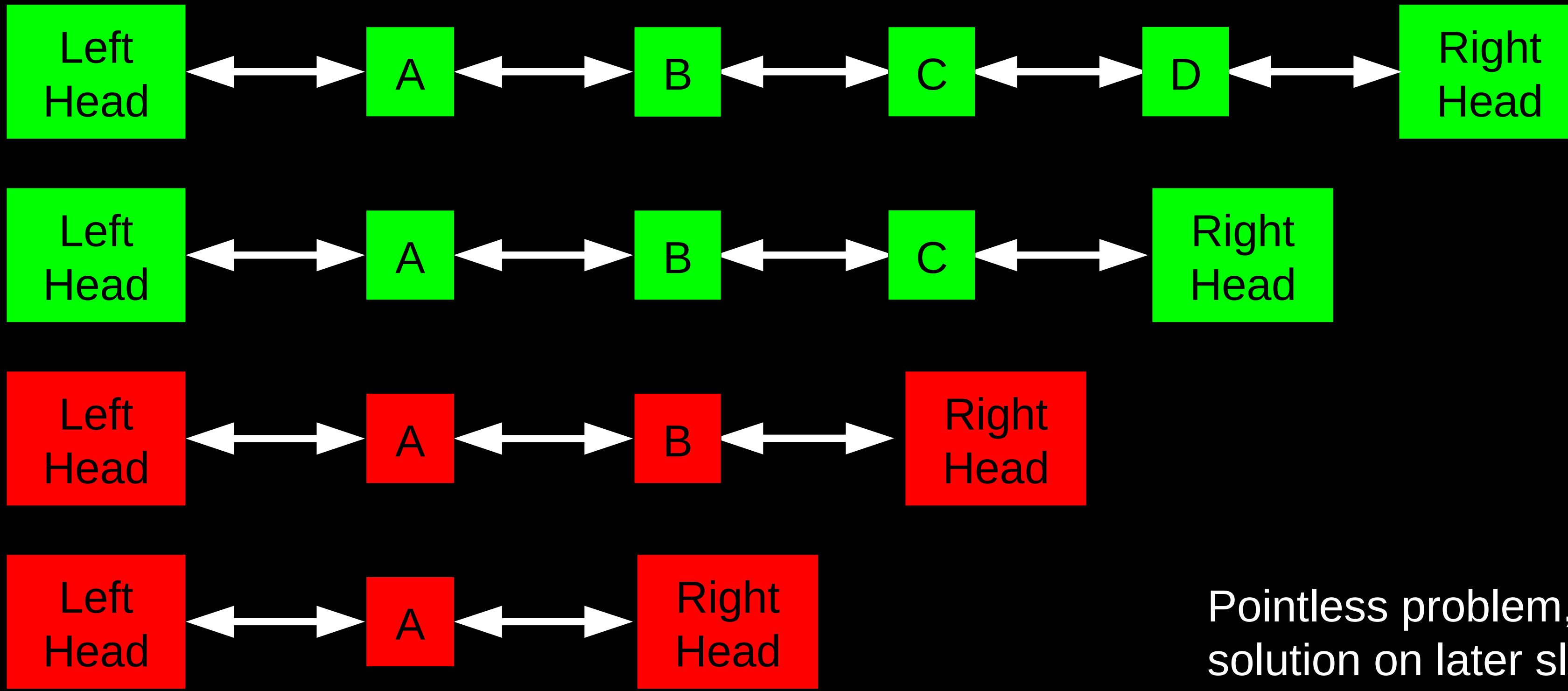


Pointless problem, but solution on later slide...

# Atomic Multi-Structure Update: Issaquah Challenge

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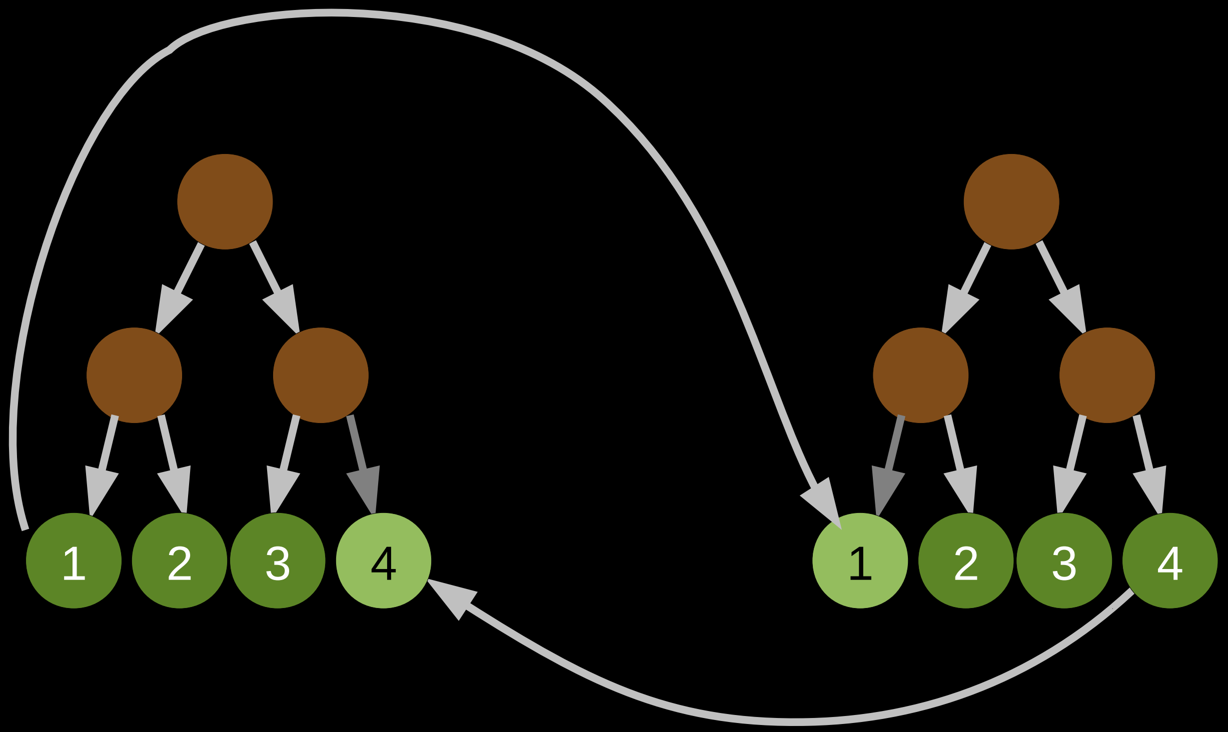
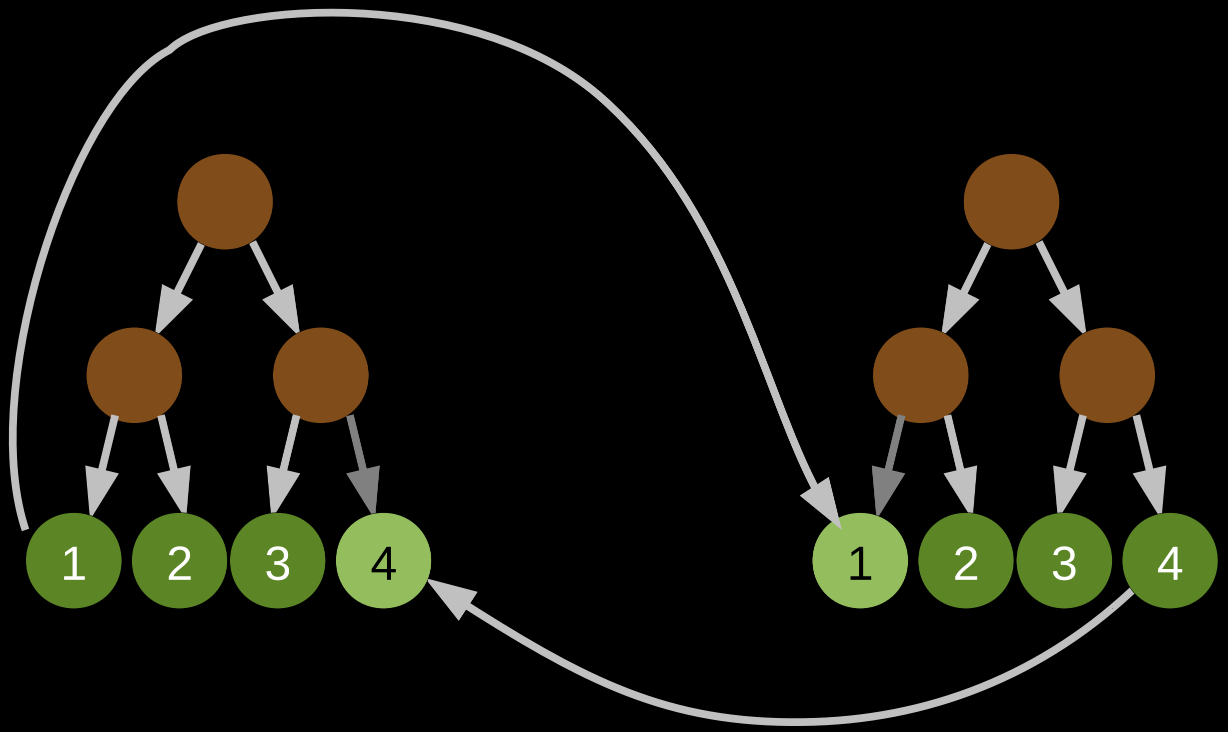


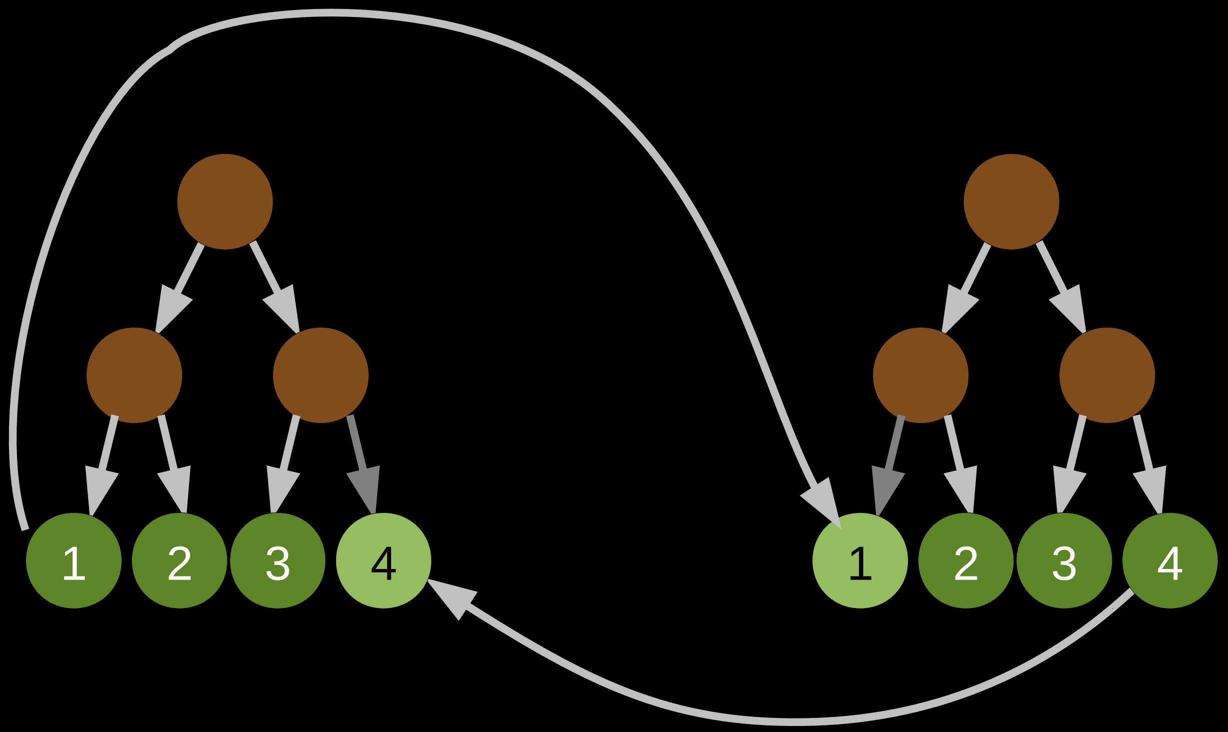

Atomically move element 1 from left to right tree
Atomically move element 4 from right to left tree

# Atomic Multi-Structure Update: Issaquah Challenge




Atomically move element 1 from left to right tree
Atomically move element 4 from right to left tree
Without contention between the two move operations!

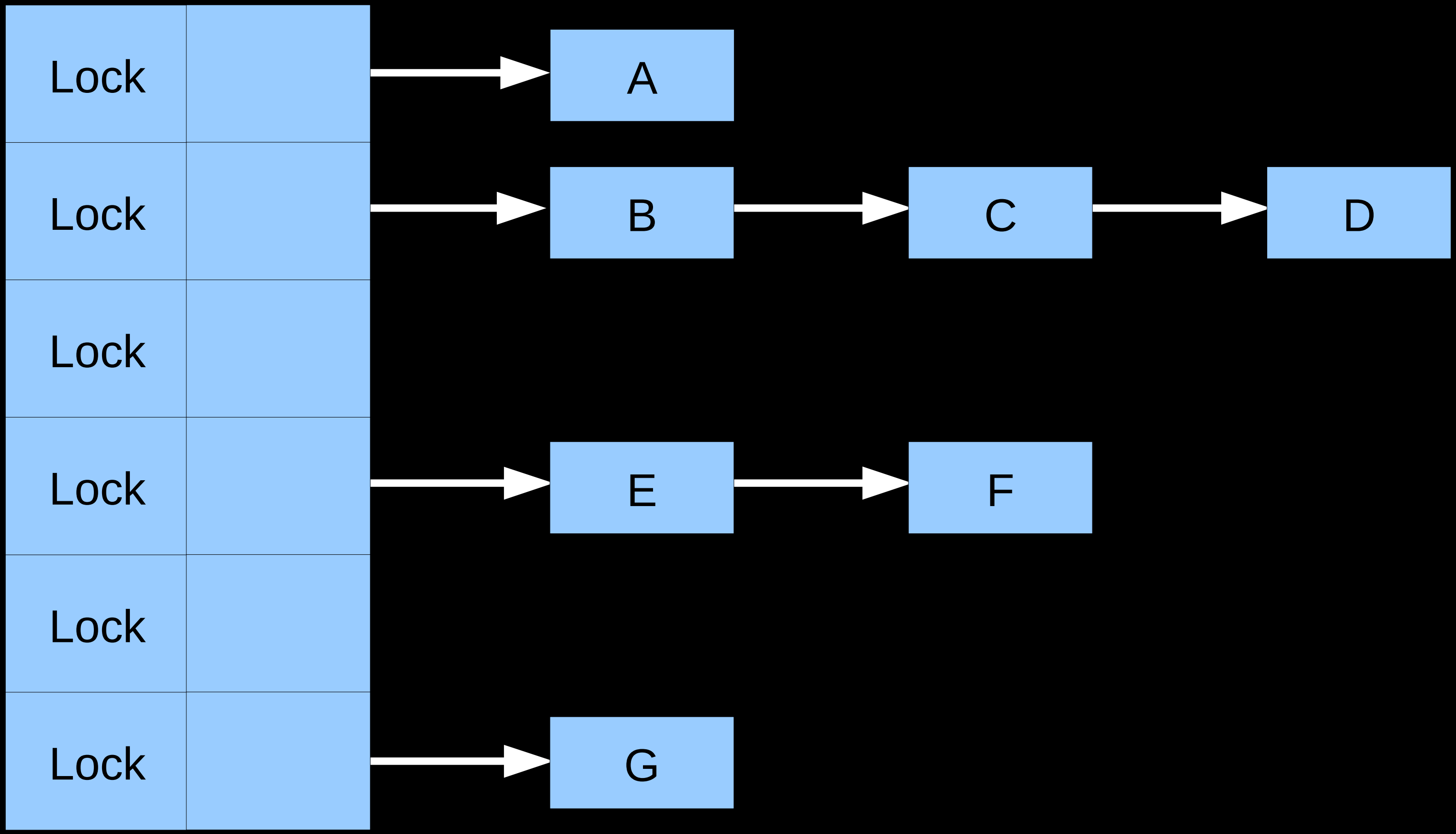
# Atomic Multi-Structure Update: Issaquah Challenge




Atomically move element 1 from left to right tree
Atomically move element 4 from right to left tree
Without contention between the two move operations!
Hence, most locking solutions "need not apply"

# But Aren't Parallel Updates A Solved Problem?

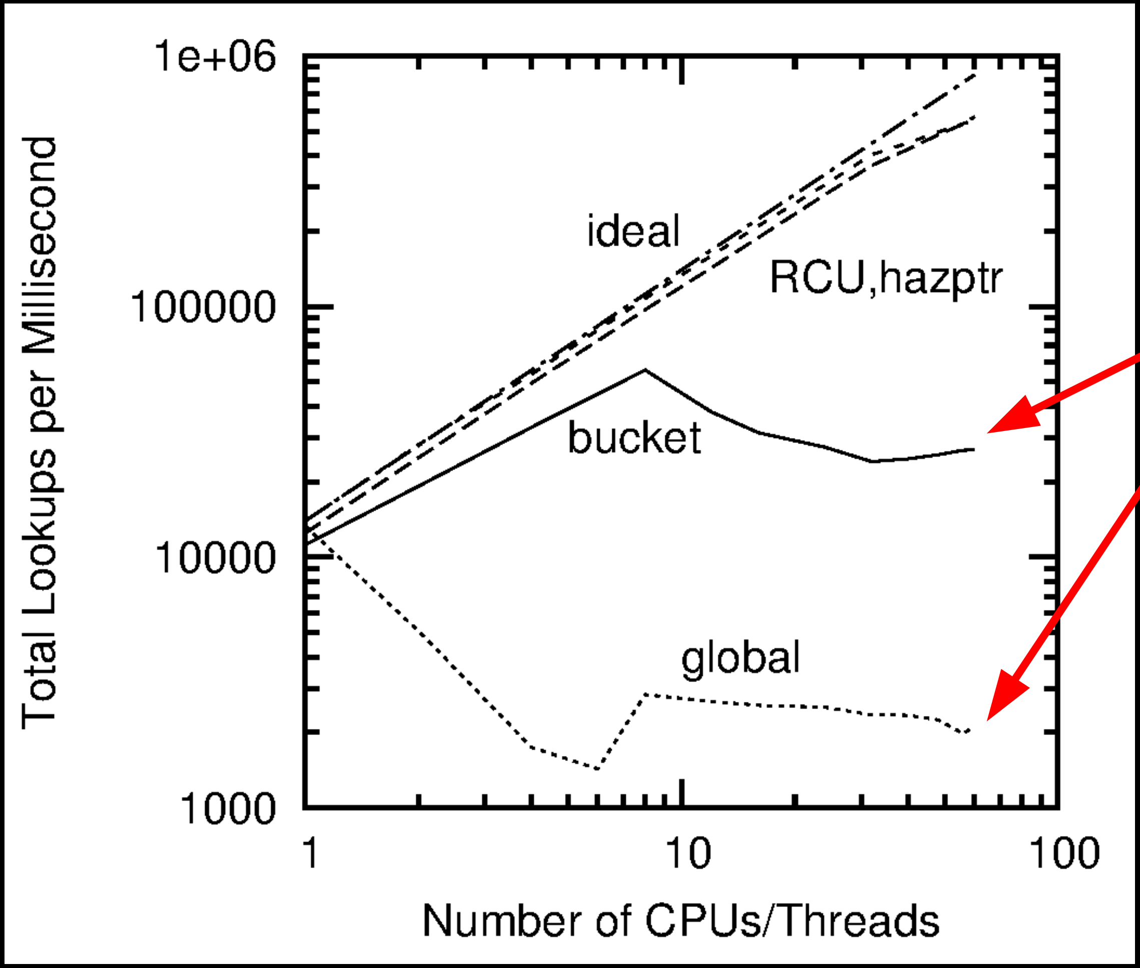
# Parallel-Processing Workhorse: Hash Tables




**Perfect partitioning leads to perfect performance and stunning scalability!**

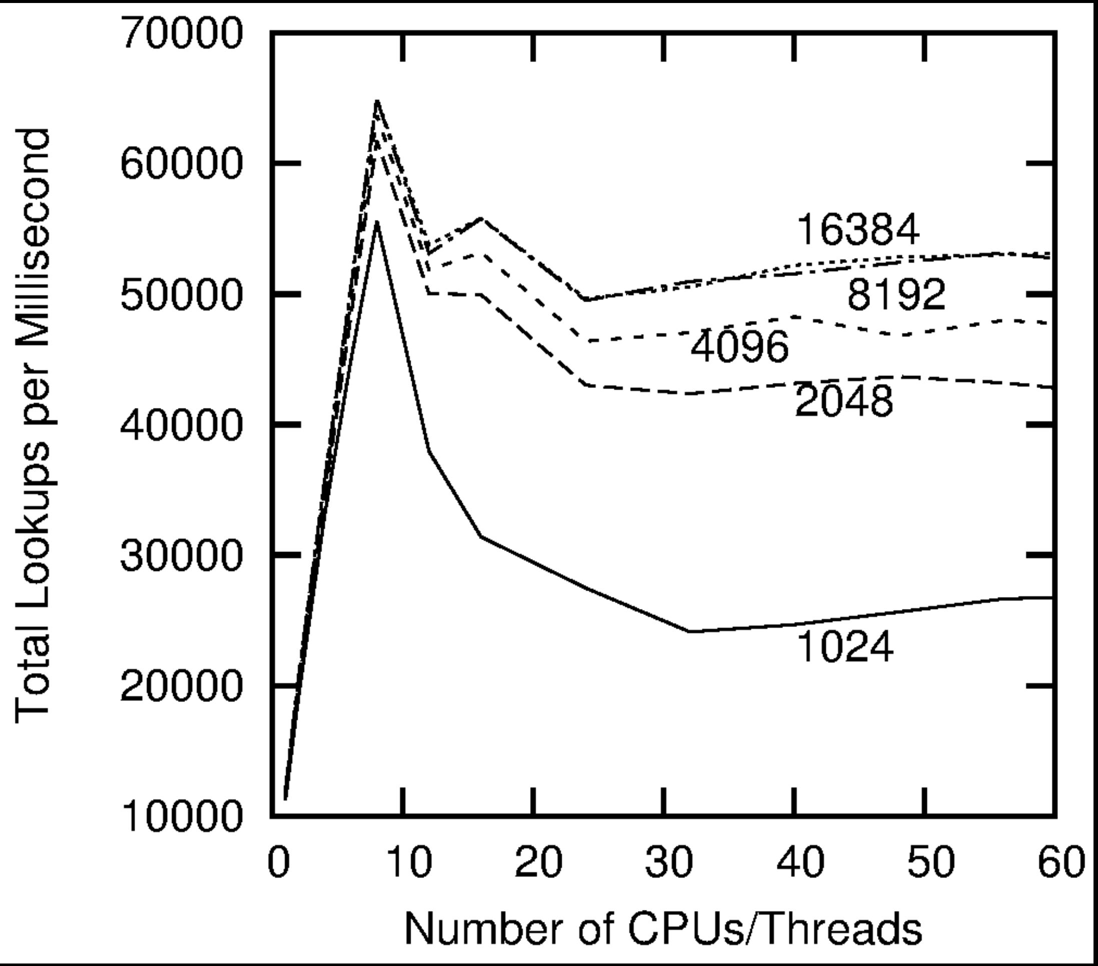
**In theory, anyway...**

# Read-Mostly Workloads Scale Well, Update-Heavy Workloads, Not So Much...



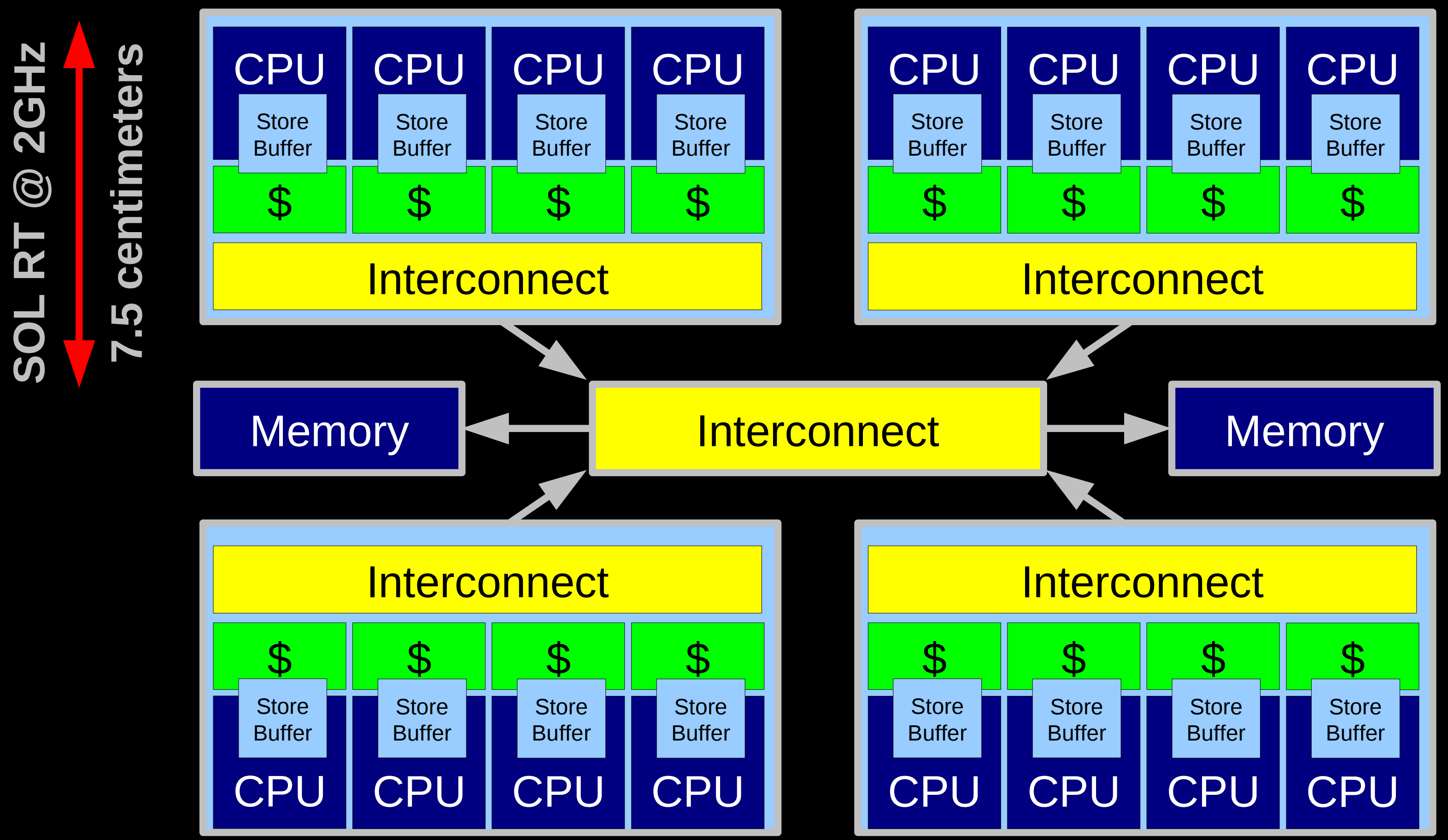

And the horrible thing? Updates are all locking ops!

# But Hash Tables Are Partitionable! # of Buckets?




Some improvement, but...

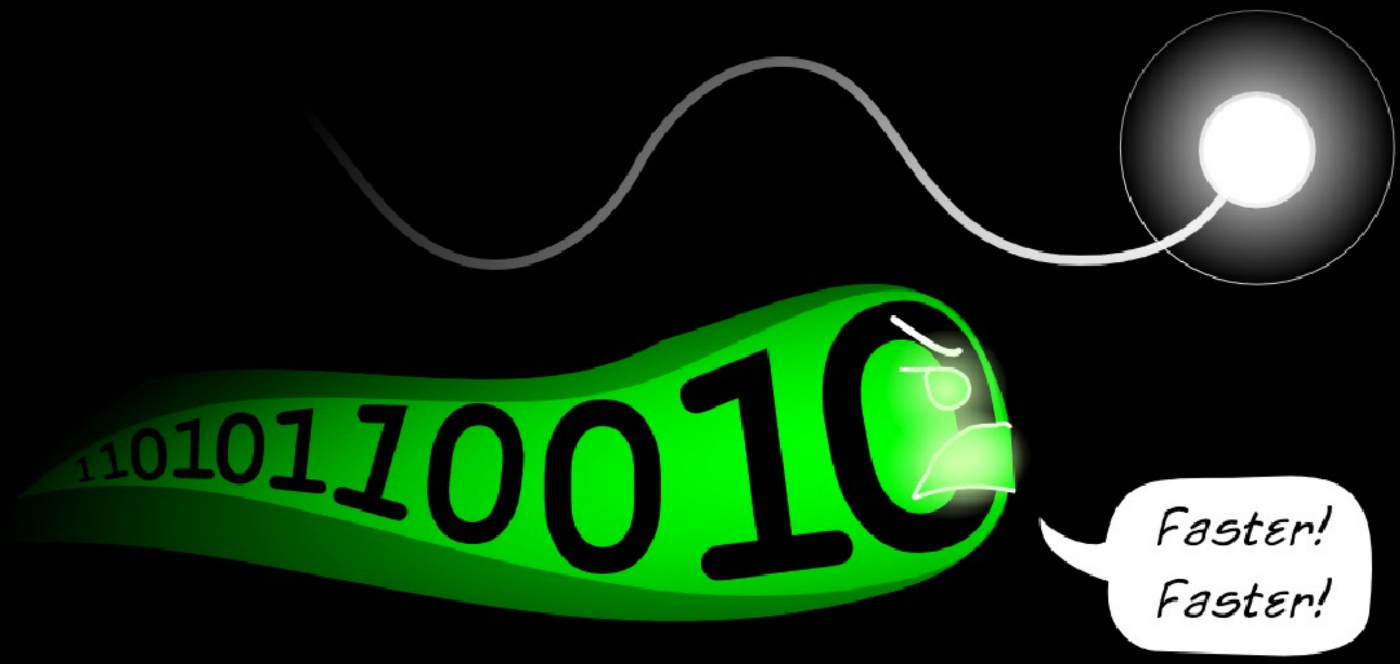
# Hardware Structure and Laws of Physics




**Electrons move at 0.03C to 0.3C in transistors and, so need locality of reference**

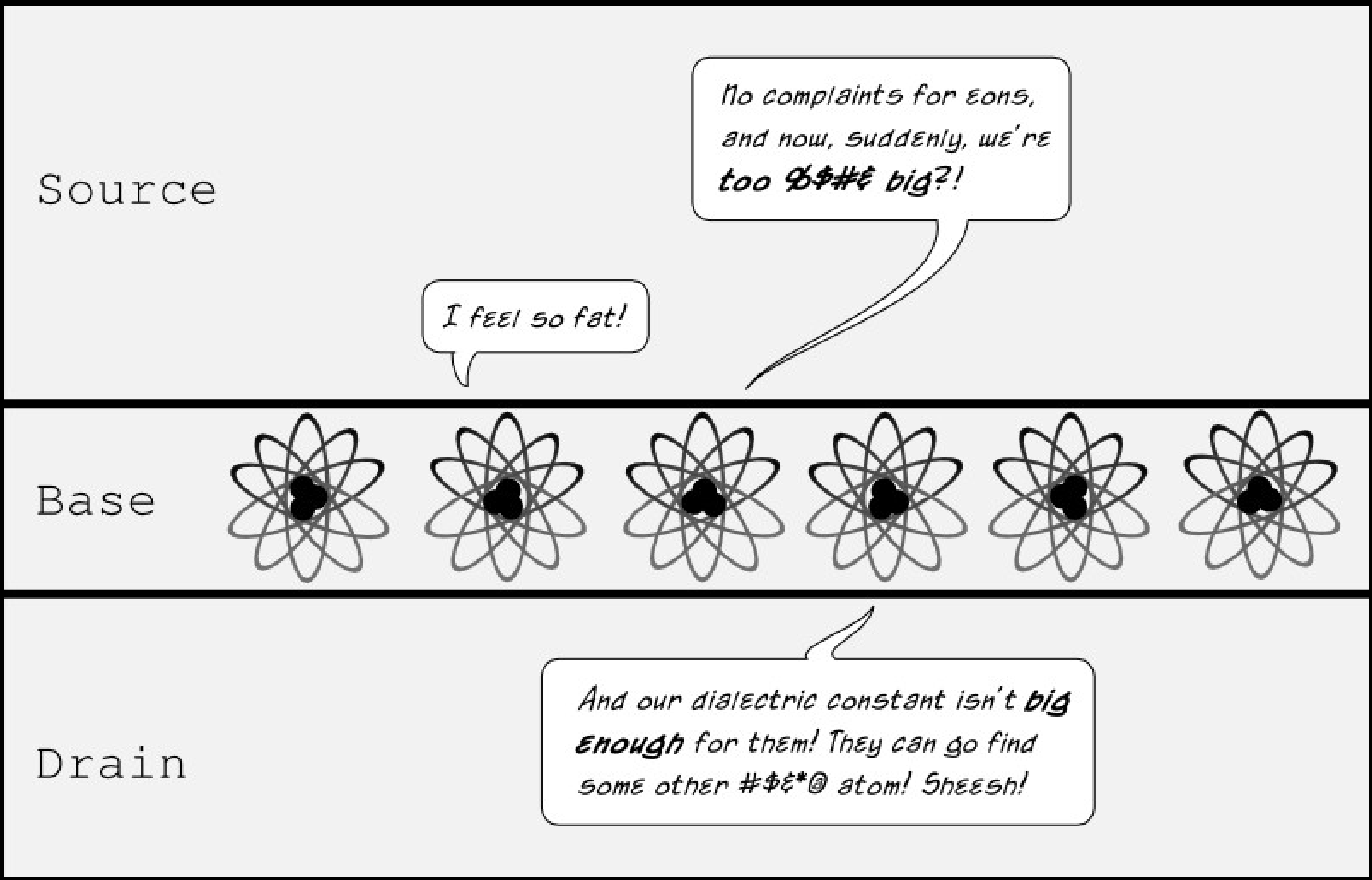
# Two Problems With Fundamental Physics...

# Problem With Physics #1: Finite Speed of Light



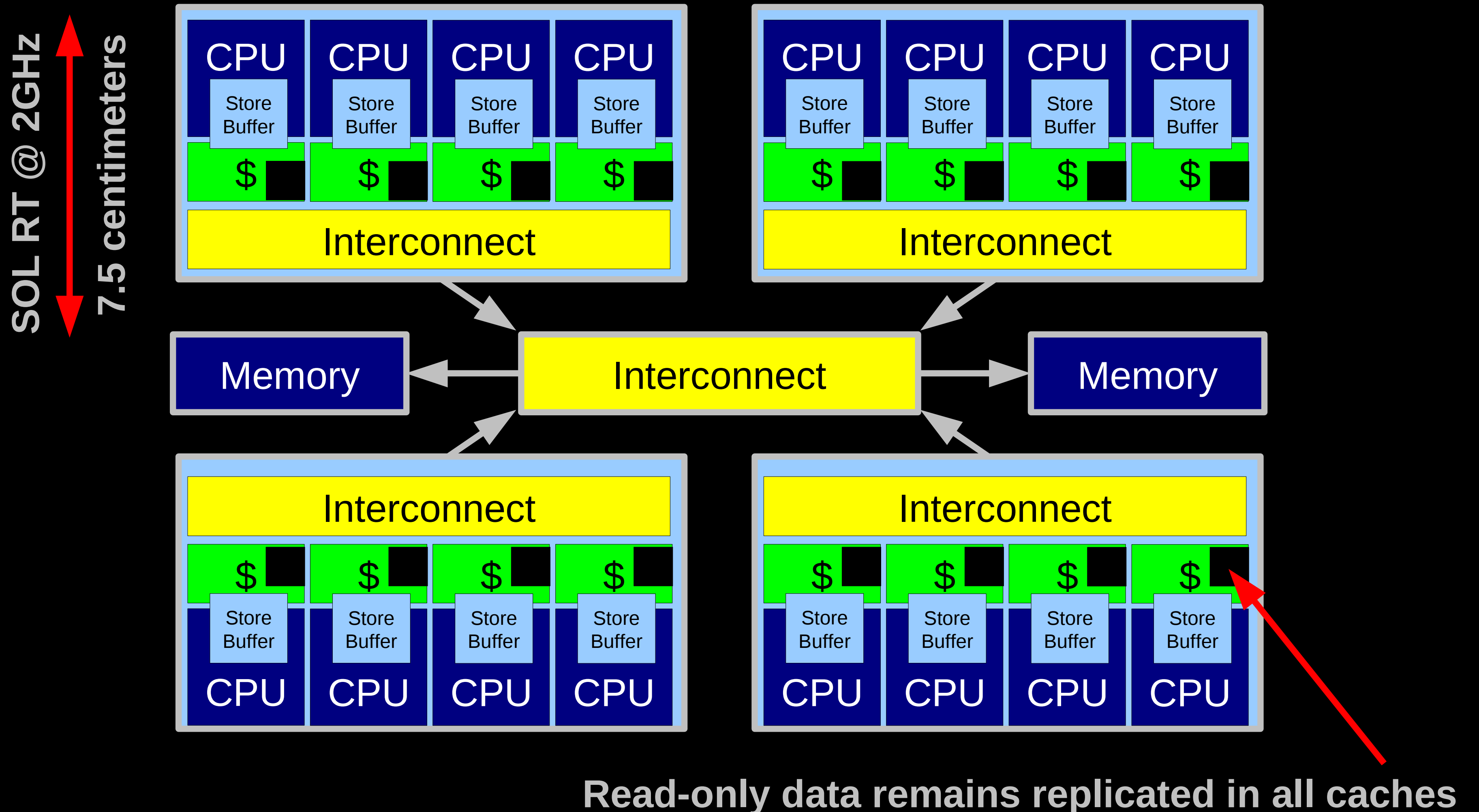

Observation by Stephen Hawking

# Problem With Physics #2: Atomic Nature of Matter

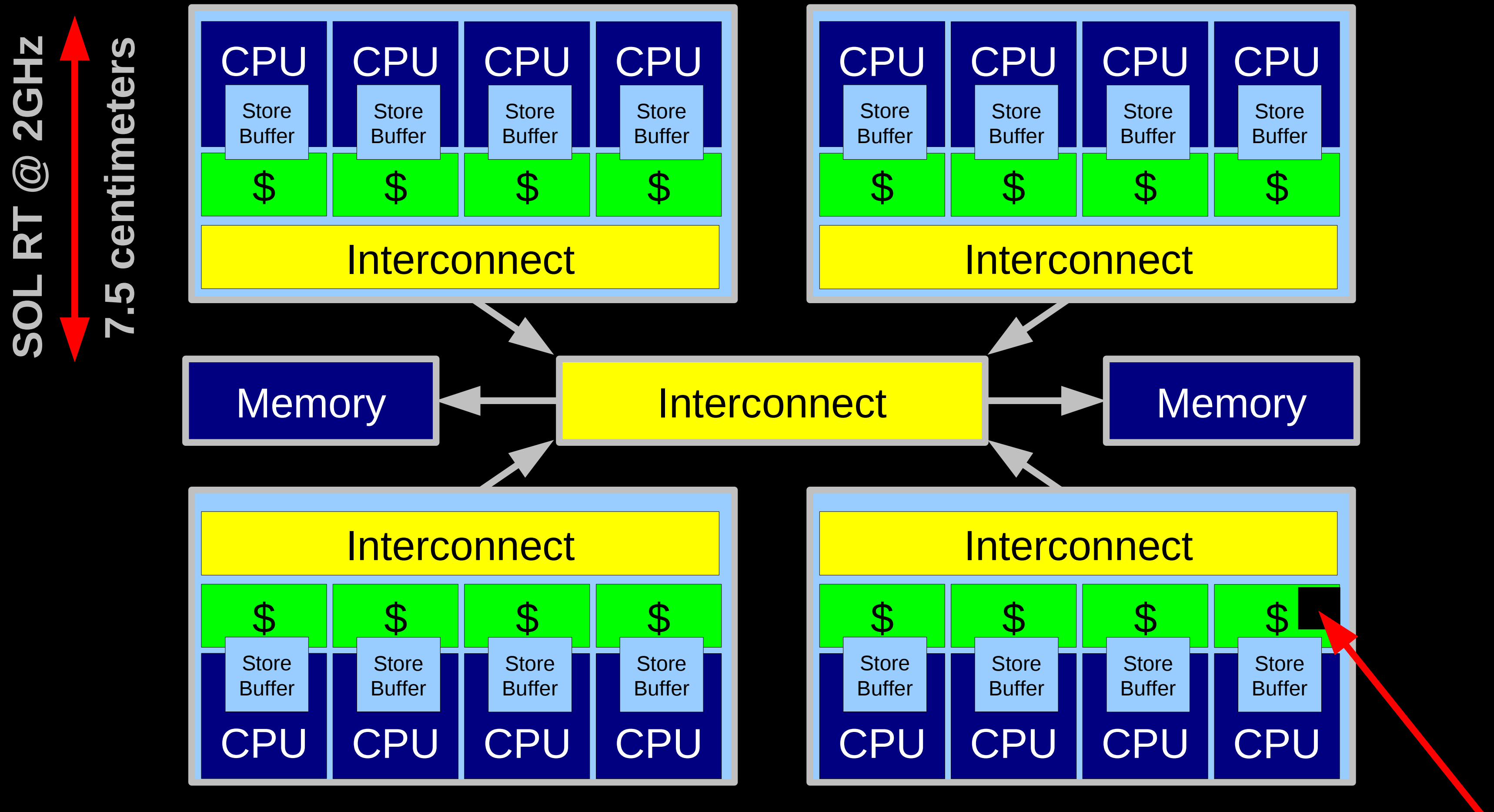



Observation by Stephen Hawking

# Read-Mostly Access Dodges The Laws of Physics!!!



# Updates, Not So Much...




**Read-only data remains replicated in all caches, but each update destroys other replicas!**

# “Doctor, it Hurts When I Do Updates!!!

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- “Then don't do updates!”

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- “Then don't do updates!”
- “But if I don't do updates, I run out of registers!”

# “Doctor, it Hurts When I Do Updates!!!

- “Then don't do updates!”
- “But if I don't do updates, I run out of registers!”

- We have no choice but to do updates, but we clearly need to be very careful with exactly ***how*** we do our updates

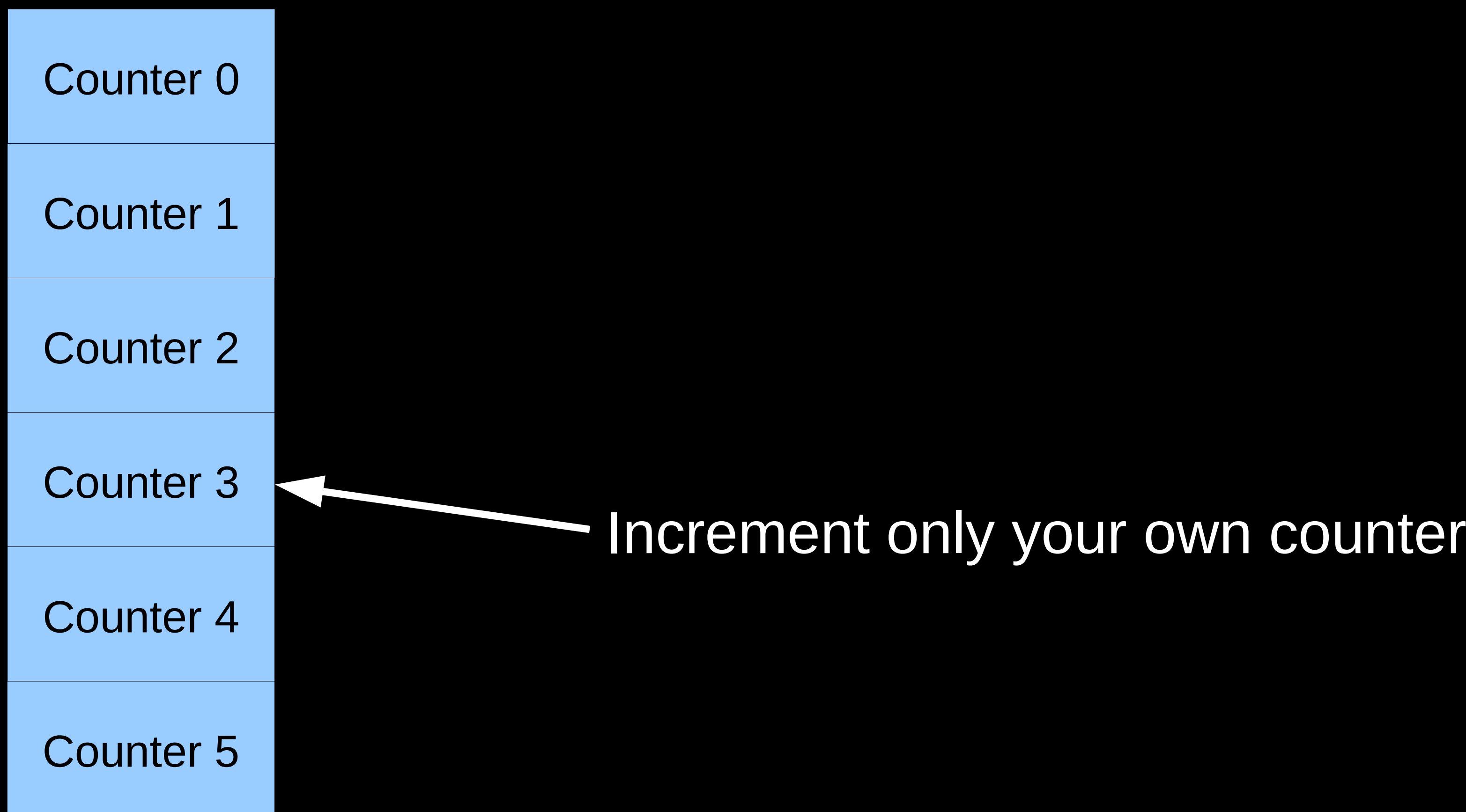
# Update-Heavy Workloads Painful for Parallelism!!! But There Are Some Special Cases...

# But There Are Some Special Cases

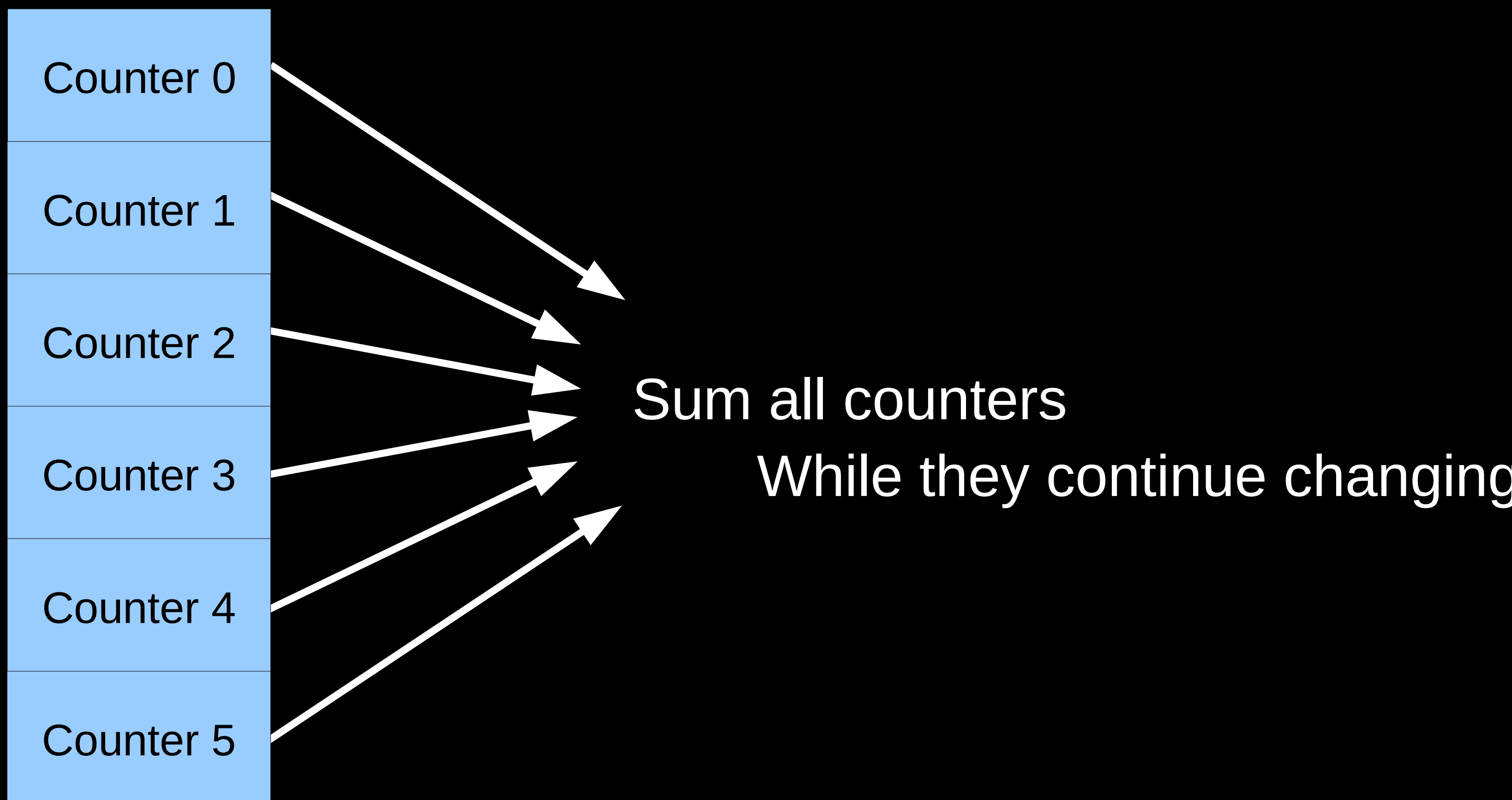
- Per-CPU/thread processing (perfect partitioning)
  - Huge number of examples, including the per-thread/CPU stack
  - We will look at split counters
- Read-only traversal to location being updated
  - Key to solving the Issaquah Challenge
- Trivial Lock-Based Concurrent Deque???

# Split Counters

# Split Counters Diagram



# Split Counters Diagram



# Split Counters Lesson

- Updates need not slow us down – if we maintain good locality
- For the split counters example, in the common case, each thread only updates its own counter
  - Reads of all counters should be rare
  - If they are not rare, use some other counting algorithm
  - There are a lot of them, see “Counting” chapter of “Is Parallel Programming Hard, And, If So, What Can You Do About It?” (http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html)

# Read-Only Traversal To Location Being Updated

# Why Read-Only Traversal To Update Location?

- Consider a binary search tree
- Classic locking methodology would:
  1) Lock root
  2) Use key comparison to select descendant
  3) Lock descendant
  4) Unlock previous node
  5) Repeat from step (2)
- The lock contention on the root is not going to be pretty!
  – And we won't get contention-free moves of independent elements, so this cannot be a solution to the Issaquah Challenge

# And This Is Why We Have RCU!

- (You can also use garbage collectors, hazard pointers, reference counters, etc.)
- Design principle: Avoid expensive operations in read-side code
- Lightest-weight conceivable read-side primitives

```
/* Assume non-preemptible (run-to-block) environment. */
#define rcu_read_lock()
#define rcu_read_unlock()
```

Quick overview, references at end of slideset.

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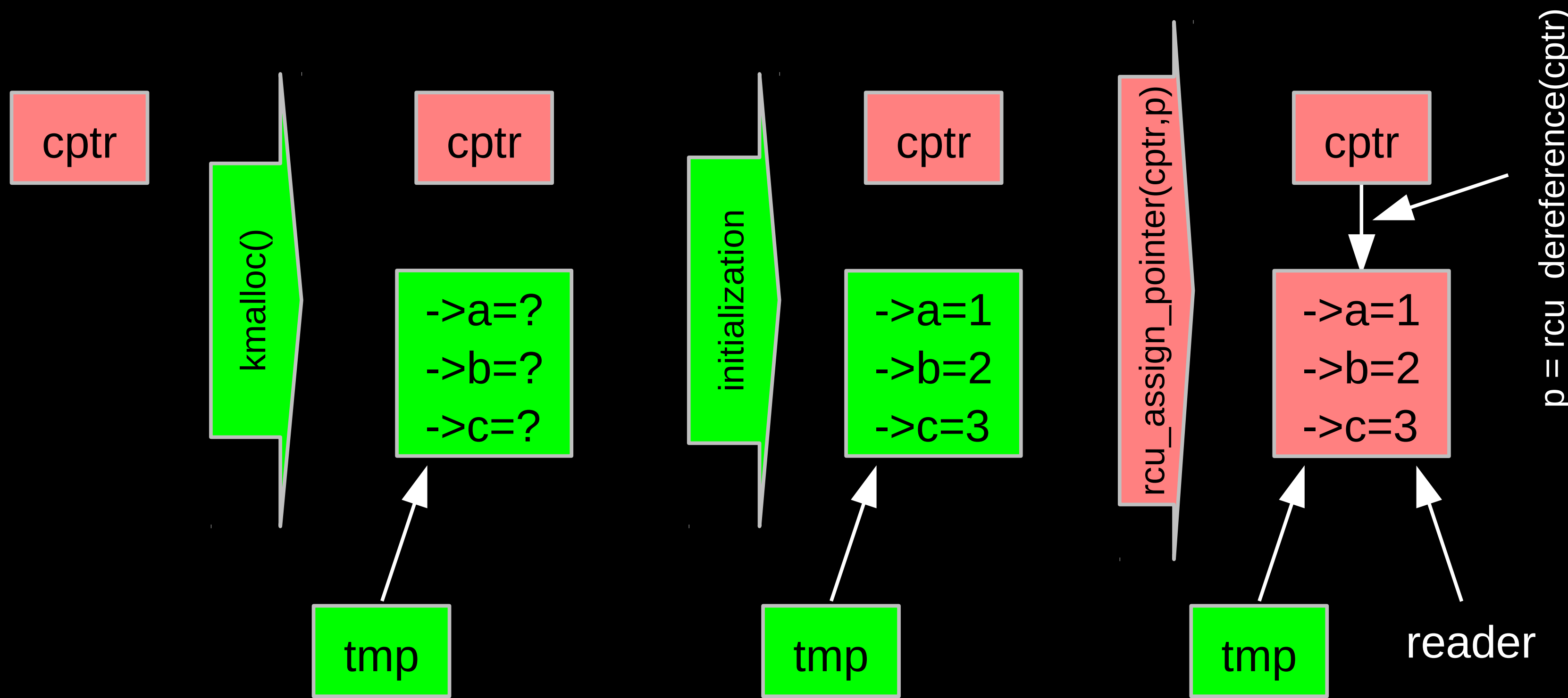
```

- I assert that this gives the best possible performance, scalability, real-time response, wait-freedom, and energy efficiency
- But how can something that does not affect machine state possibly be used as a synchronization primitive???

Quick overview, references at end of slideset.

# RCU Addition to a Linked Structure

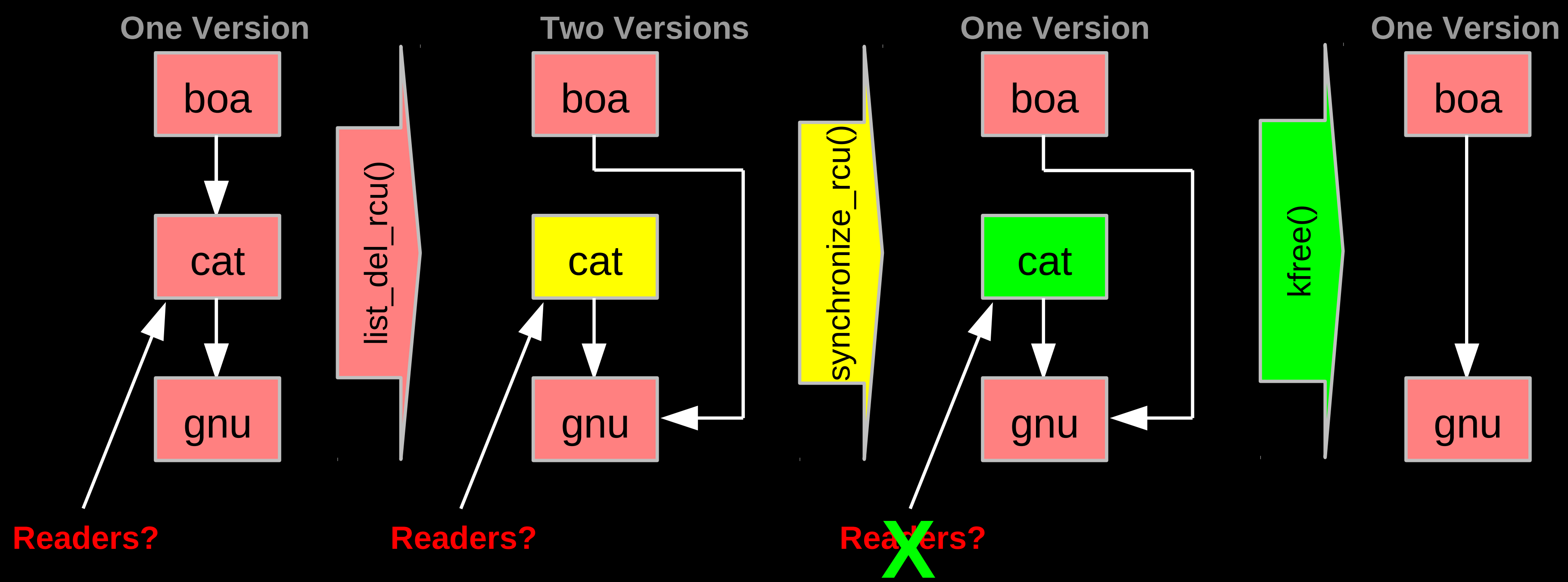
Key:
- Dangerous for updates: all readers can access
- Still dangerous for updates: pre-existing readers can access (next slide)
- Safe for updates: inaccessible to all readers




**But if all we do is add, we have a big memory leak!!!**

# RCU Safe Removal From Linked Structure

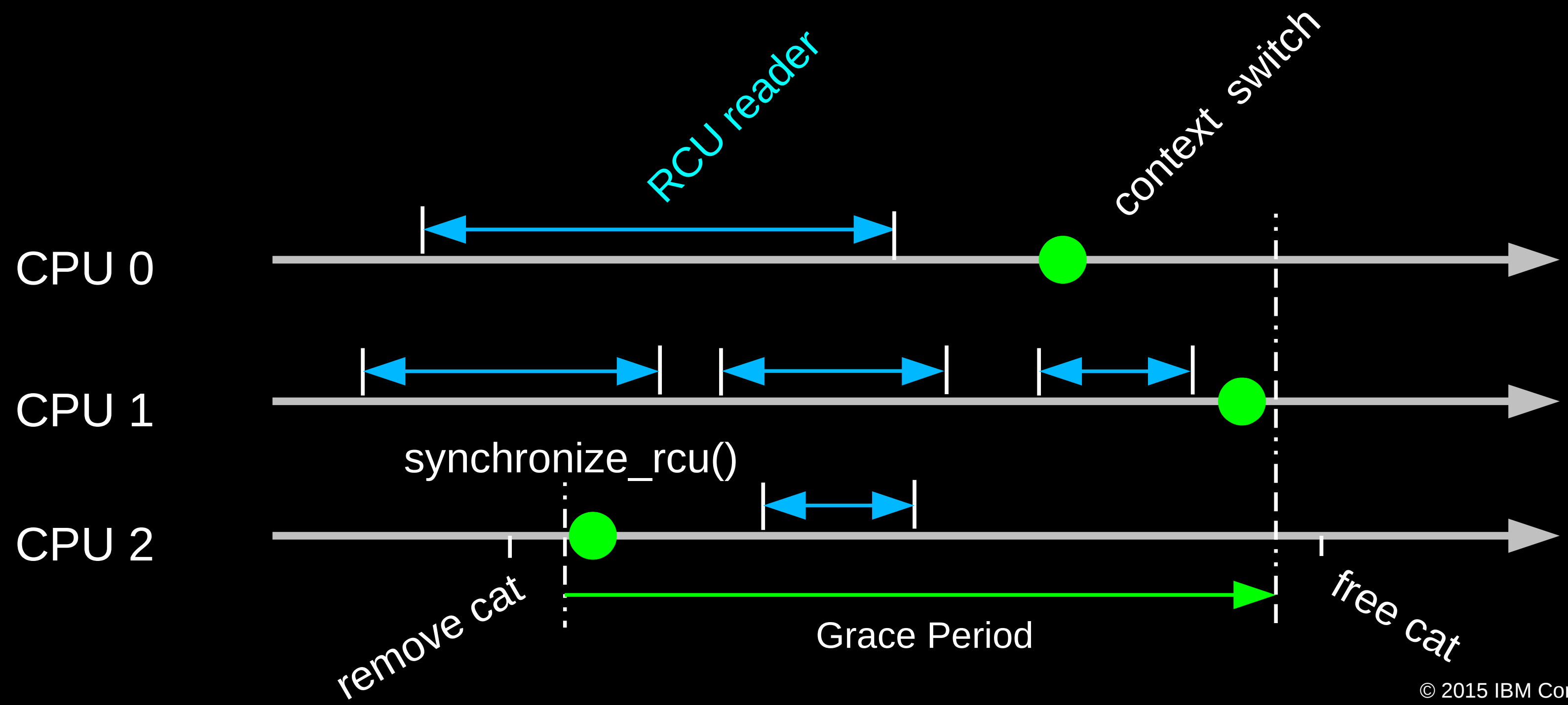
- Combines waiting for readers and multiple versions:
  - Writer removes the cat's element from the list (list_del_rcu())
  - Writer waits for all readers to finish (synchronize_rcu())
  - Writer can then free the cat's element (kfree())




**But if readers leave no trace in memory, how can we possibly tell when they are done???**

# RCU Waiting for Pre-Existing Readers: QSBR

- Non-preemptive environment (CONFIG_PREEMPT=n)
  - RCU readers are not permitted to block
  - Same rule as for tasks holding spinlocks
- CPU context switch means all that CPU's readers are done
- *Grace period* ends after all CPUs execute a context switch



# Synchronization Without Changing Machine State???

- But rcu_read_lock() and rcu_read_unlock() do not need to change machine state
  - Instead, they act on the developer, who must avoid blocking within RCU read-side critical sections
- RCU is therefore ***synchronization via social engineering***
- As are all other synchronization mechanisms:
  - "Avoid data races"
  - "Access shared variables only while holding the corresponding lock"
  - "Access shared variables only within transactions"
- RCU is unusual is being a purely social-engineering approach
  - But RCU implementations for preemptive environments do use lightweight code in addition to social engineering

# Better Read-Only Traversal To Update Location

# Better Read-Only Traversal To Update Location

- An improved locking methodology might do the following:
  - rcu_read_lock()
  - Traversal:
    - Start at root without locking
    - Use key comparison to select descendant
    - Repeat until update location is reached
    - Acquire locks on update location
    - Do consistency checks, retry from root if inconsistent
  - Carry out update
  - rcu_read_unlock()
- Eliminates contention on root node!
- But need some sort of consistency-check mechanism...
  - RCU protects against freeing, not necessarily removal
  - “Removed” flags on individual data elements

# Deletion-Flagged Read-Only Traversal

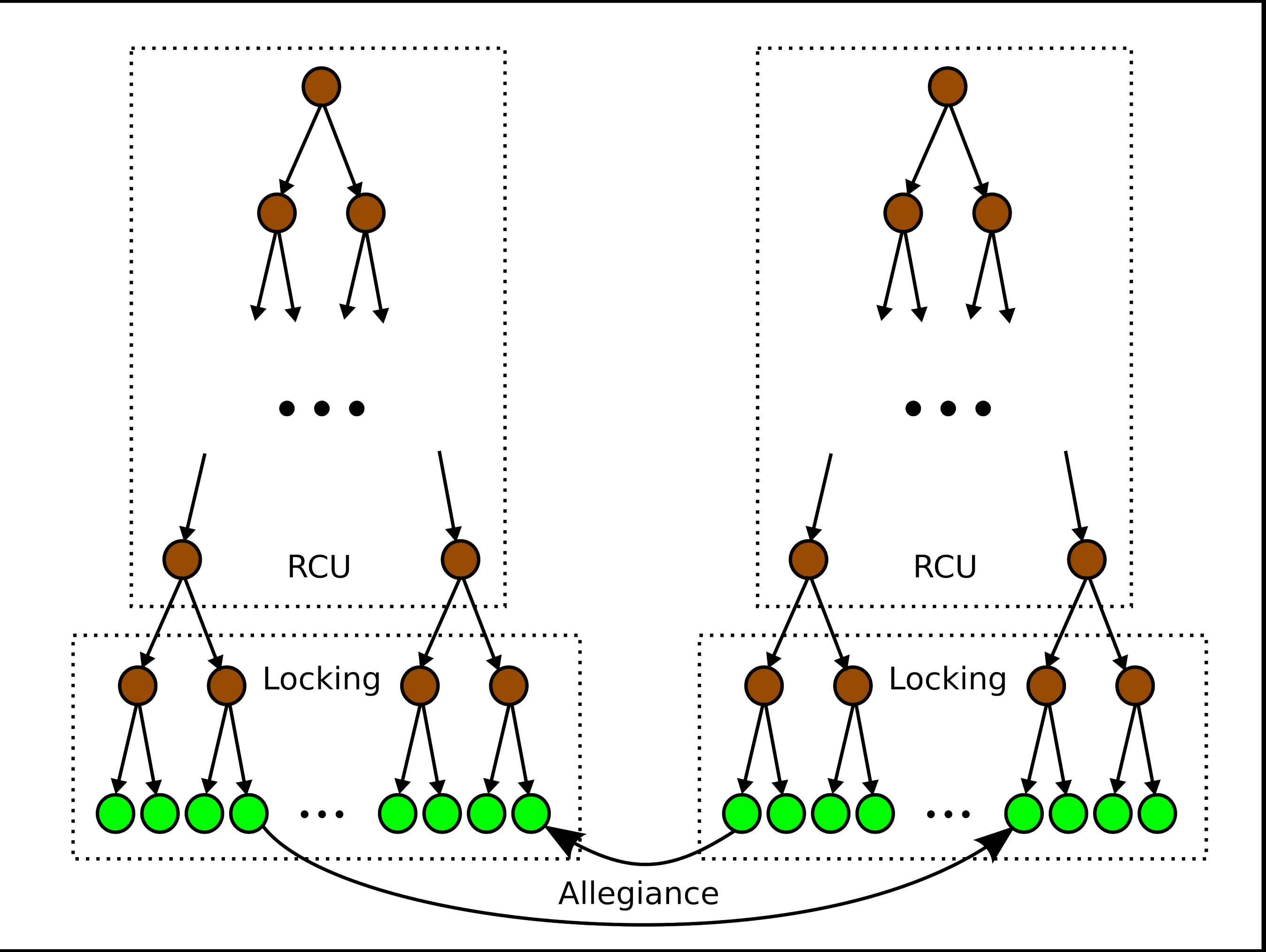
- for (;;)
  - rcu_read_lock()
  - Start at root without locking
  - Use key comparison to select descendant
  - Repeat until update location is reached
  - Acquire locks on update location
  - If to-be-updated location's “removed” flag is not set:
    - Break out of “for” loop
  - Release locks on update location
  - rcu_read_unlock()
- Carry out update
- Release locks on update location and rcu_read_unlock()

# Read-Only Traversal To Location Being Updated

- Focus contention on portion of structure being updated
  - And preserve locality of reference to different parts of structure
- Of course, full partitioning is better!
- Read-only traversal technique citations:
  - Arbel & Attiya, “Concurrent Updates with RCU: Search Tree as an Example”, PODC'14 (very similar lookup, insert, and delete)
  - McKenney, Sarma, & Soni, “Scaling dcache with RCU”, Linux Journal, January 2004
  - And possibly: Pugh, “Concurrent Maintenance of Skip Lists”, University of Maryland Technical Report CS-TR-2222.1, June 1990
  - And maybe also: Kung & Lehman, “Concurrent Manipulation of Binary Search Trees”, ACM TODS, September, 1980

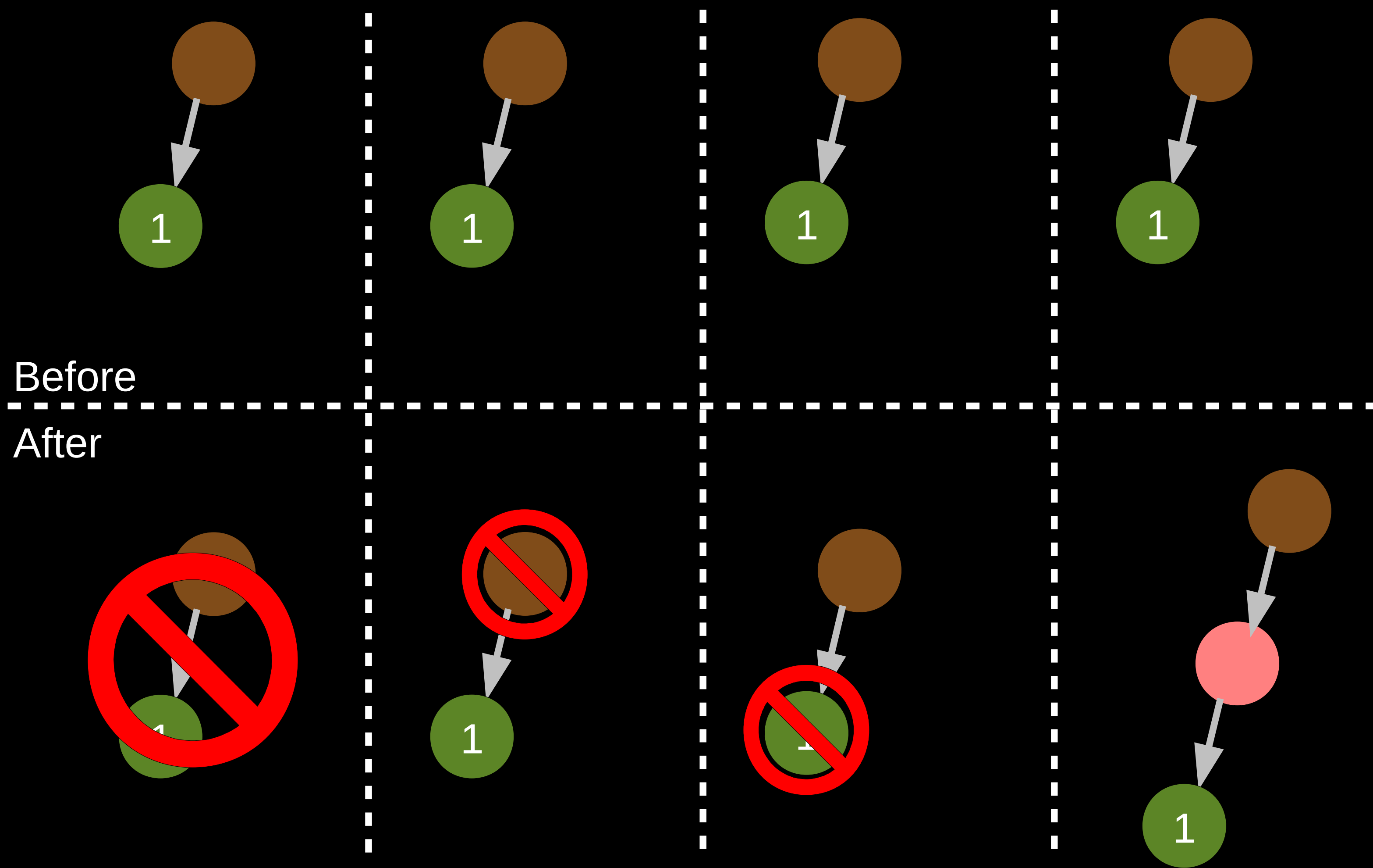
# Issaquah Challenge: One Solution

# Locking Regions for Binary Search Tree




Same tree algorithm with a few existence-oriented annotations

# Possible Upsets While Acquiring Locks...



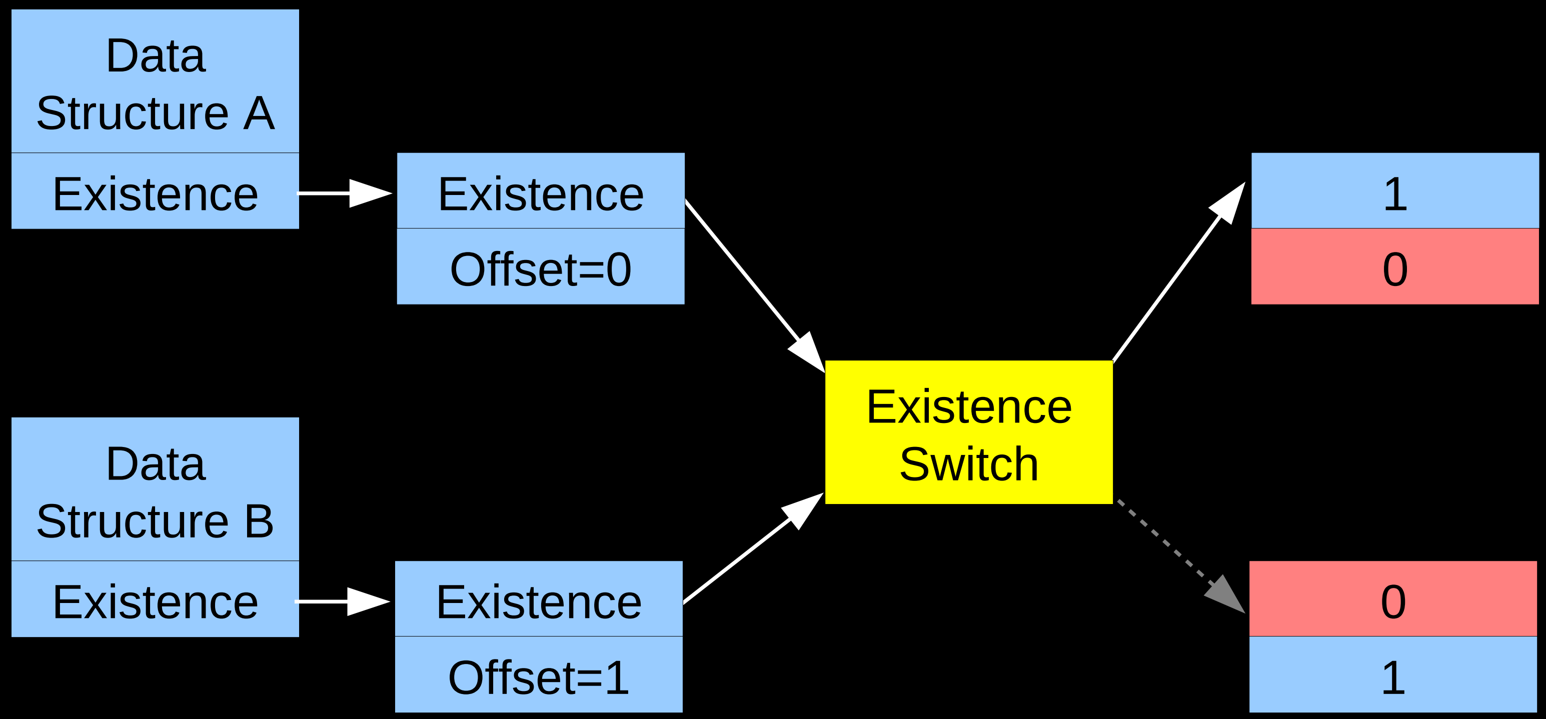

What to do?
Drop locks and retry!!!

# Existence Structures

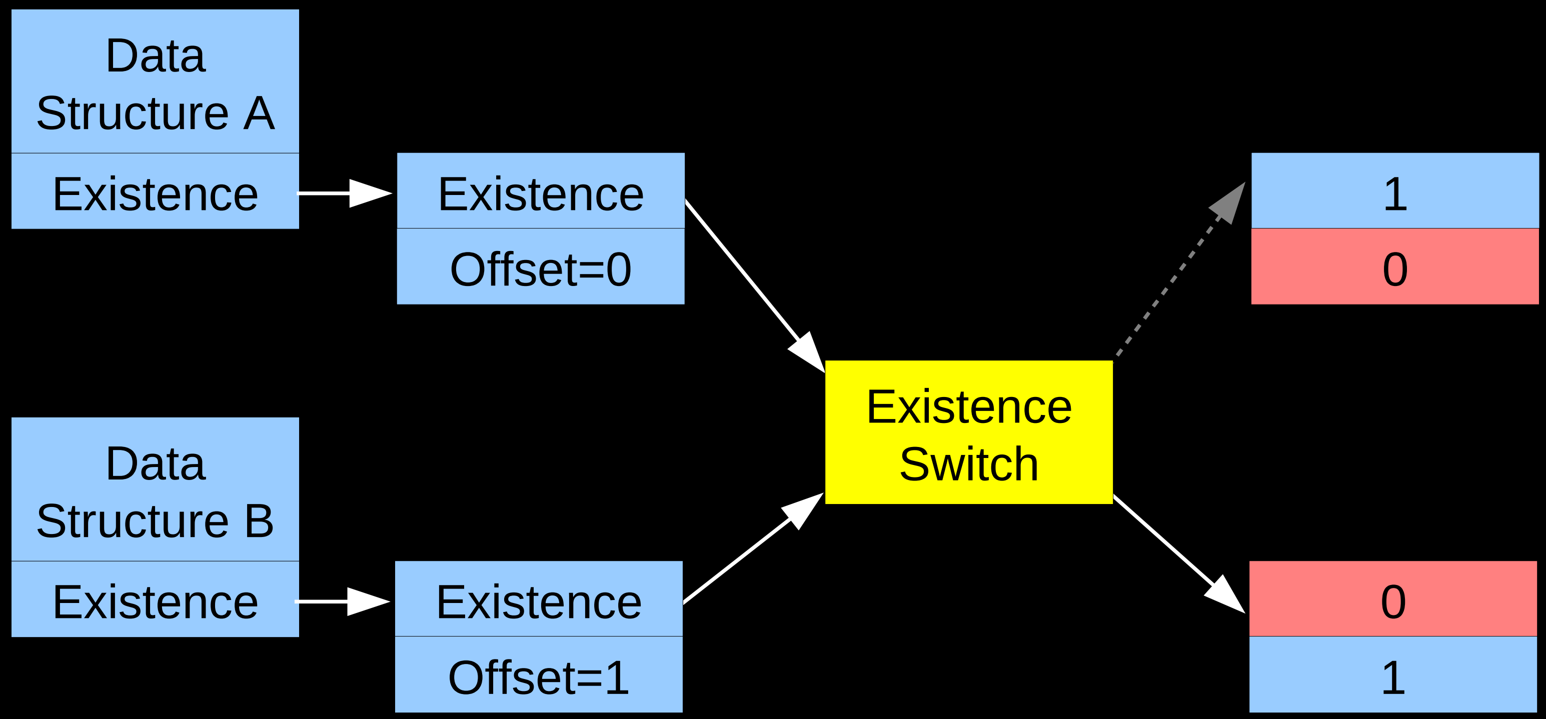
# Existence Structures

- Solving yet another computer-science problem by adding an additional level of indirection...

# Example Existence Structure Before Switch



# Example Existence Structure After Switch



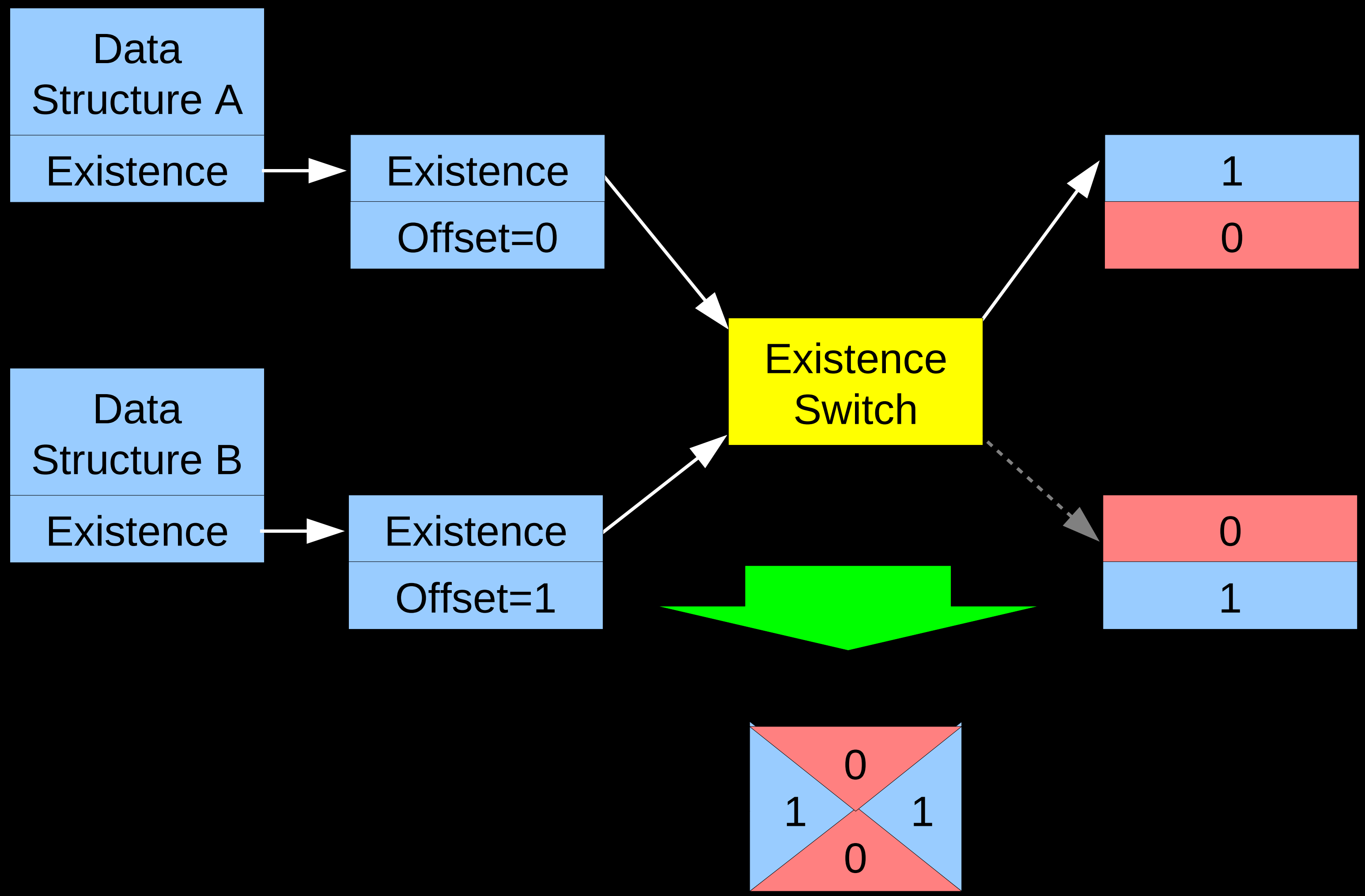
# Existence Structure Definition

```
/* Existence-switch array. */
const int existence_array[4] = { 1, 0, 0, 1 };

/* Existence structure associated with each moving structure. */
struct existence {
        const int **existence_switch;
        int offset;
};

/* Existence-group structure associated with multi-structure change. */
struct existence_group {
        struct existence outgoing;
        struct existence incoming;
        const int *existence_switch;
        struct rcu_head rh;  /* Used by RCU asynchronous free. */
};
```

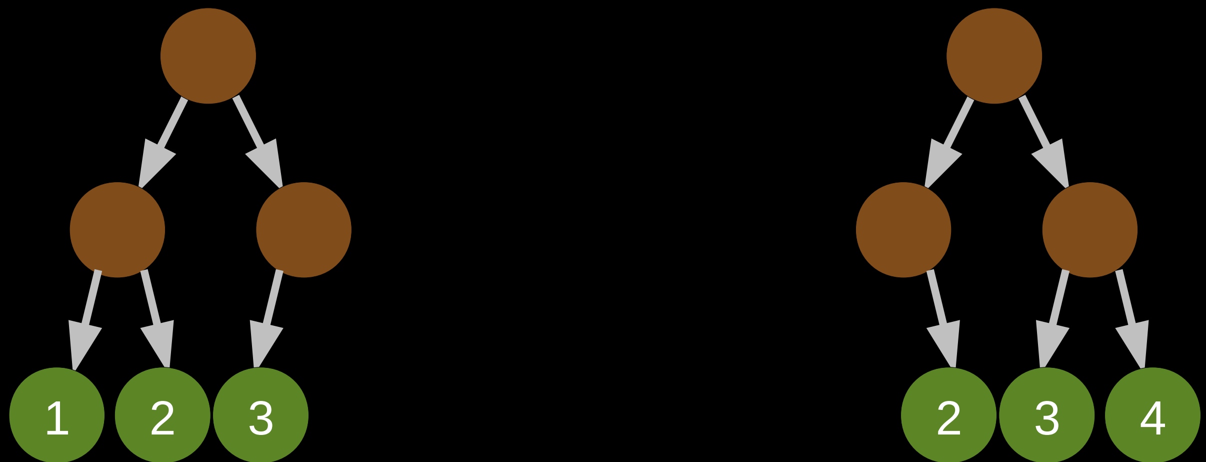
# Example Existence Structure: Abbreviation



# But Levels of Indirection Are Expensive!

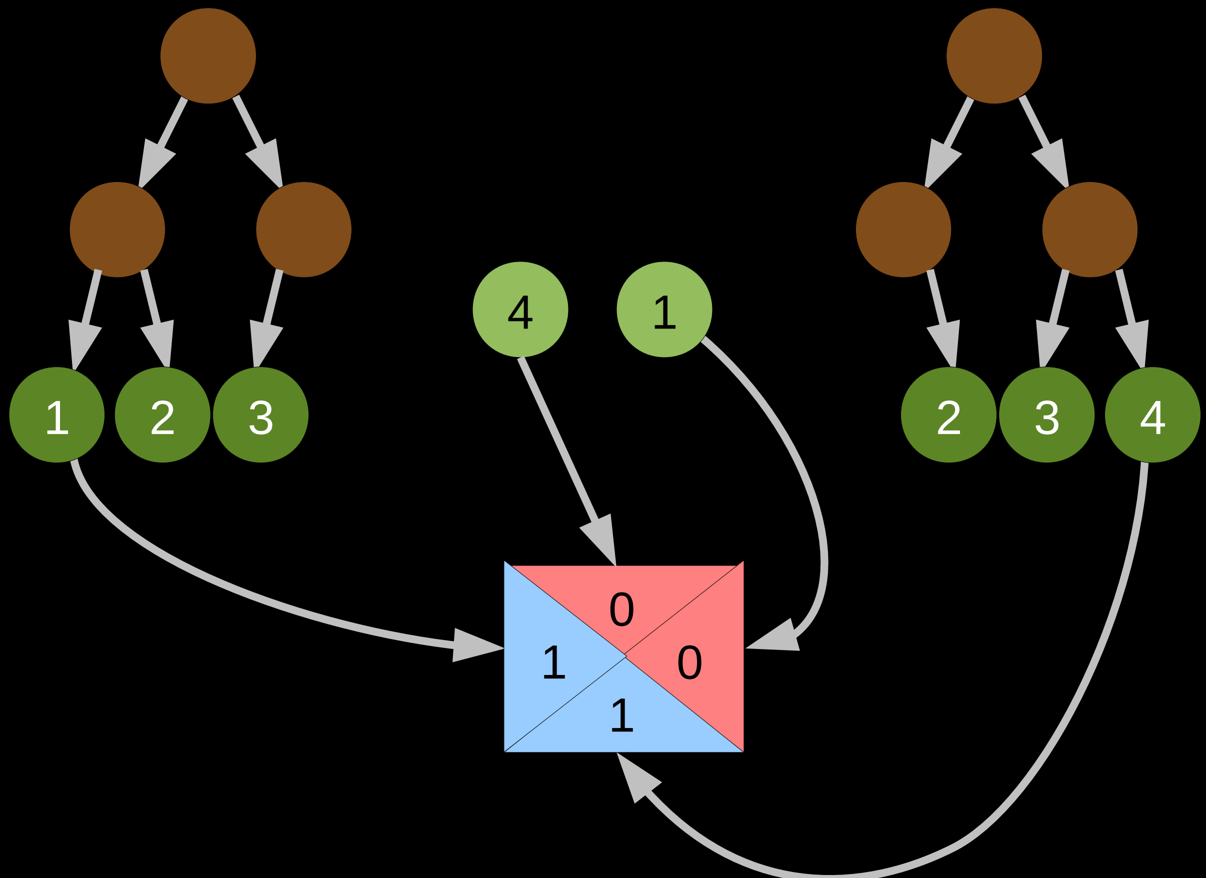
- And I didn't just add one level of indirection, I added three!
- But most of the time, elements exist and are not being moved
- So represent this common case with a NULL pointer
  - If the existence pointer is NULL, element exists: No indirection needed
  - Backwards of the usual use of a NULL pointer, but so it goes!
- In the uncommon case, traverse existence structure as shown on the preceding slides
  - Expensive, multiple cache misses, but that is OK in the uncommon case
- There is no free lunch:
  - With this optimization, loads need smp_load_acquire() rather than READ_ONCE(), ACCESS_ONCE(), or rcu_dereference()
- Can use low-order pointer bits to remove two levels of indirection
  - Kudos to Dmitry Vyukov for this trick

# Abbreviated Existence Switch Operation (1/6)



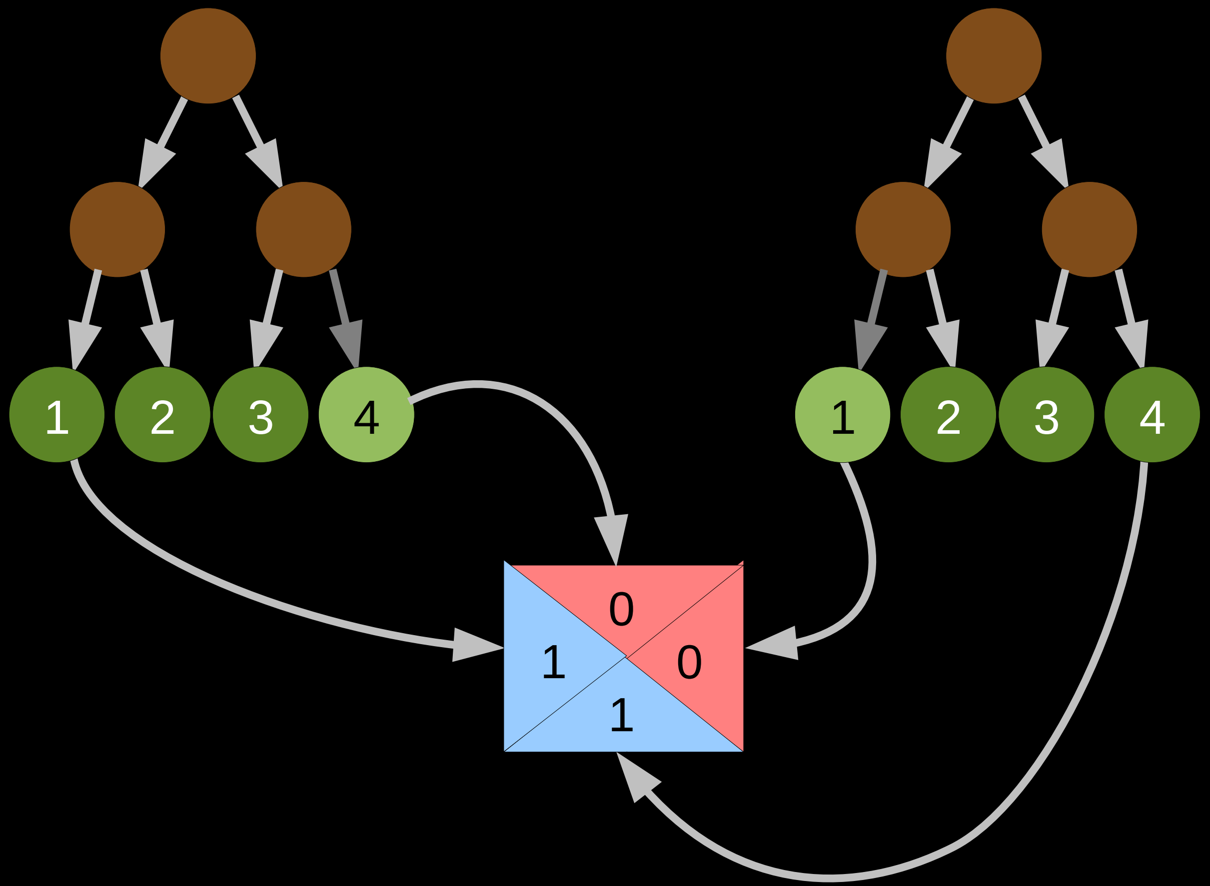

Initial state: First tree contains 1,2,3, second tree contains 2,3,4.
All existence pointers are NULL.

# Abbreviated Existence Switch Operation (2/6)



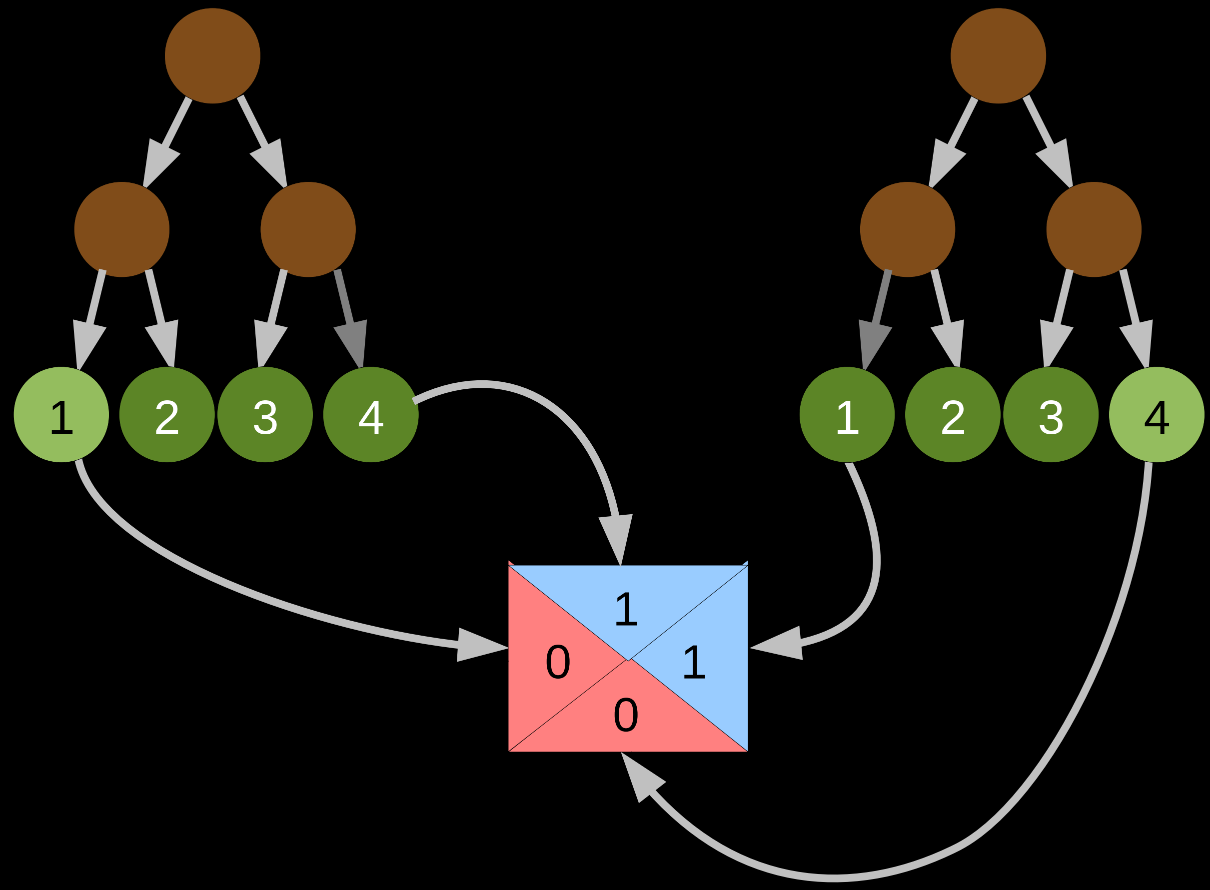

First tree contains 1,2,3, second tree contains 2,3,4.

# Abbreviated Existence Switch Operation (3/6)



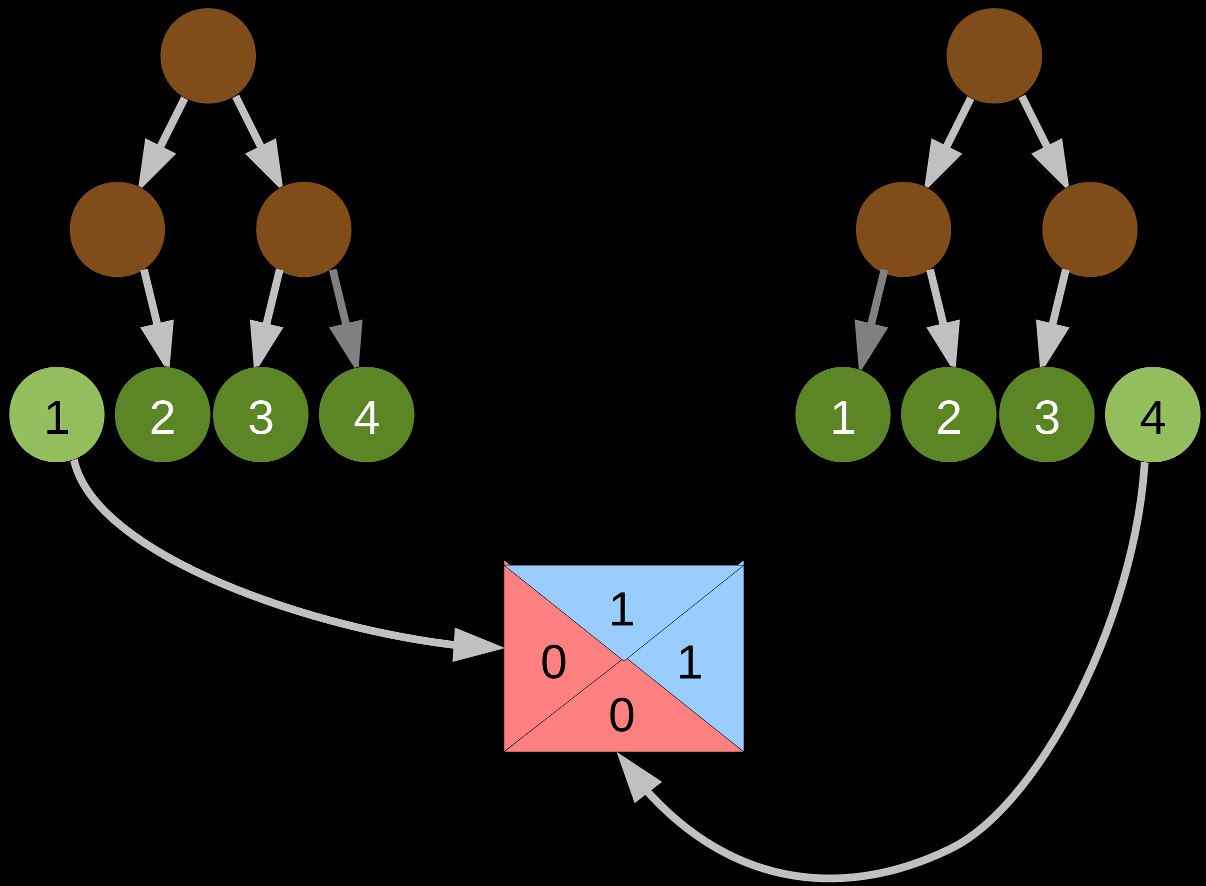

After insertion, same: First tree contains 1,2,3, second tree contains 2,3,4.

# Abbreviated Existence Switch Operation (4/6)



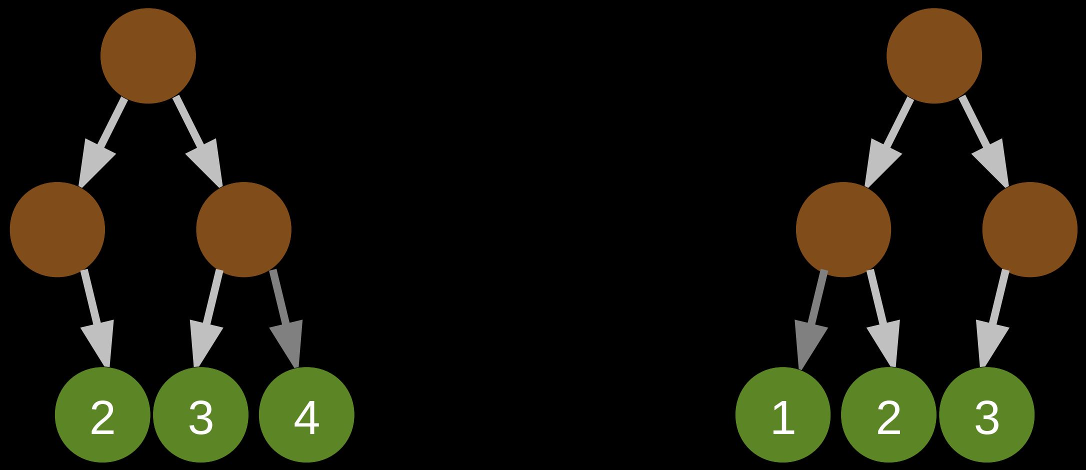

After existence switch: First tree contains 2,3,4, second tree contains 1,2,3.
Transition is single store, thus atomic! (But lookups need barriers in this case.)

# Abbreviated Existence Switch Operation (5/6)




Unlink old nodes and allegiance structure

# Abbreviated Allegiance Switch Operation (6/6)




After waiting a grace period, can free up existence structures and old nodes
And data structure preserves locality of reference!

# Existence Structures

- Existence-structure reprise:
  - Each data element has an existence pointer
  - NULL pointer says “member of current structure”
  - Non-NULL pointer references an existence structure
    - Existence of multiple data elements can be switched atomically
- But this needs a good API to have a chance of getting it right!
  - Especially given that a NULL pointer means that the element exists!!!

# Existence APIs

- `struct existence_group *existence_alloc(void);`
- `void existence_free(struct existence_group *egp);`
- `struct existence *existence_get_outgoing(struct existence_group *egp);`
- `struct existence *existence_get_incoming(struct existence_group *egp);`
- `void existence_set(struct existence **epp, struct existence *ep);`
- `void existence_clear(struct existence **epp);`
- `int existence_exists(struct existence **epp);`
- `int existence_exists_relaxed(struct existence **epp);`
- `void existence_switch(struct existence_group *egp);`

# Existence Operations for Trees

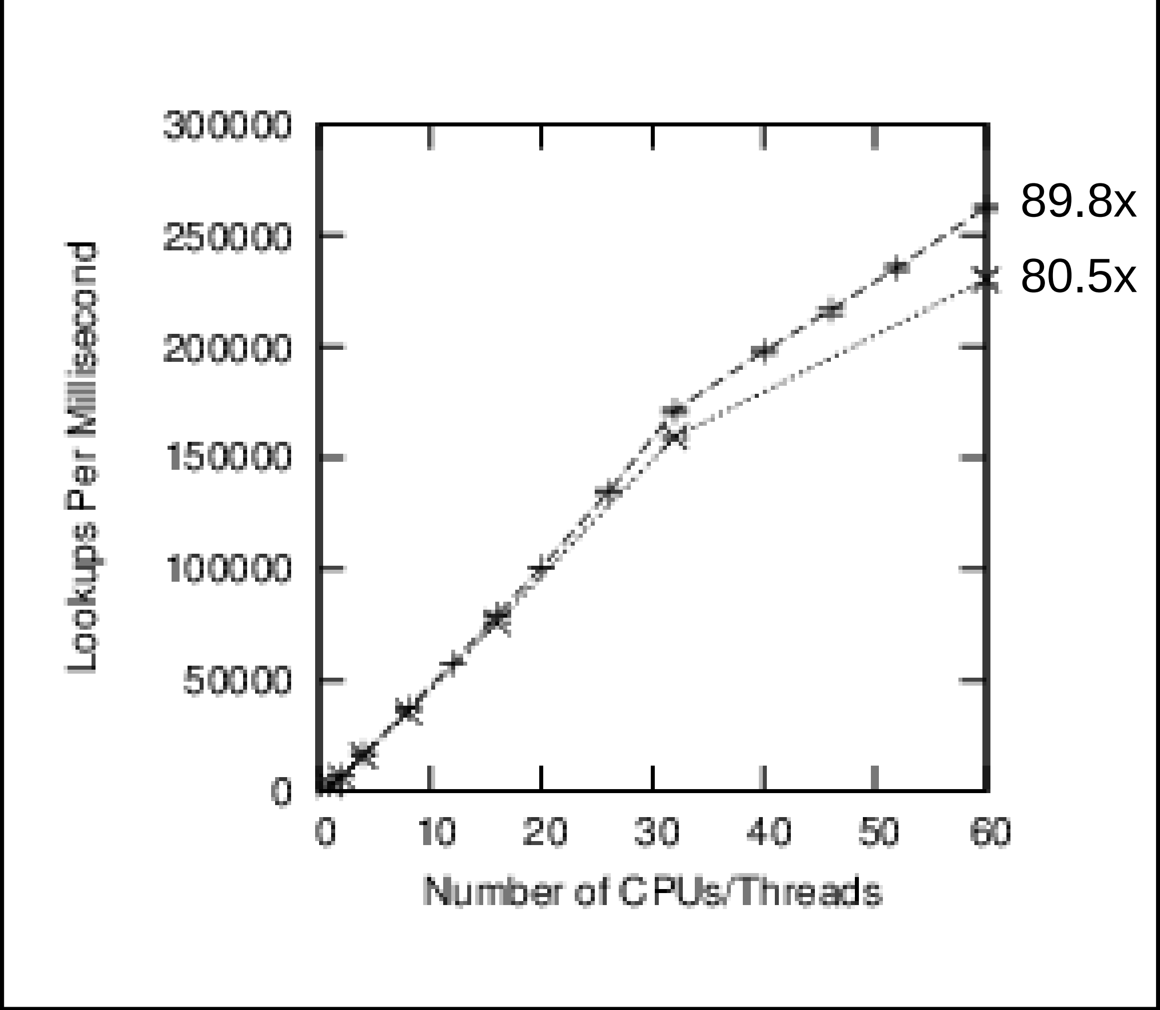
```
▪ int tree_atomic_move(struct treeroot *srcp, struct treeroot *dstp,
                       int key, void **data_in)
▪ int tree_existence_add(struct treeroot *trp, int key,
                                  struct existence *ep, void **data)
▪ int tree_existence_remove(struct treeroot *trp, int key,
                                     struct existence *ep)
▪ int tree_insert_existence(struct treeroot *trp, int key, void *data,
                              struct existence *node_existence, int wait)
▪ int tree_delete_existence(struct treeroot *trp, int key,
                                     void **data, void *matchexistence, int wait)
```

Same tree algorithm with a few existence-oriented annotations

# Pseudo-Code for Atomic Tree Move

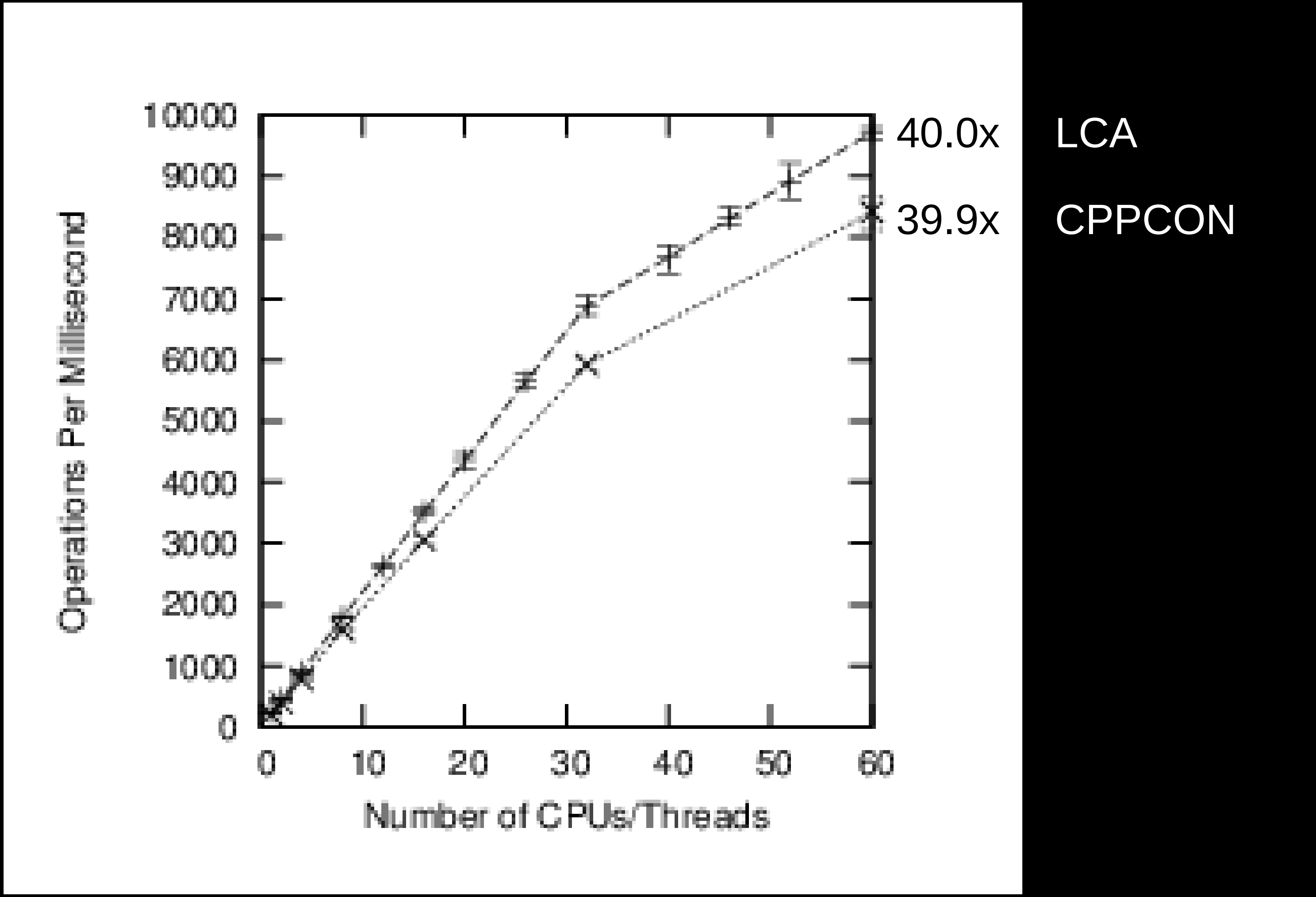
- Allocate existence_group structure (existence_alloc())
- Add outgoing existence structure to item in source tree (existence_set())
  - If operation fails, report error to caller
- Insert new element (with source item's data pointer) to destination tree with incoming existence structure (variant of tree_insert())
  - If operation fails, remove existence structure from item in source tree, free and report error to caller
- Invoke existence_switch() to flip incoming and outgoing
- Delete item from source tree (variant of tree_delete())
- Remove existence structure from item in destination tree (existence_clear())
- Free existence_group structure (existence_free())

# Existence Structures: Performance and Scalability



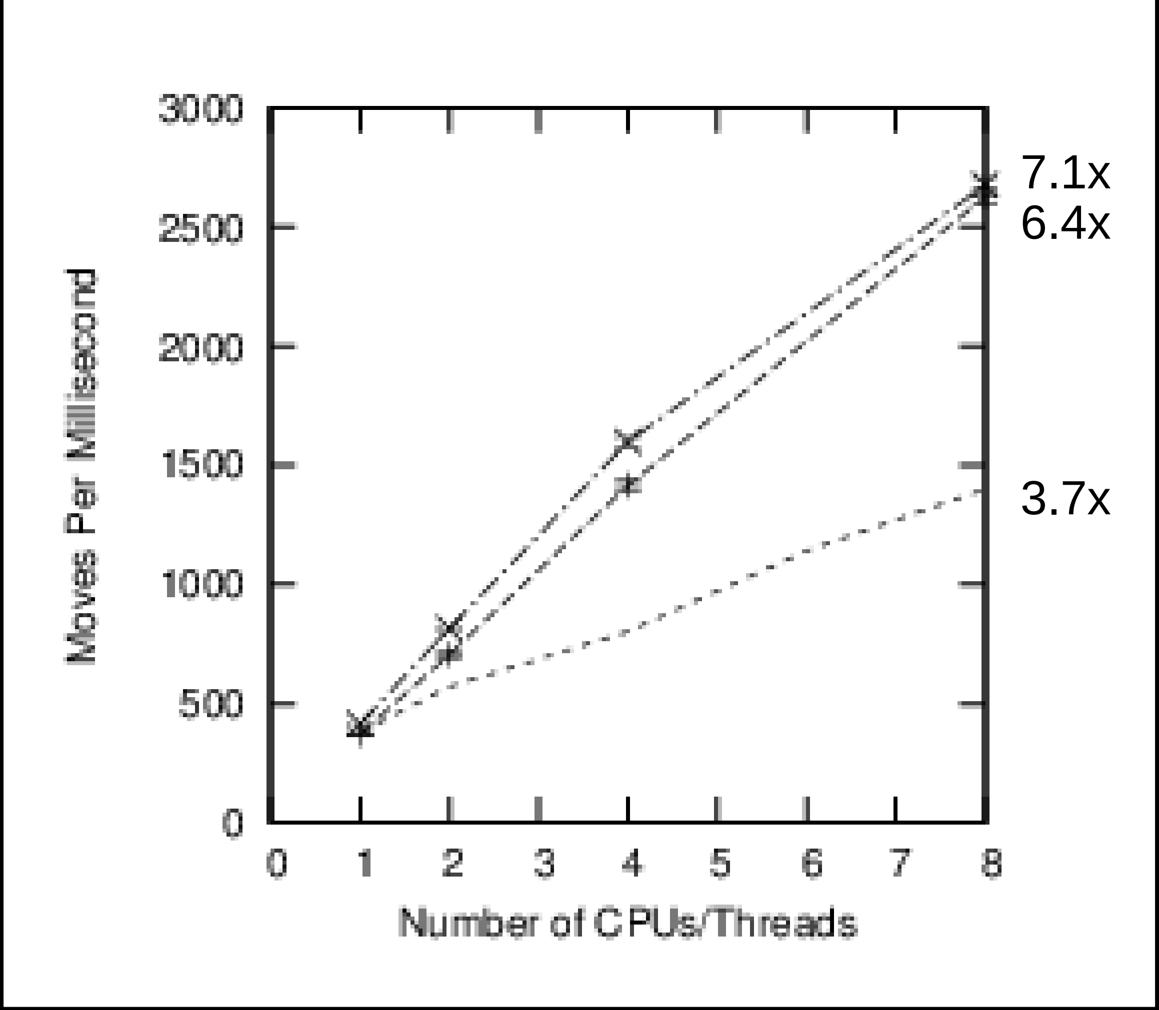

100% lookups
Super-linear as expected based on range partitioning
(Hash tables about 3x faster)

# Existence Structures: Performance and Scalability




90% lookups, 3% insertions, 3% deletions, 3% full tree scans, 1% moves
(Workload approximates Gramoli et al. CACM Jan. 2014)

# Existence Structures: Performance and Scalability



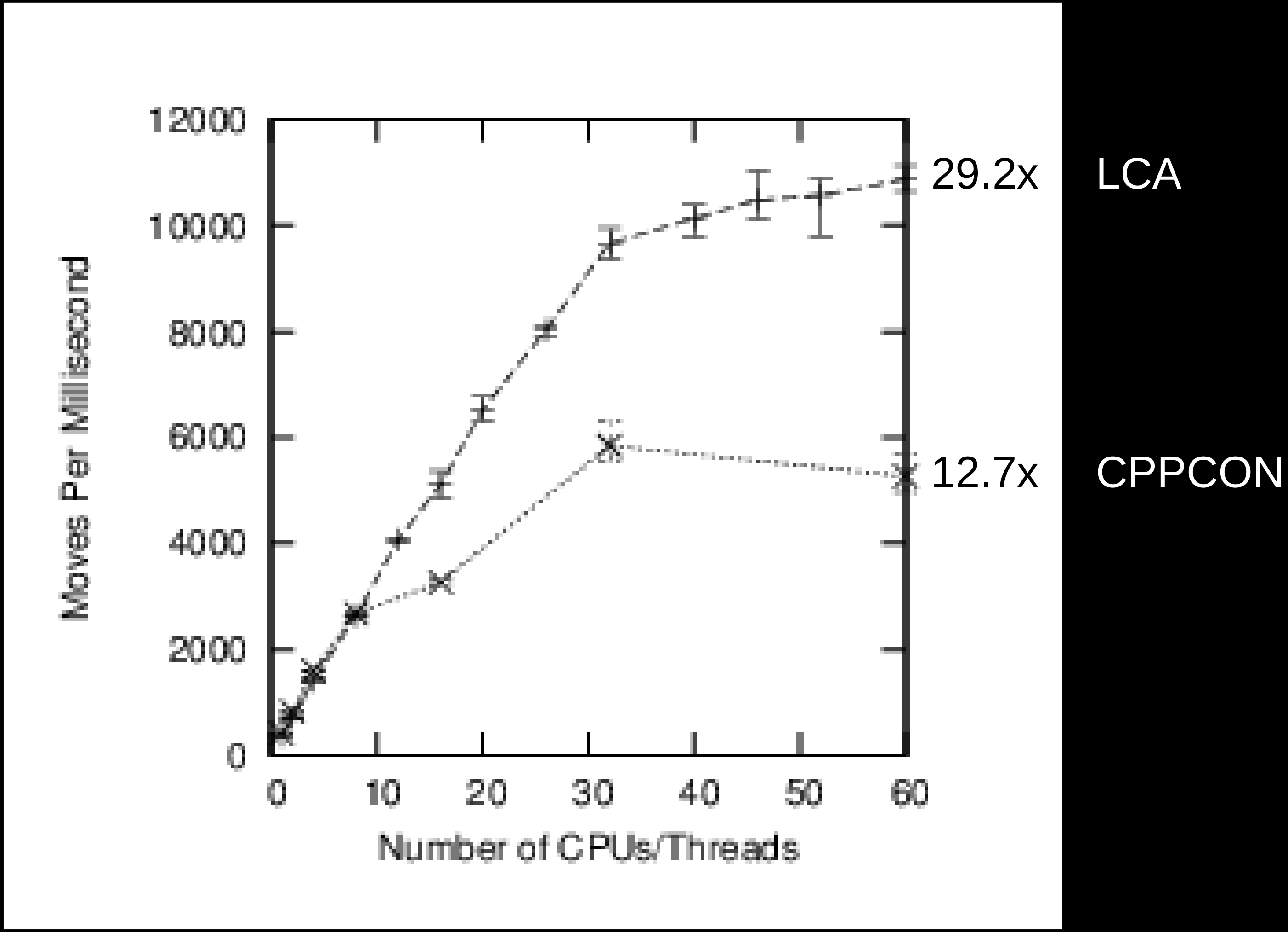

LCA

CPPCON

N4037

100% moves (worst case)

# Existence Structures: Performance and Scalability




100% moves: Still room for improvement!

Issues: allocators and user-space RCU (both fixable)

# Existence Structures: Towards Update Scalability

- “Providing perfect performance and scalability is like committing the perfect crime. There are 50 things that might go wrong, and if you are a genius, you might be able to foresee and forestall 25 of them.” – Paraphrased from Body Heat, w/apologies to Kathleen Turner fans
- Issues thus far:
  - Getting possible-upset checks right
  - Non-scalable random-number generator
  - Non-scalable memory allocator
  - Node alignment (false sharing)
  - Premature deletion of moved elements (need to remove allegiance!)
  - Unbalanced trees (false sharing)
  - User-space RCU configuration (need per-thread call_rcu() handling)
  - Getting memory barriers correct (probably more needed here)
  - Threads working concurrently on adjacent elements (false sharing)
  - Need to preload destination tree for move operations (contention!)
  - Issues from less-scalable old version of user-space RCU library
  - More memory-allocation tuning
  - Wakeup interface to user-space RCU library (instead of polling)
  - More URCU tuning
- Next steps: More detailed profiling for poorly scaling scenarios

# Existence Advantages and Disadvantages

- Existence requires focused developer effort
- Existence specialized to linked structures (for now, anyway)
- Existence requires explicit memory management
  - Might eventually be compatible with shared pointer, but not yet
- Existence-based exchange operations require linked structures that accommodate duplicate elements
  - Current prototypes disallow duplicates
- Existence permits irrevocable operations
- Existence can exploit locking hierarchies, reducing the need for contention management
- Existence achieves semi-decent performance and scalability
- Existence's use of synchronization primitives preserves locality of reference
- Existence is compatible with old hardware
- Existence is a downright mean memory-allocator and RCU test case!!!

# When Might You Use Existence-Based Update?

- We really don't know yet
- Best guess is when one or more of the following holds ***and*** you are willing to invest significant developer effort to gain performance and scalability:
  - Many small updates to large linked data structure
  - Complex updates that cannot be efficiently implemented with single pointer update
  - Need compatibility with hardware not supporting transactional memory
  - Need to be able to do irrevocable operations (e.g., I/O) as part of data-structure update

# Existence Structures: Production Readiness

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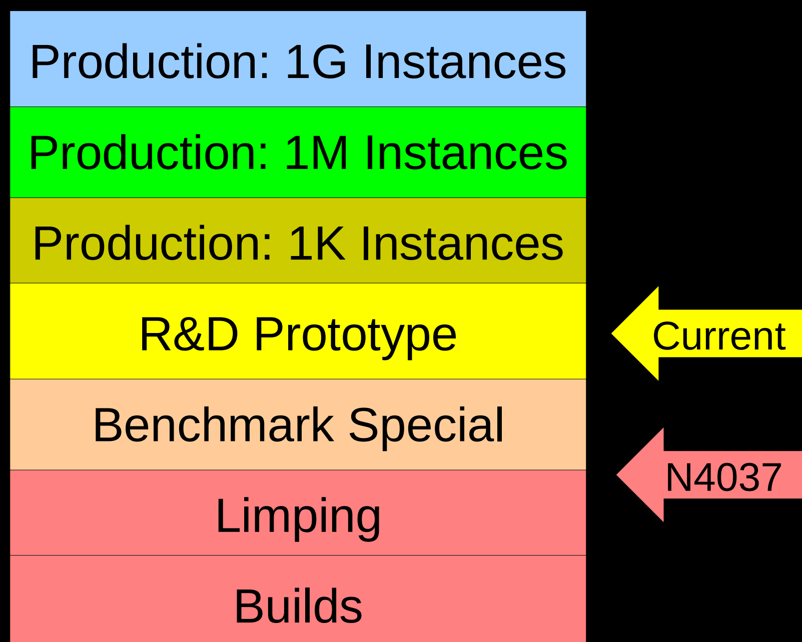
- No, it is ***not*** production ready (but getting there)
  - In happy contrast to a few months ago...



# Existence Structures: Production Readiness

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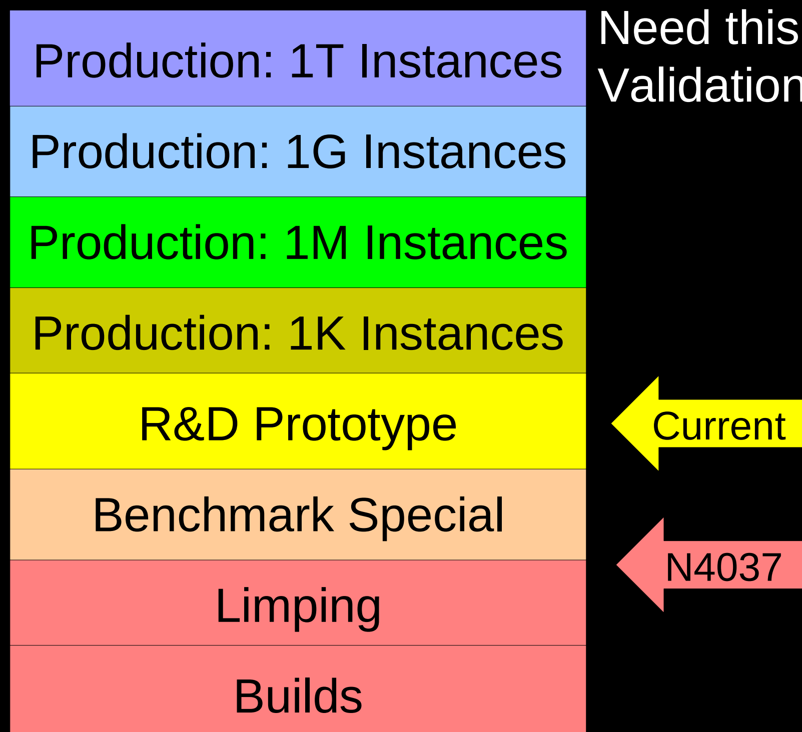
Need this for Internet of Things,
Validation is a ***big*** unsolved problem



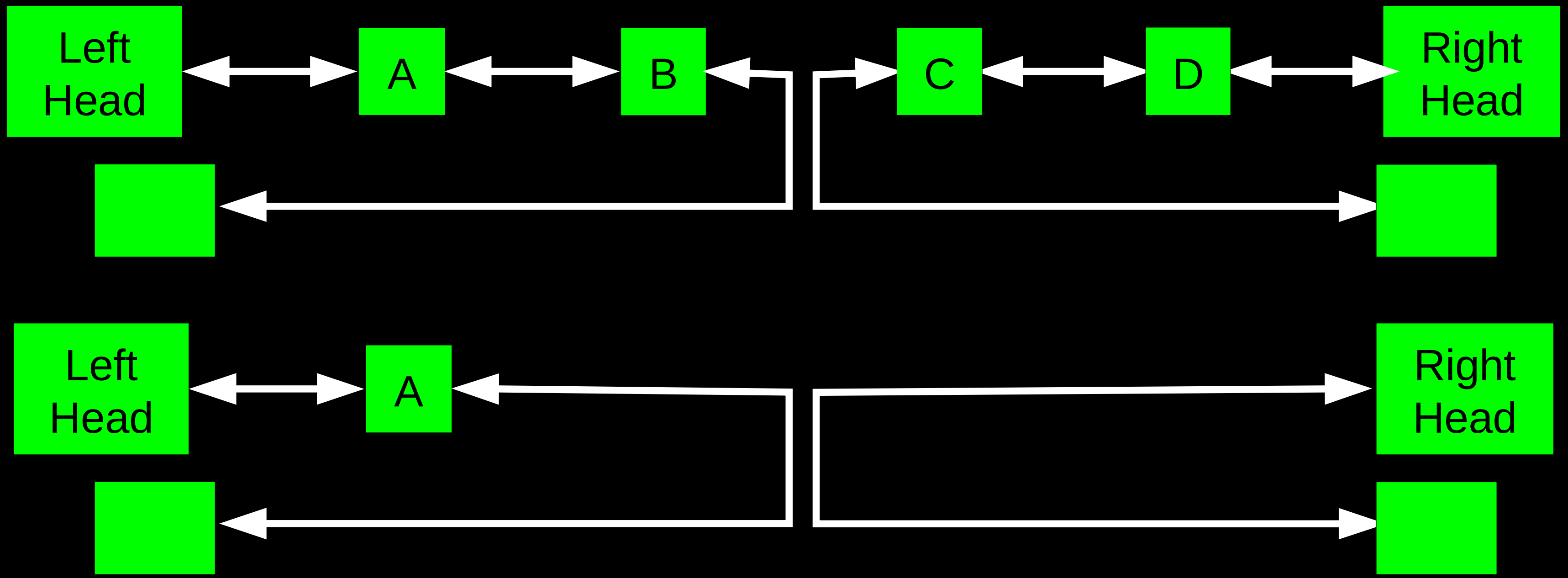
# Existence Structures: Known Antecedents

- Fraser: “Practical Lock-Freedom”, Feb 2004
  - Insistence on lock freedom: High complexity, poor performance
  - Similarity between Fraser's OSTM commit and existence switch
- McKenney, Krieger, Sarma, & Soni: “Atomically Moving List Elements Between Lists Using Read-Copy Update”, Apr 2006
  - Block concurrent operations while large update is carried out
- Triplett: “Scalable concurrent hash tables via relativistic programming”, Sept 2009
- Triplett: “Relativistic Causal Ordering: A Memory Model for Scalable Concurrent Data Structures”, Feb 2012
  - Similarity between Triplett's key switch and allegiance switch
  - Could share nodes between trees like Triplett does between hash chains, but would impose restrictions and API complexity

# Trivial Lock-Based Concurrent Deque

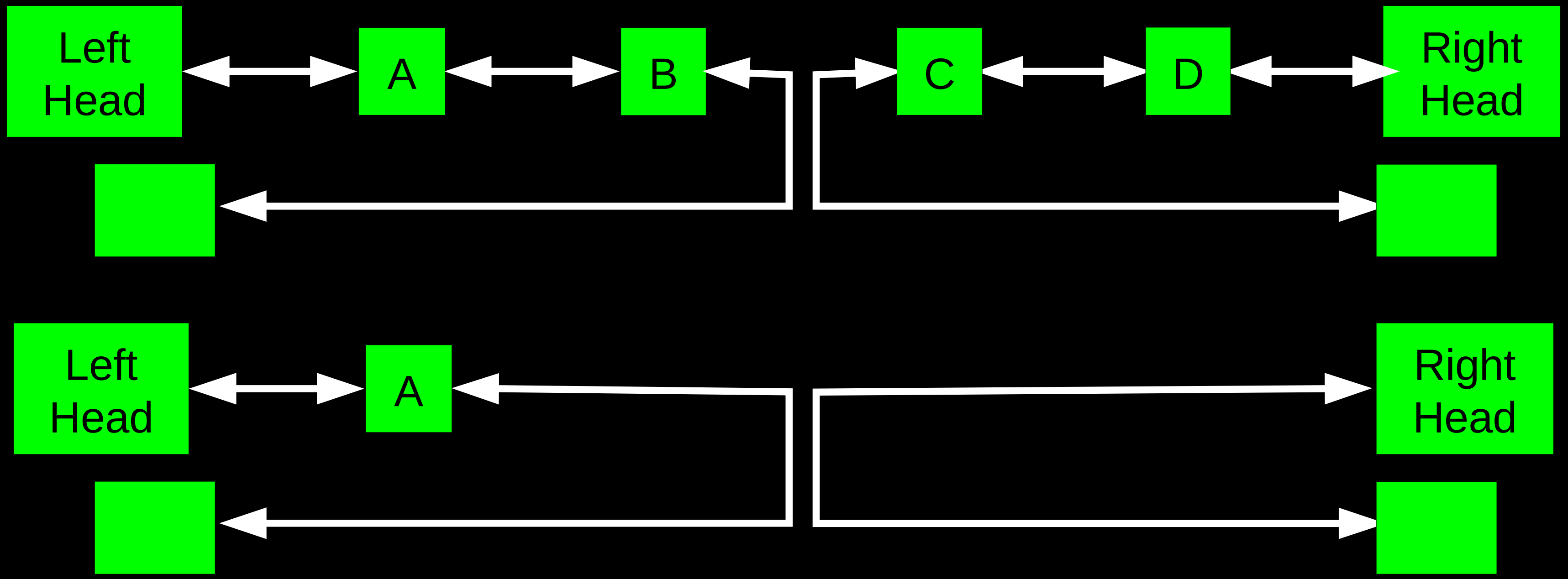
# Trivial Lock-Based Concurrent Deque

- Use two lock-based dequeues
  - Can always insert concurrently: grab dequeue's lock
  - Can always remove concurrently unless one or both are empty
    - If yours is empty, grab both locks in order!



# Trivial Lock-Based Concurrent Deque

- Use two lock-based dequeues
  - Can always insert concurrently: grab dequeue's lock
  - Can always remove concurrently unless one or both are empty
    - If yours is empty, grab both locks in order!
- But why push all your data through one deque???



# Summary

# Summary

- There is currently no silver bullet:
  - Split counters
    - Extremely specialized
  - Per-CPU/thread processing
    - Not all algorithms can be efficiently partitioned
  - Stream-based applications
    - Specialized
  - Read-only traversal to location being updated
    - Great for small updates to large data structures, but limited otherwise
  - Hardware lock elision
    - Some good potential, and some potential limitations
- Linux kernel: Good progress by combining approaches
- Lots of opportunity for collaboration and innovation

# To Probe Deeper (1/4)

- Hash tables:
  – http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Chapter 10
- Split counters:
  – http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Chapter 5
  – http://events.linuxfoundation.org/sites/events/files/slides/BareMetal.2014.03.09a.pdf
- Perfect partitioning
  – Candide et al: “Dynamo: Amazon's highly available key-value store”
    - http://doi.acm.org/10.1145/1323293.1294281
  – McKenney: “Is Parallel Programming Hard, And, If So, What Can You Do About It?”
    - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Section 6.5
  – McKenney: “Retrofitted Parallelism Considered Grossly Suboptimal”
    - Embarrassing parallelism vs. humiliating parallelism
    - https://www.usenix.org/conference/hotpar12/retro%EF%AC%81tted-parallelism-considered-grossly-sub-optimal
  – McKenney et al: “Experience With an Efficient Parallel Kernel Memory Allocator”
    - http://www.rdrop.com/users/paulmck/scalability/paper/mpalloc.pdf
  – Bonwick et al: “Magazines and Vmem: Extending the Slab Allocator to Many CPUs and Arbitrary Resources”
    - http://static.usenix.org/event/usenix01/full_papers/bonwick/bonwick_html/
  – Turner et al: “PerCPU Atomics”
    - http://www.linuxplumbersconf.org/2013/ocw//system/presentations/1695/original/LPC%20-%20PerCpu%20Atomics.pdf

# To Probe Deeper (2/4)

- Stream-based applications:
  - Sutton: “Concurrent Programming With The Disruptor”
    - http://www.youtube.com/watch?v=UvE389P6Er4
    - http://lca2013.linux.org.au/schedule/30168/view_talk
  - Thompson: “Mechanical Sympathy”
    - http://mechanical-sympathy.blogspot.com/
- Read-only traversal to update location
  - Arcangeli et al: “Using Read-Copy-Update Techniques for System V IPC in the Linux 2.5 Kernel”
    - https://www.usenix.org/legacy/events/usenix03/tech/freenix03/full_papers/arcangeli/arcangeli_html/index.html
  - Corbet: “Dcache scalability and RCU-walk”
    - https://lwn.net/Articles/419811/
  - Xu: “bridge: Add core IGMP snooping support”
    - http://kerneltrap.com/mailarchive/linux-netdev/2010/2/26/6270589
  - Triplett et al., “Resizable, Scalable, Concurrent Hash Tables via Relativistic Programming”
    - http://www.usenix.org/event/atc11/tech/final_files/Triplett.pdf
  - Howard: “A Relativistic Enhancement to Software Transactional Memory”
    - http://www.usenix.org/event/hotpar11/tech/final_files/Howard.pdf
  - McKenney et al: “URCU-Protected Hash Tables”
    - http://lwn.net/Articles/573431/

# To Probe Deeper (3/4)

- Hardware lock elision: Overviews
  - Kleen: “Scaling Existing Lock-based Applications with Lock Elision”
    - http://queue.acm.org/detail.cfm?id=2579227
- Hardware lock elision: Hardware description
  - POWER ISA Version 2.07
    - http://www.power.org/documentation/power-isa-version-2-07/
  - Intel® 64 and IA-32 Architectures Software Developer Manuals
    - http://www.intel.com/content/www/us/en/processors/architectures-software-developer-manuals.html
  - Jacobi et al: “Transactional Memory Architecture and Implementation for IBM System z”
    - http://www.microsymposia.org/micro45/talks-posters/3-jacobi-presentation.pdf
- Hardware lock elision: Evaluations
  - http://pcl.intel-research.net/publications/SC13-TSX.pdf
  - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Section 16.3
- Hardware lock elision: Need for weak atomicity
  - Herlihy et al: “Software Transactional Memory for Dynamic-Sized Data Structures”
    - http://research.sun.com/scalable/pubs/PODC03.pdf
  - Shavit et al: “Data structures in the multicore age”
    - http://doi.acm.org/10.1145/1897852.1897873
  - Haas et al: “How FIFO is your FIFO queue?”
    - http://dl.acm.org/citation.cfm?id=2414731
  - Gramoli et al: “Democratizing transactional programming”
    - http://doi.acm.org/10.1145/2541883.2541900

# To Probe Deeper (4/4)

- RCU
  - Desnoyers et al.: “User-Level Implementations of Read-Copy Update”
    - http://www.rdrop.com/users/paulmck/RCU/urcu-main-accepted.2011.08.30a.pdf
    - http://www.computer.org/cms/Computer.org/dl/trans/td/2012/02/extras/ttd2012020375s.pdf
  - McKenney et al.: “RCU Usage In the Linux Kernel: One Decade Later”
    - http://rdrop.com/users/paulmck/techreports/survey.2012.09.17a.pdf
    - http://rdrop.com/users/paulmck/techreports/RCUUsage.2013.02.24a.pdf
  - McKenney: “Structured deferral: synchronization via procrastination”
    - http://doi.acm.org/10.1145/2483852.2483867
  - McKenney et al.: “User-space RCU” https://lwn.net/Articles/573424/
- Possible future additions
  - Boyd-Wickizer: “Optimizing Communications Bottlenecks in Multiprocessor Operating Systems Kernels”
    - http://pdos.csail.mit.edu/papers/sbw-phd-thesis.pdf
  - Clements et al: “The Scalable Commutativity Rule: Designing Scalable Software for Multicore Processors”
    - http://www.read.seas.harvard.edu/~kohler/pubs/clements13scalable.pdf
  - McKenney: “N4037: Non-Transactional Implementation of Atomic Tree Move”
    - http://www.rdrop.com/users/paulmck/scalability/paper/AtomicTreeMove.2014.05.26a.pdf
  - McKenney: “C++ Memory Model Meets High-Update-Rate Data Structures”
    - http://www2.rdrop.com/users/paulmck/RCU/C++Updates.2014.09.11a.pdf

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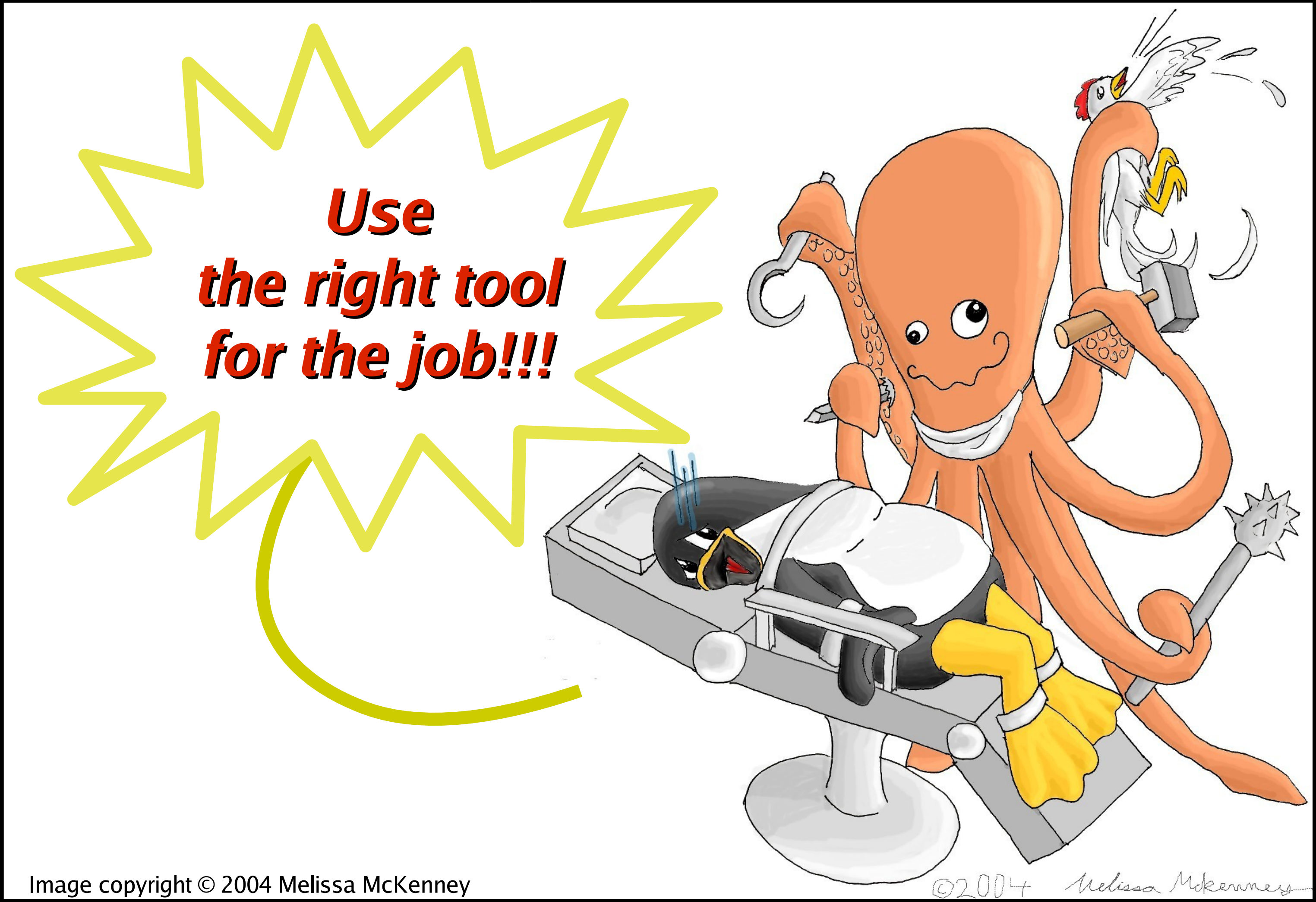
# Questions?


Use
the right tool
for the job!!!
Image copyright © 2004 Melissa McKenney

# BACKUP

# Toy Implementation of RCU: 20 Lines of Code, Full Read-Side Performance!!!

- Read-side primitives:

```
#define rcu_read_lock()
#define rcu_read_unlock()
#define rcu_dereference(p) \
({ \
        typeof(p) _p1 = (*(volatile typeof(p)*)&(p)); \
        smp_read_barrier_depends(); \
        _p1; \
})
```

- Update-side primitives

```
#define rcu_assign_pointer(p, v) \
({ \
        smp_wmb(); \
        (p) = (v); \
})
void synchronize_rcu(void)
{
        int cpu;

        for_each_online_cpu(cpu)
                run_on(cpu);
}
```

Only 9 of which are needed on sequentially consistent systems...
And some people still insist that RCU is complicated... ;-)

# RCU Usage: Readers

- Pointers to RCU-protected objects are guaranteed to exist throughout a given RCU read-side critical section

```
rcu_read_lock(); /* Start critical section. */
p = rcu_dereference(cptr); /* consume load */
/* *p guaranteed to exist. */
do_something_with(p);
rcu_read_unlock(); /* End critical section. */
/* *p might be freed!!! */
```

- The rcu_read_lock(), rcu_dereference() and rcu_read_unlock() primitives are very light weight
- However, updaters must use more care...

# RCU Usage: Updaters

- Updaters must wait for an *RCU grace period* to elapse between making something inaccessible to readers and freeing it

```
spin_lock(&updater_lock);
q = cptr; /* Can be relaxed load. */
rcu_assign_pointer(cptr, newp); /* store release */
spin_unlock(&updater_lock);
synchronize_rcu(); /* Wait for grace period. */
kfree(q);
```

- RCU grace period waits for all pre-exiting readers to complete their RCU read-side critical sections

# Hardware Lock Elision: Potential Game Changers

What must happen for HTM to take over the world?

# Hardware Lock Elision: Potential Game Changers

- Forward-progress guarantees
  - Mainframe is a start, but larger sizes would be helpful
- Transaction-size increases
- Improved debugging support
  - Gottschich et al: “But how do we really debug transactional memory?”
- Handle irrevocable operations (unbuffered I/O, syscalls, ...)
- Weak atomicity

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- Weak atomicity – but of course the Linux-kernel RCU maintainer and weak-memory advocate ***would*** say that...

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  - Shavit: “Data structures in the multicore age”
  - Haas et al: “How FIFO is your FIFO queue?”
  - Gramoli et al: “Democratizing transactional memory”
- With these additions, much greater scope possible