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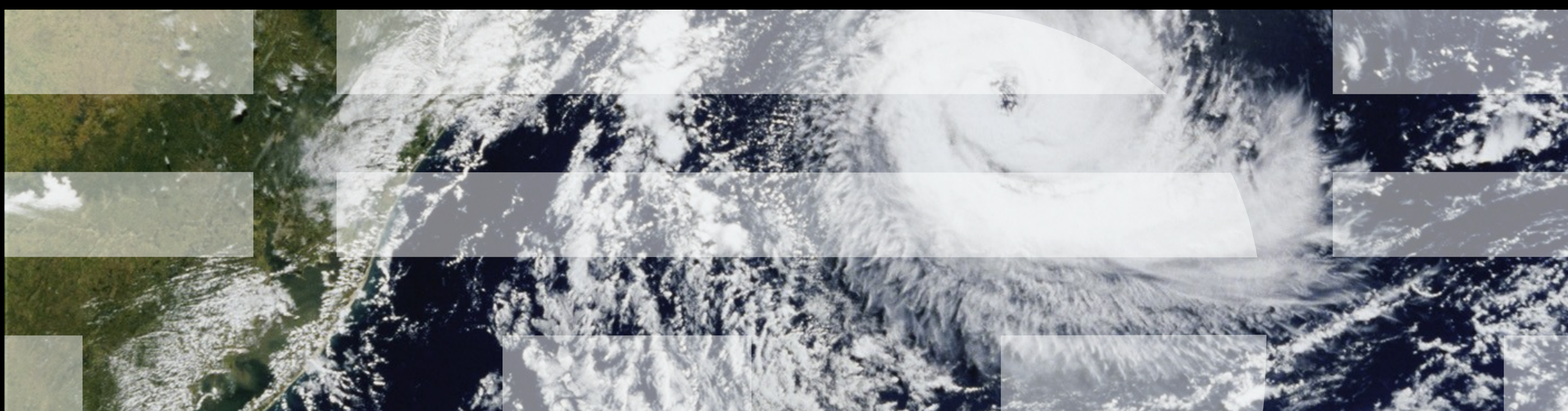
22 October 2013

Introduction to RCU Concepts

Liberal application of procrastination for accommodation of the laws of physics – for more than two decades!



Mutual Exclusion

- What mechanisms can enforce mutual exclusion?

Example Application

Example Application

- Schrödinger wants to construct an in-memory database for the animals in his zoo (example from CACM article)
  - Births result in insertions, deaths in deletions
  - Queries from those interested in Schrödinger's animals
  - Lots of short-lived animals such as mice: High update rate
  - Great interest in Schrödinger's cat (perhaps queries from mice?)

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- Schrödinger wants to construct an in-memory database for the animals in his zoo (example in upcoming ACM Queue)
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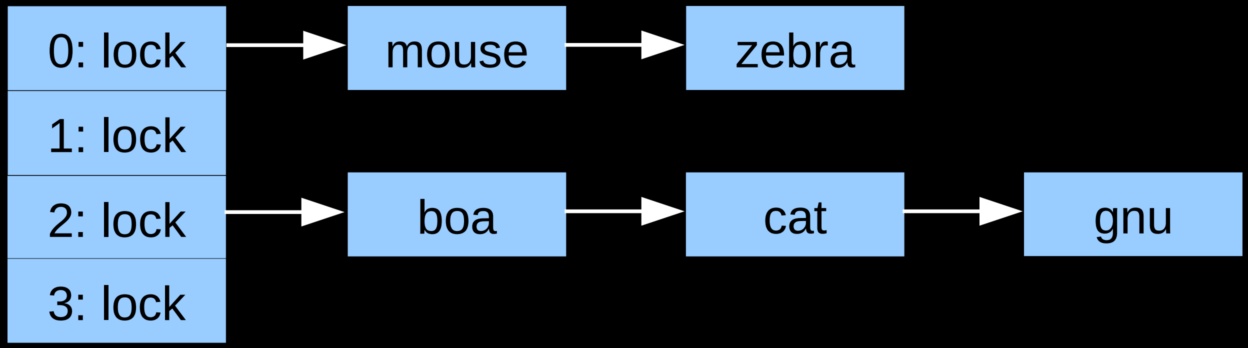
- Simple approach: chained hash table with per-bucket locking



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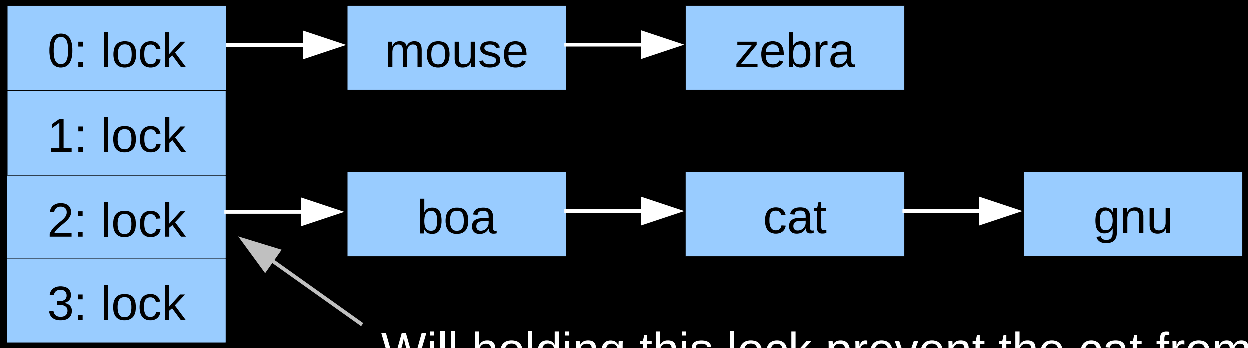
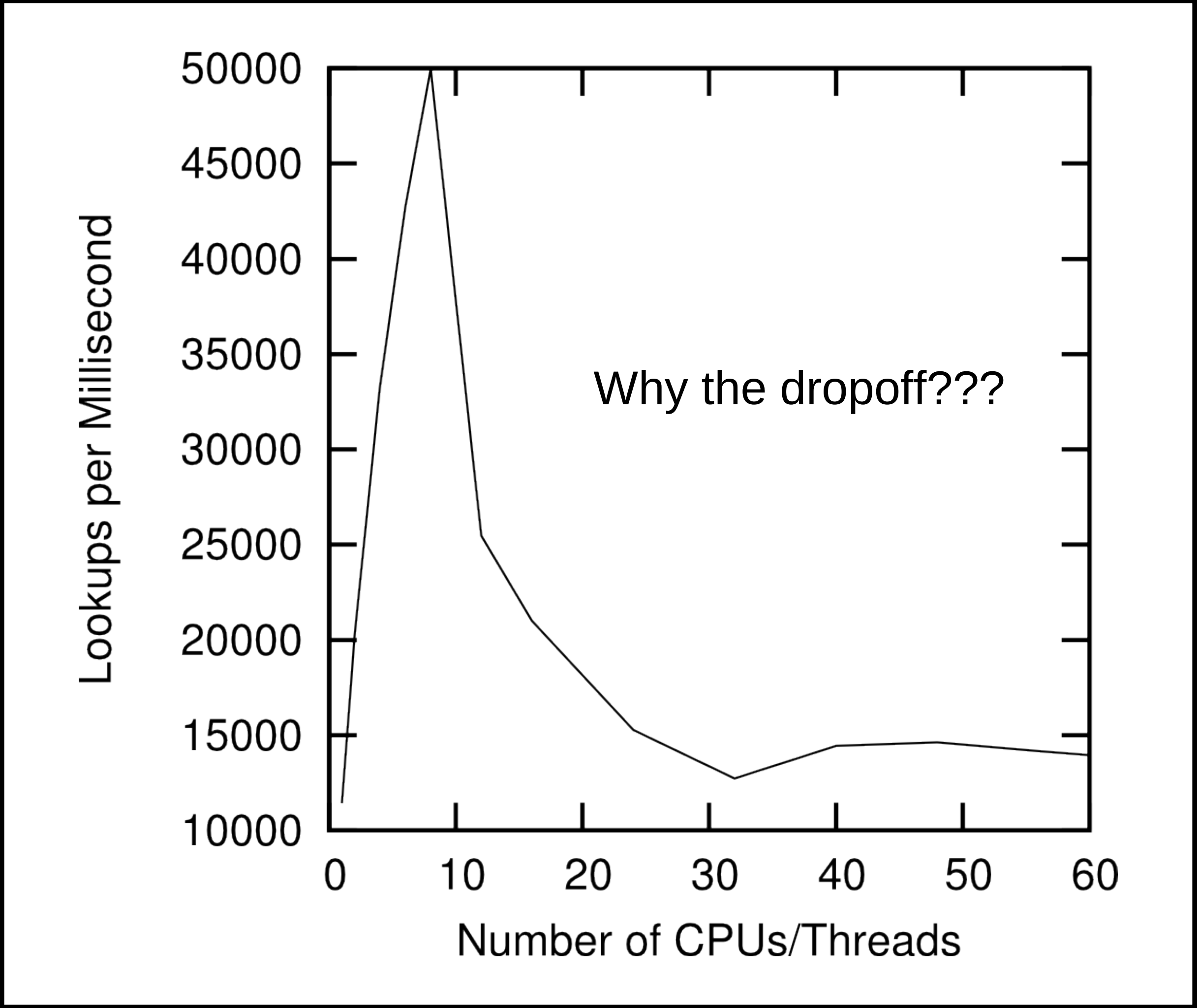


Will holding this lock prevent the cat from dying?

Read-Only Bucket-Locked Hash Table Performance

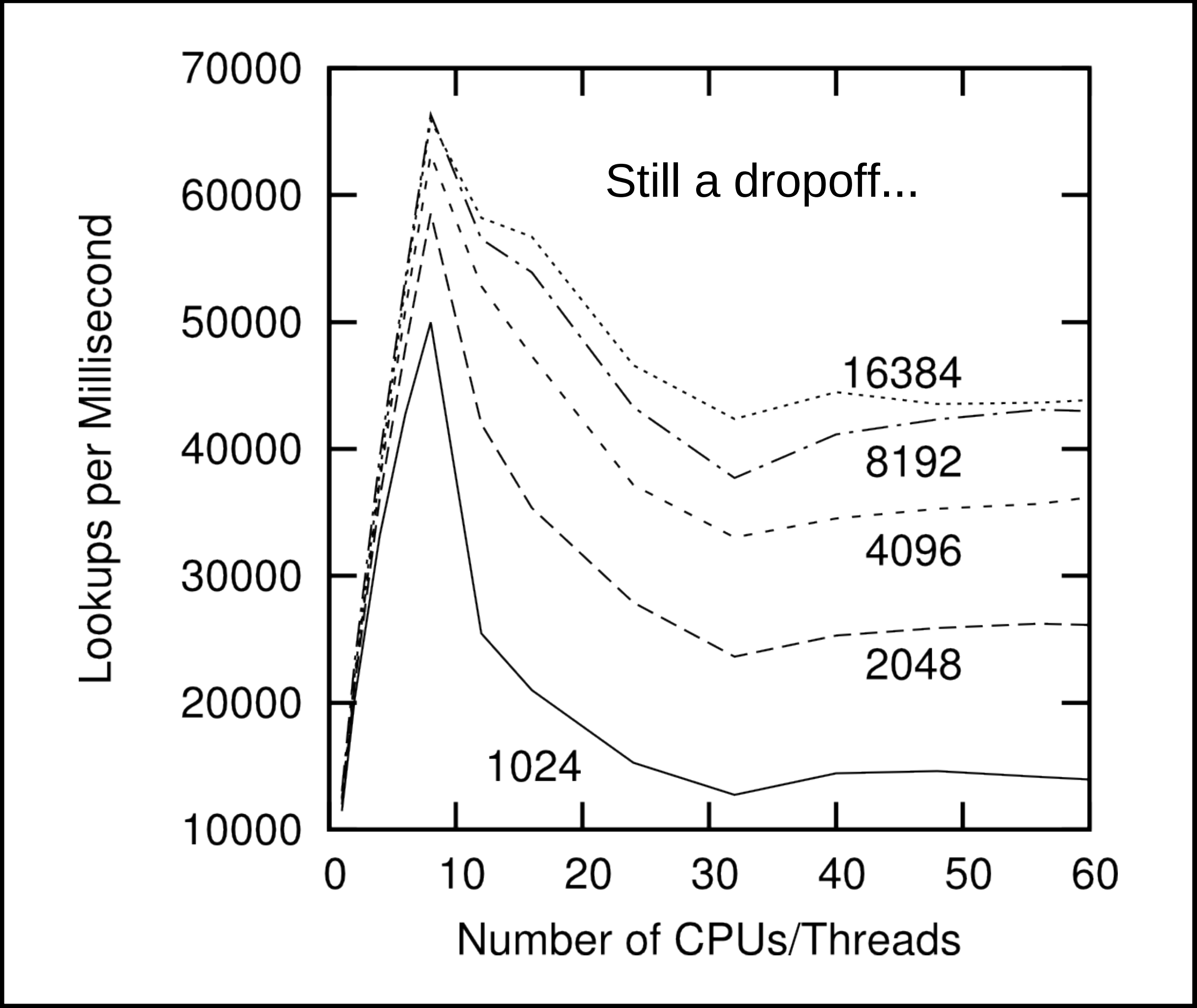
2GHz Intel Xeon Westmere-EX (64 CPUs)
1024 hash buckets

Read-Only Bucket-Locked Hash Table Performance



2GHz Intel Xeon Westmere-EX, 1024 hash buckets

Varying Number of Hash Buckets

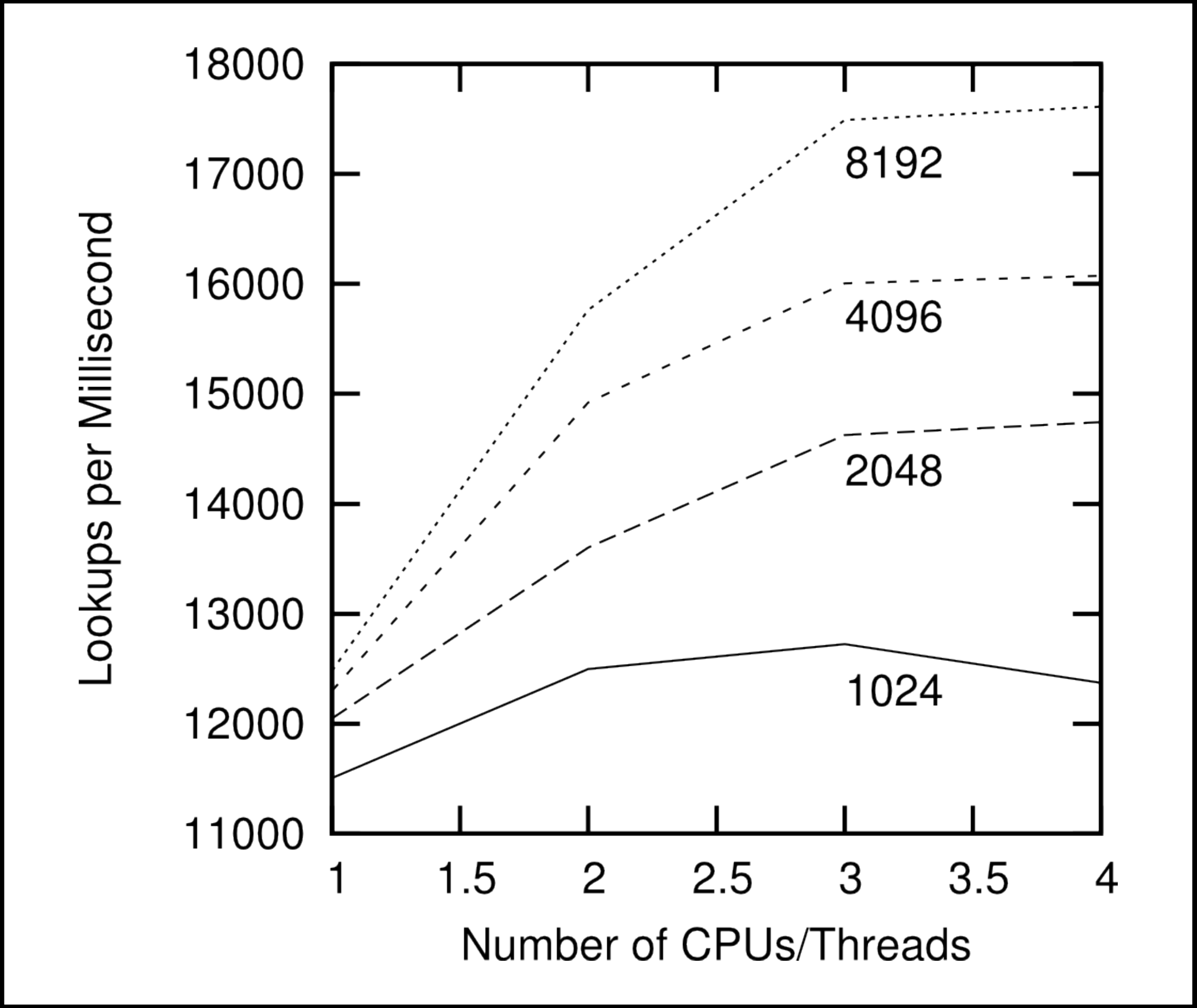


2GHz Intel Xeon Westmere-EX

NUMA Effects???

- /sys/devices/system/cpu/cpu0/cache/index0/shared_cpu_list:
  - 0,32
- /sys/devices/system/cpu/cpu0/cache/index1/shared_cpu_list:
  - 0,32
- /sys/devices/system/cpu/cpu0/cache/index2/shared_cpu_list:
  - 0,32
- /sys/devices/system/cpu/cpu0/cache/index3/shared_cpu_list:
  - 0-7,32-39
- Two hardware threads per core, eight cores per socket
- Try using only one CPU per socket: CPUs 0, 8, 16, and 24

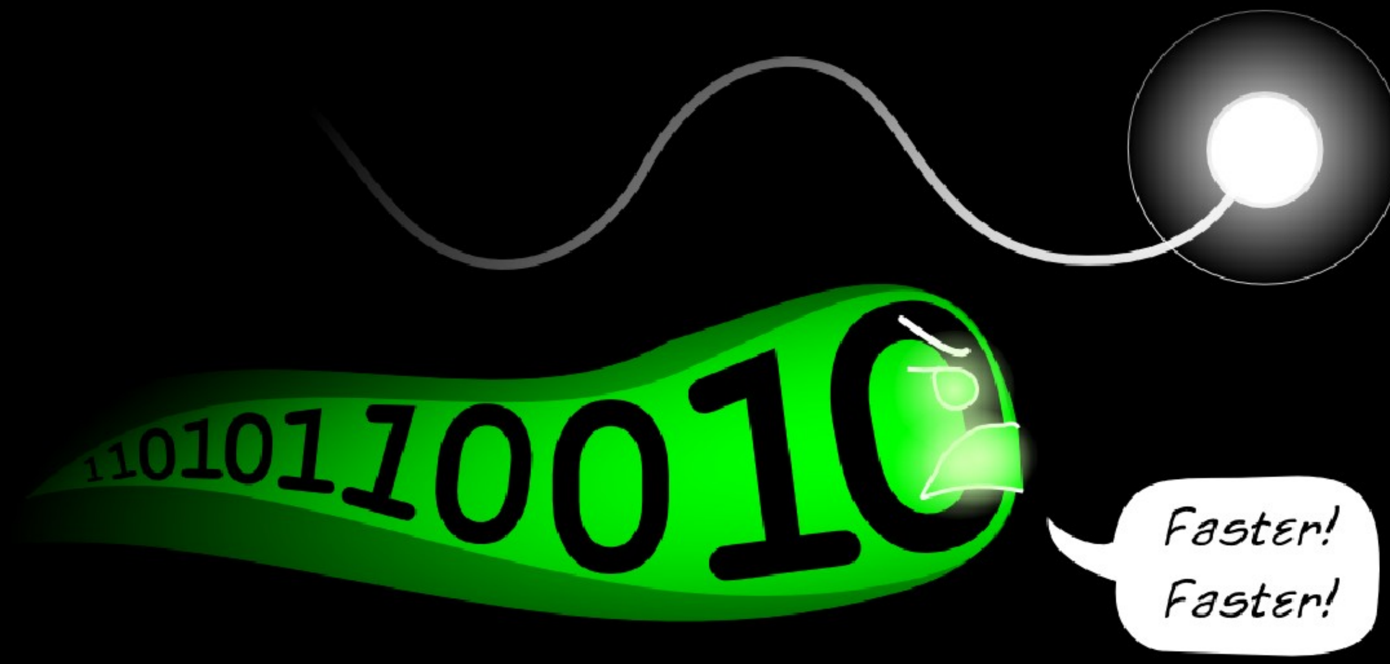
Bucket-Locked Hash Performance: 1 CPU/Socket



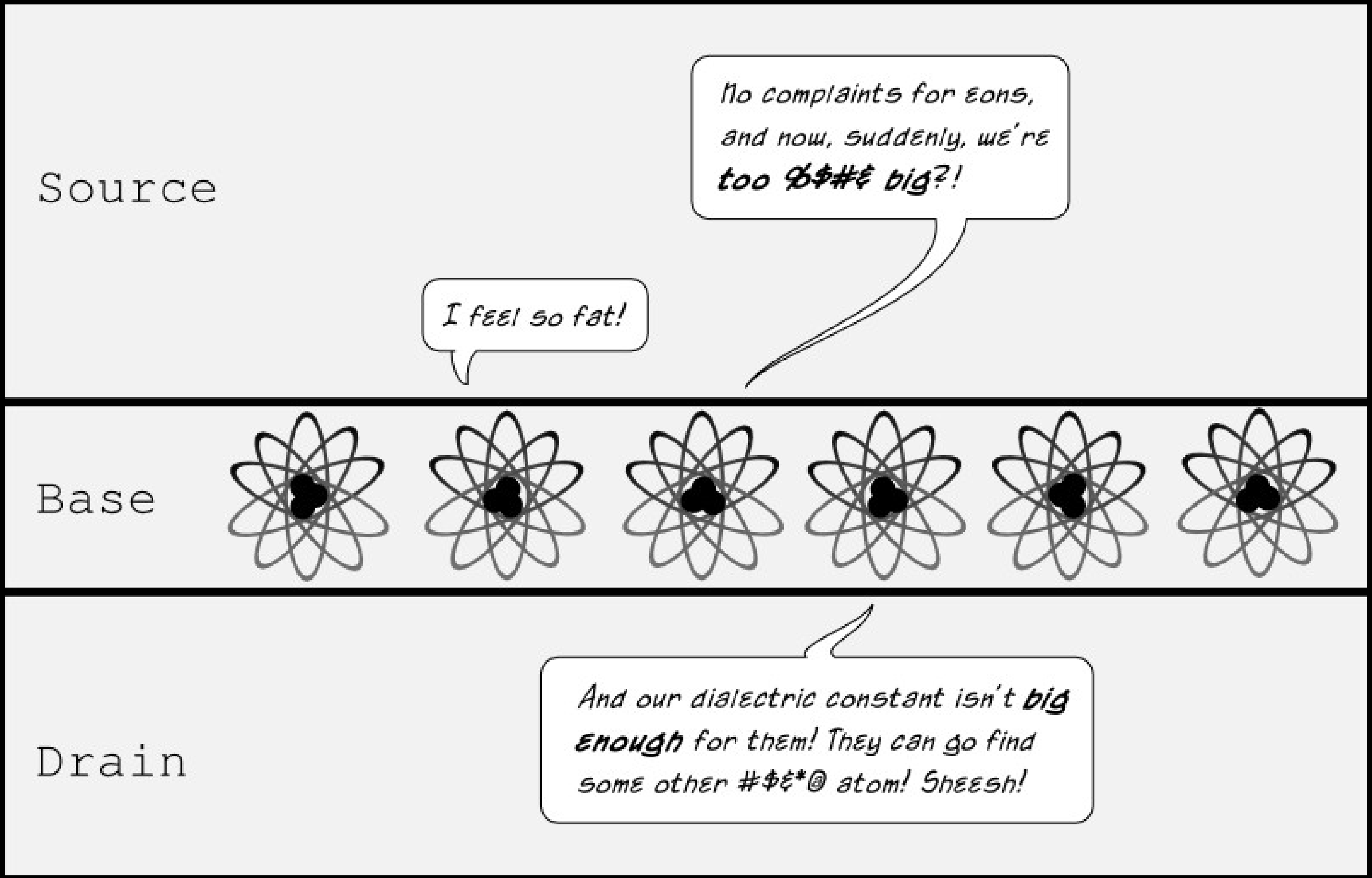
2GHz Intel Xeon Westmere-EX: This is not the sort of scalability Schrödinger requires!!!

Performance of Synchronization Mechanisms

Problem With Physics #1: Finite Speed of Light

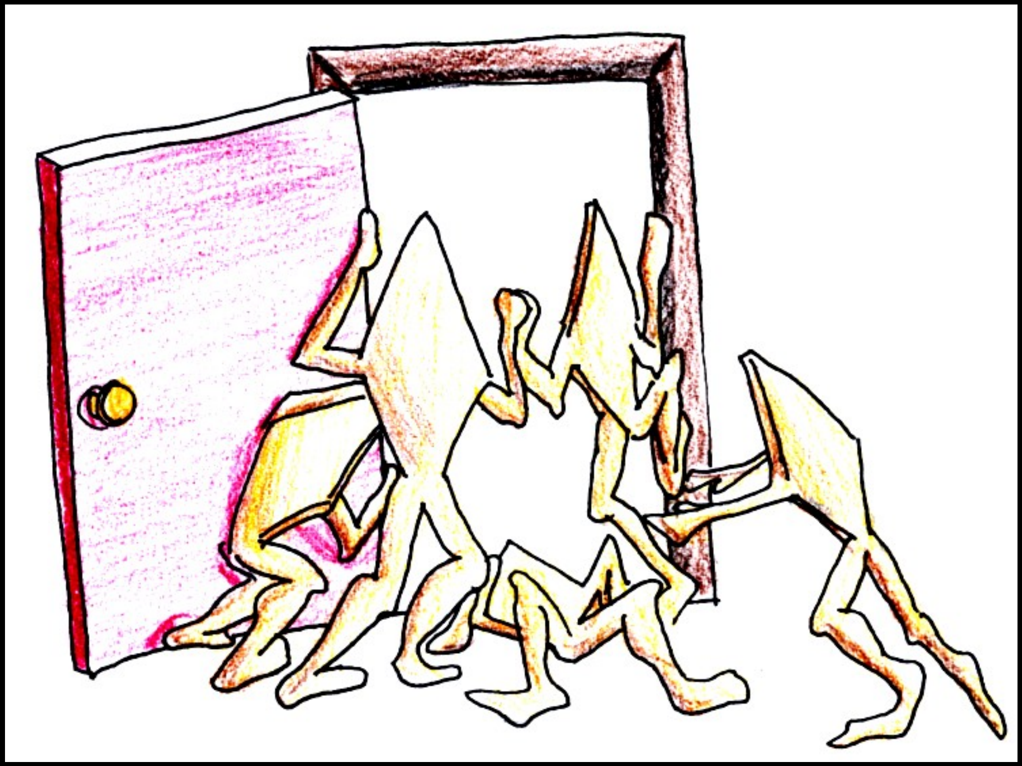


Problem With Physics #2: Atomic Nature of Matter



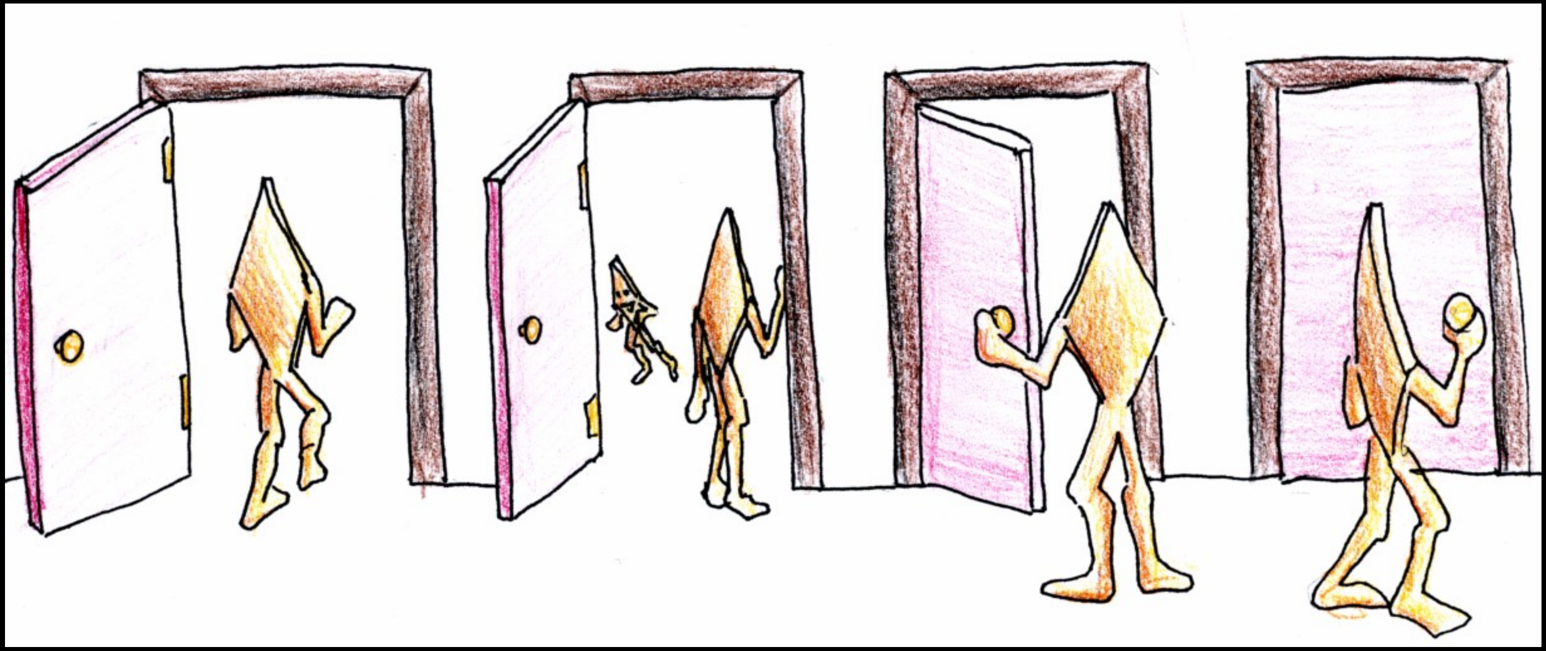
How Can Software Live With This Hardware???

Design Principle: Avoid Bottlenecks



Only one of something: bad for performance and scalability.
Also typically results in high complexity.

Design Principle: Avoid Bottlenecks



Many instances of something good! Full partitioning even better!!!
Avoiding tightly coupled interactions is an excellent way to avoid bugs.
But NUMA effects defeated this for per-bucket locking!!!

Design Principle: Get Your Money's Worth

- If synchronization is expensive, use large critical sections
- On Nehalem, off-socket atomic operation costs ~260 cycles
  - So instead of a single-cycle critical section, have a 26000-cycle critical section, reducing synchronization overhead to about 1%
- Of course, we also need to keep contention low, which usually means we want short critical sections
  - Resolve this by applying parallelism at as high a level as possible
  - Parallelize entire applications rather than low-level algorithms!

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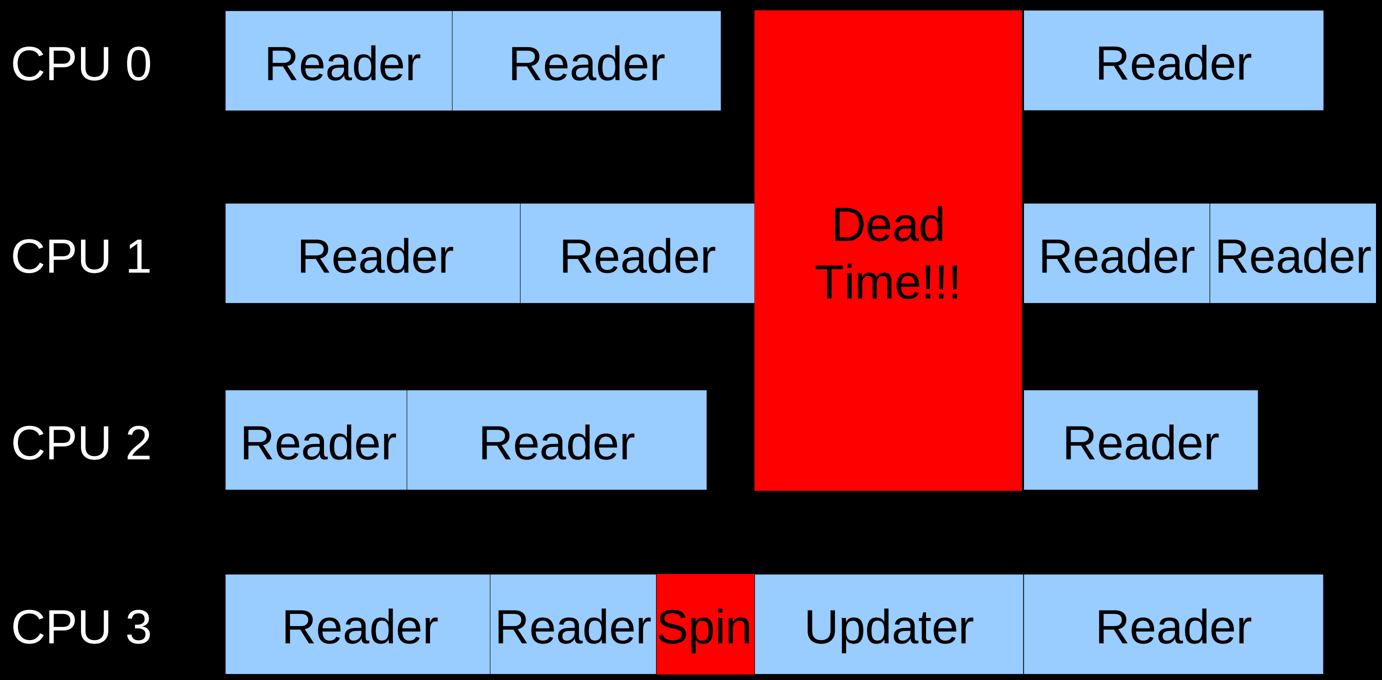
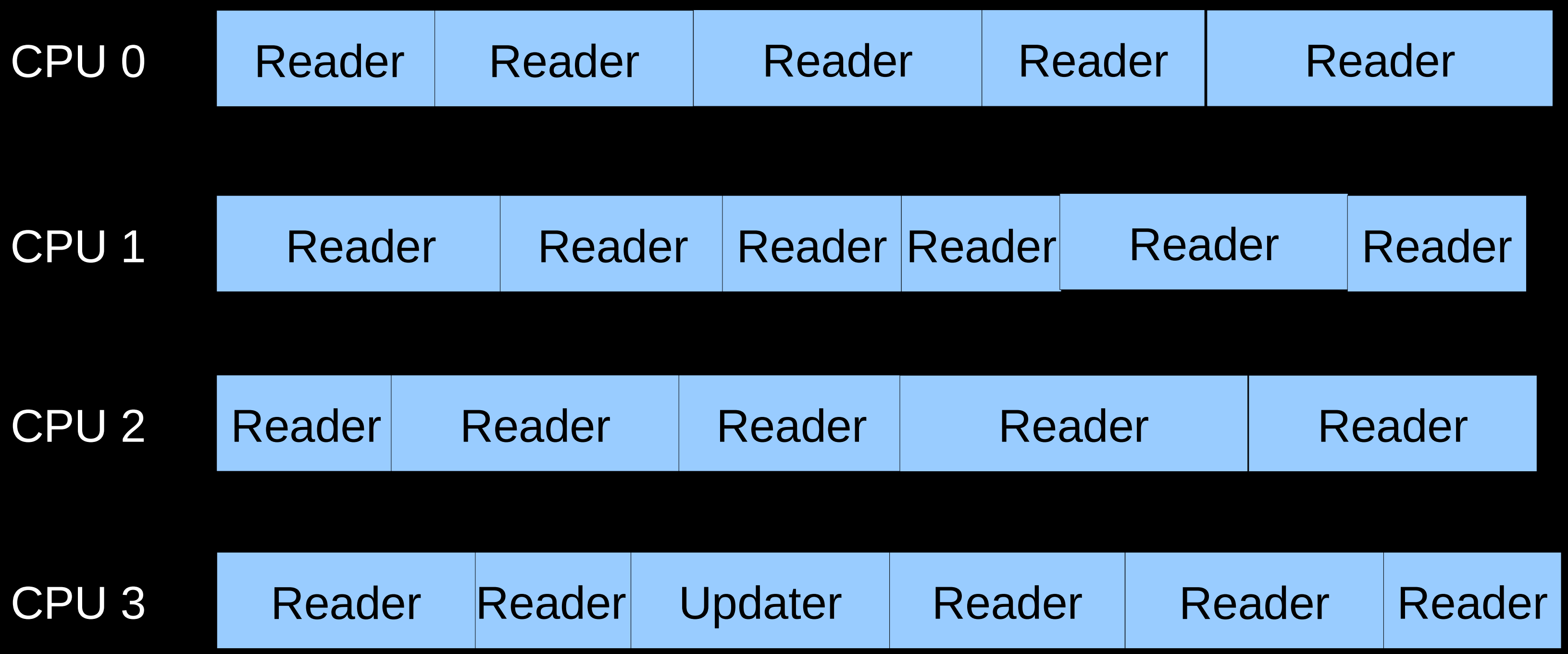
  - Resolve this by applying parallelism at as high a level as possible
  - Parallelize entire applications rather than low-level algorithms!
  - But the low overhead hash-table insertion/deletion operations do not provide much scope for long critical sections...

Design Principle: Avoid Mutual Exclusion!!!



Plus lots of time waiting for the lock's cache line...

Design Principle: Avoiding Mutual Exclusion



No Dead Time!

But How Can This Possibly Be Implemented???

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But How Can This Possibly Be Implemented???

Hazard Pointers and RCU!!!

RCU: Keep It Basic: Guarantee Only Existence

- Pointer to RCU-protected object guaranteed to exist throughout RCU read-side critical section

```
rcu_read_lock(); /* Start critical section. */
p = rcu_dereference(cptr);
/* *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 take care...

RCU: How Updaters Guarantee Existence

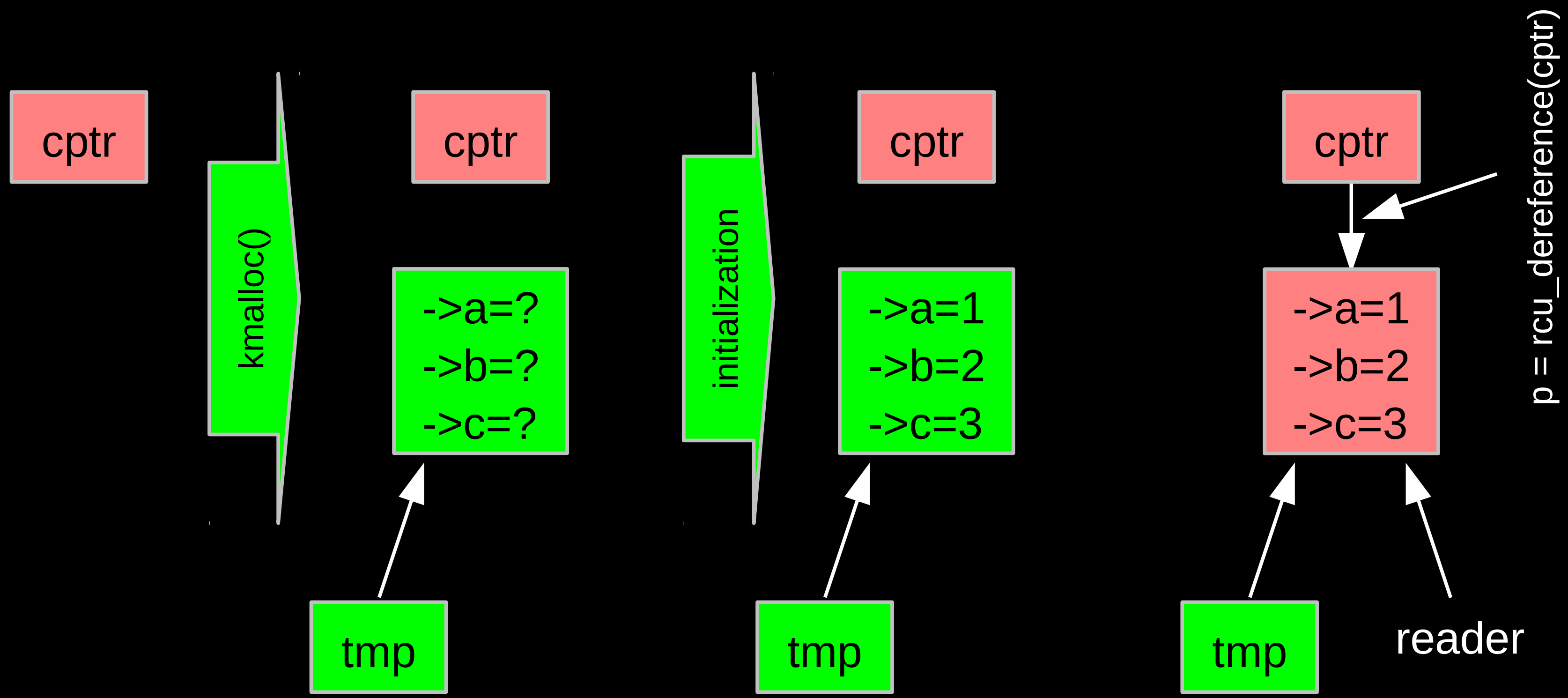
- Updaters must wait for an *RCU grace period* to elapse between making something inaccessible to readers and freeing it

```
spin_lock(&updater_lock);
q = cptr;
rcu_assign_pointer(cptr, new_p);
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
- Next slides give diagram representation

Publication of And Subscription to New Data

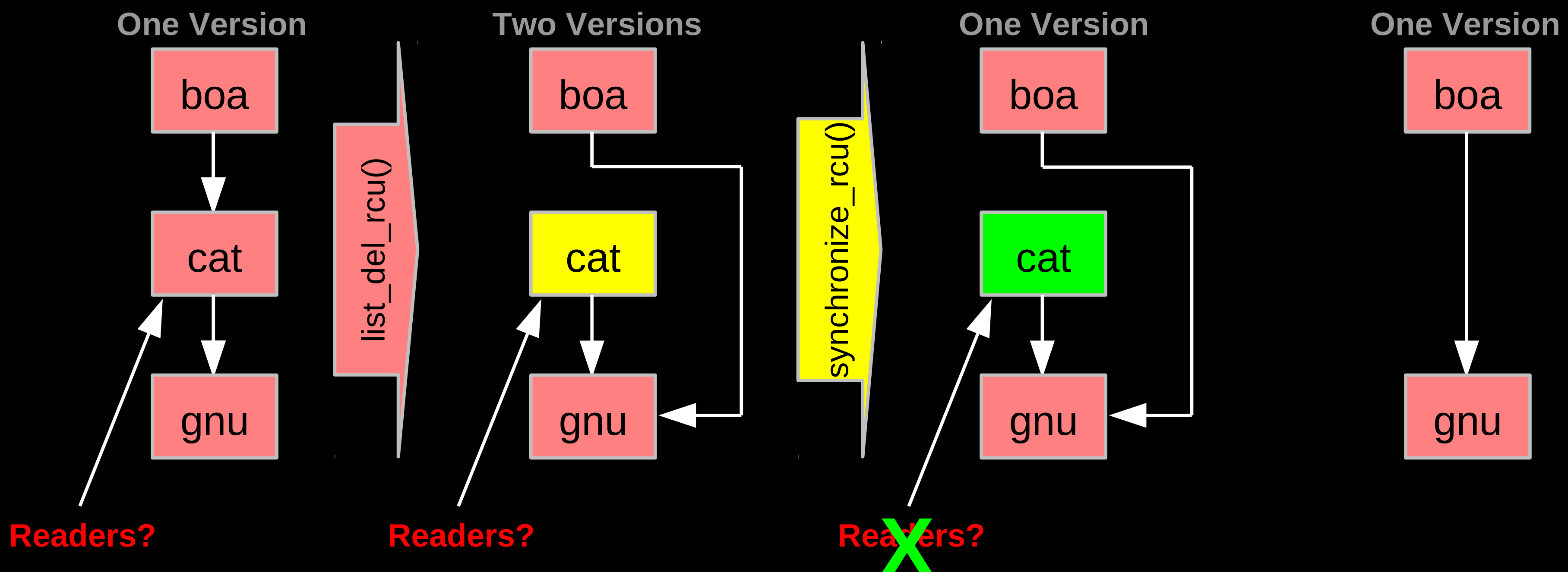
Key:
- Dangerous for updates: all readers can access
- Still dangerous for updates: pre-existing readers can access (next slide)
- Safe for updates: inaccessible to all readers



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

RCU Removal From Linked List

- 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())



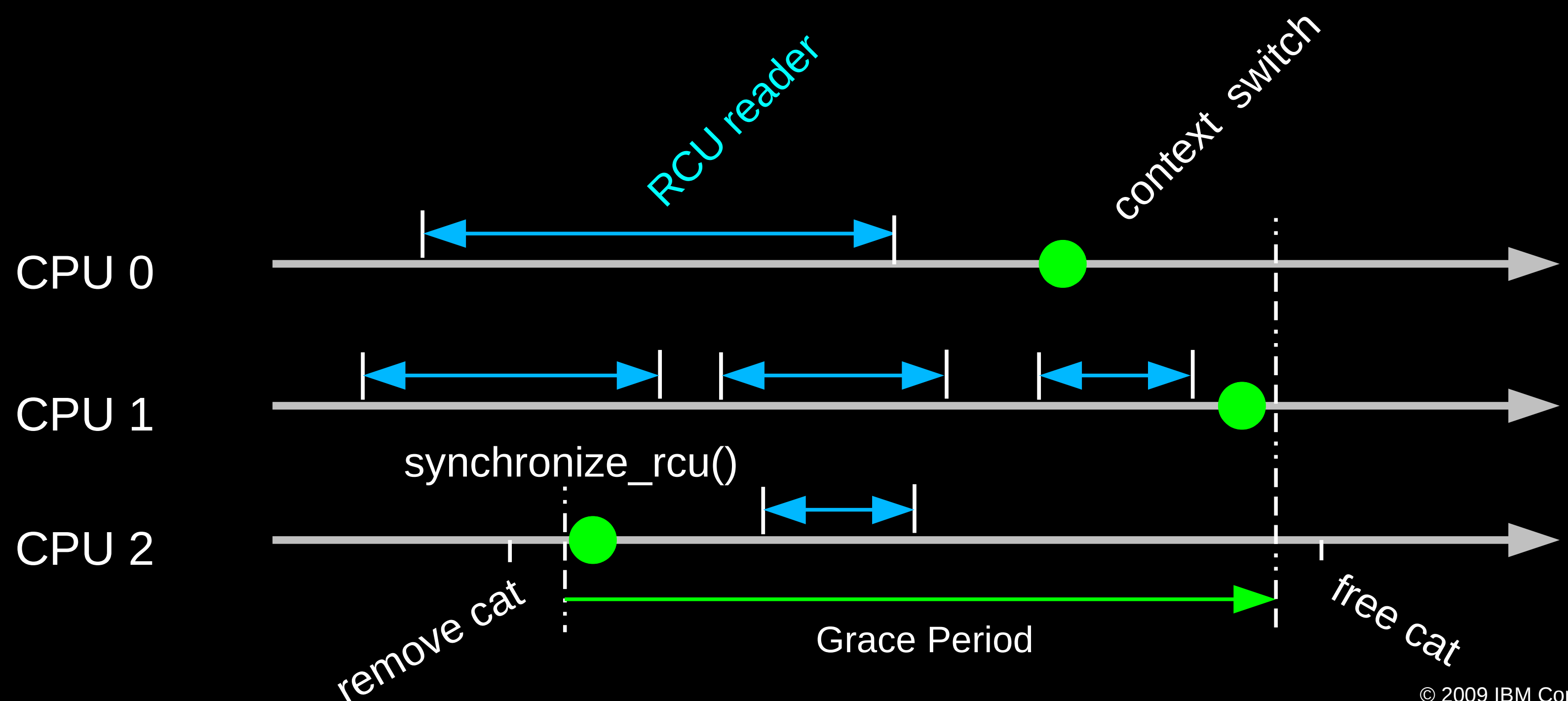
But if readers leave no trace in memory, how can we possibly tell when they are done???

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

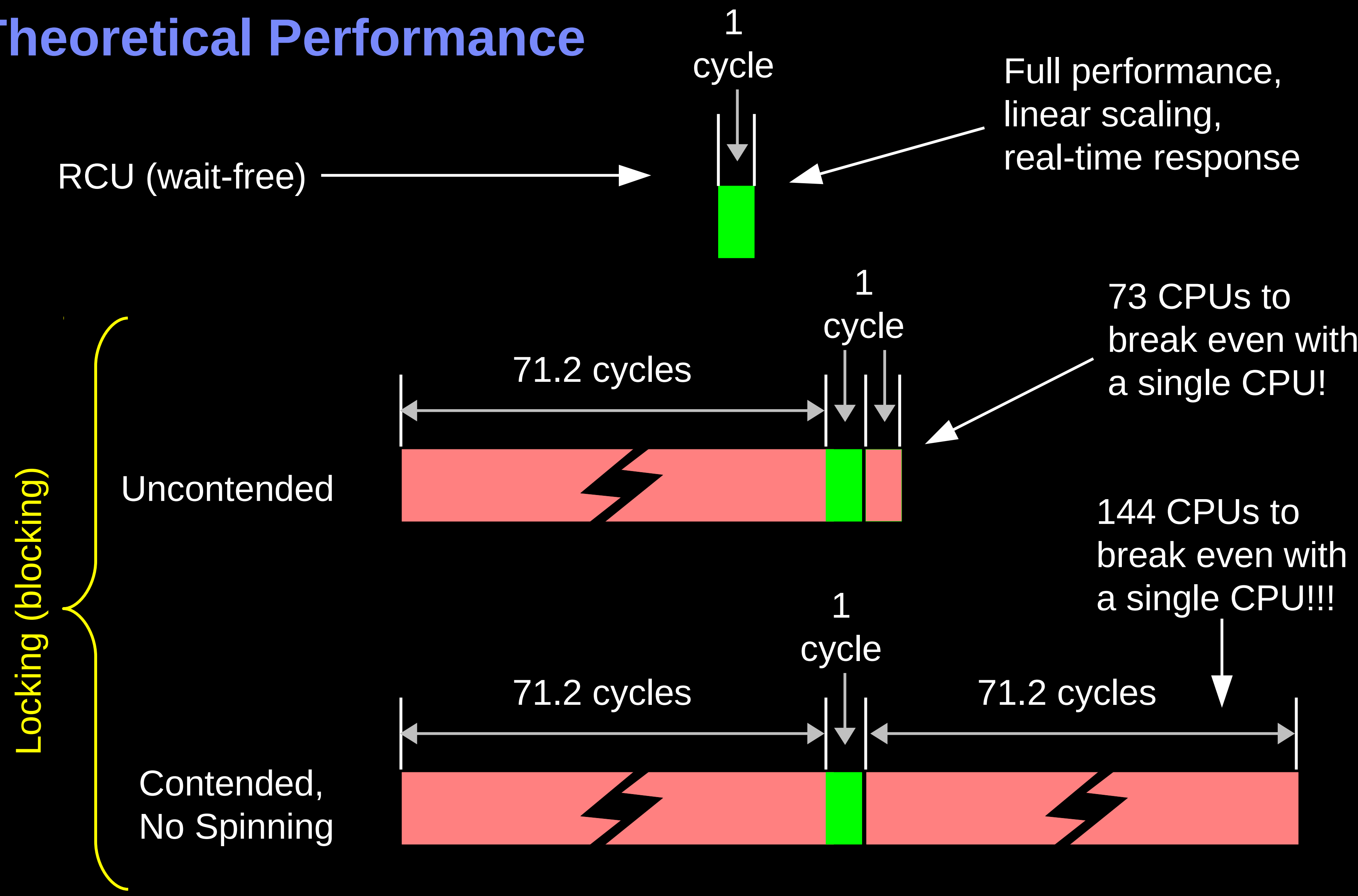
Waiting for Pre-Existing Readers: QSBR

- 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* begins after synchronize_rcu() call and ends after all CPUs execute a context switch



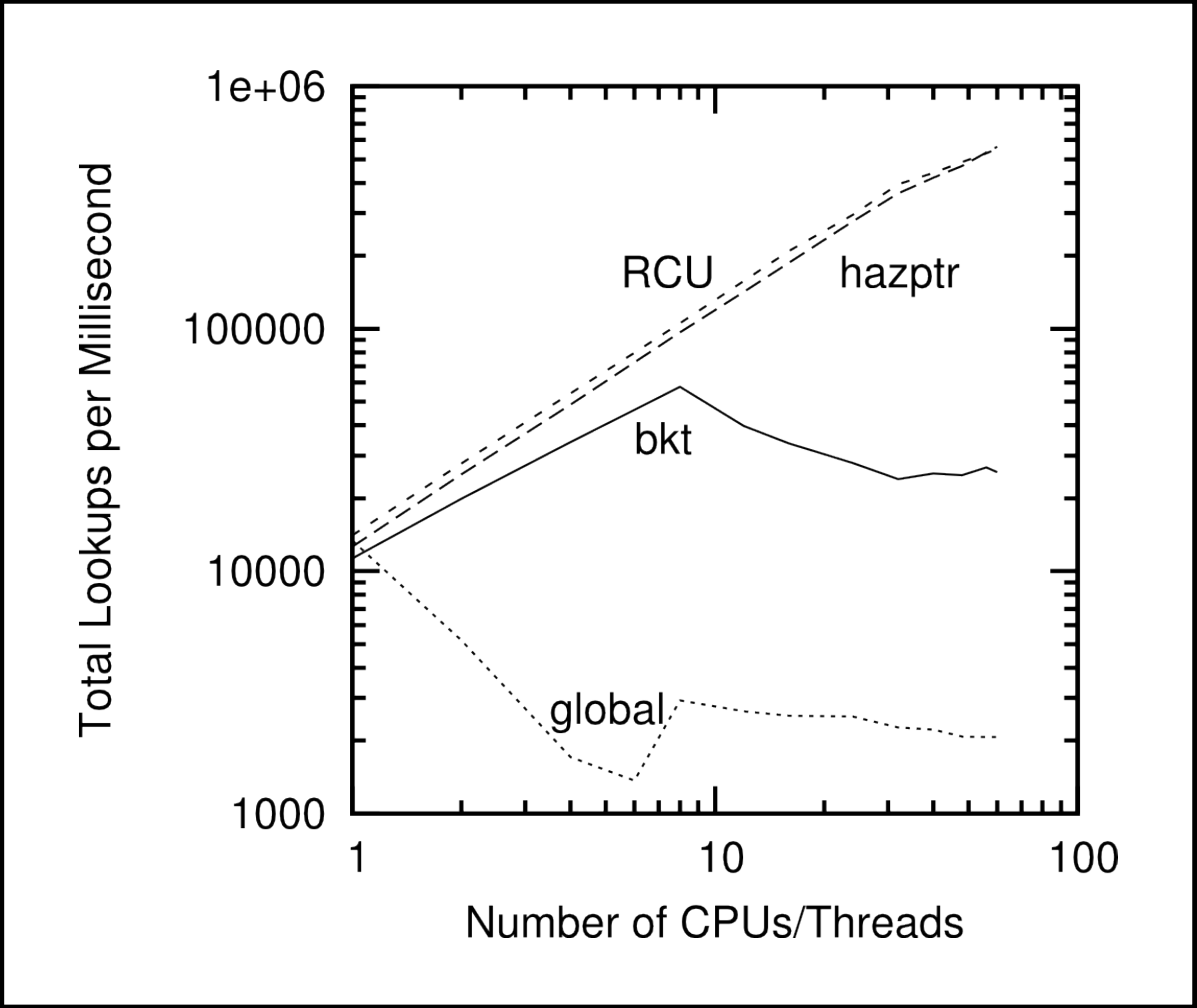
Performance

Theoretical Performance



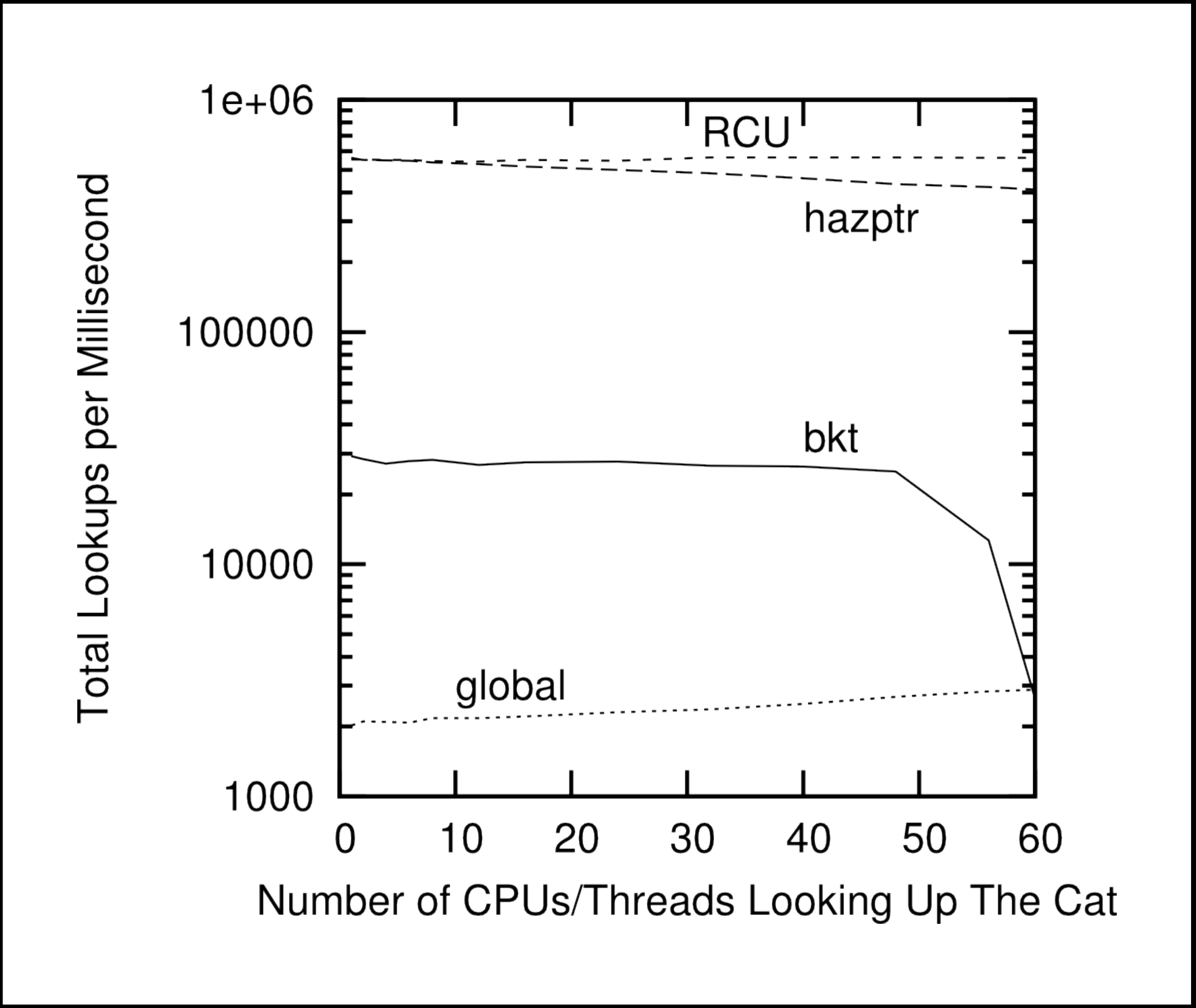
Measured Performance

Schrödinger's Zoo: Read-Only



RCU and hazard pointers scale quite well!!!

Schrödinger's Zoo: Read-Only Cat-Heavy Workload



RCU handles locality quite well, hazard pointers not bad, bucket locking horribly

Schrödinger's Zoo: Reads and Updates

Mechanism	Reads	Failed Reads	Cat Reads	Adds	Deletes
Global Locking	799	80	639	77	77
Per-Bucket Locking	13,555	6,177	1,197	5,370	5,370
Hazard Pointers	41,011	6,982	27,059	4,860	4,860
RCU	85,906	13,022	59,873	2,440	2,440

RCU Performance: “Free is a *Very* Good Price!!!” And Nothing Is Faster Than Doing Nothing!!!

RCU Area of Applicability

Read-Mostly, Stale &
Inconsistent Data OK
(RCU Works Great!!!)

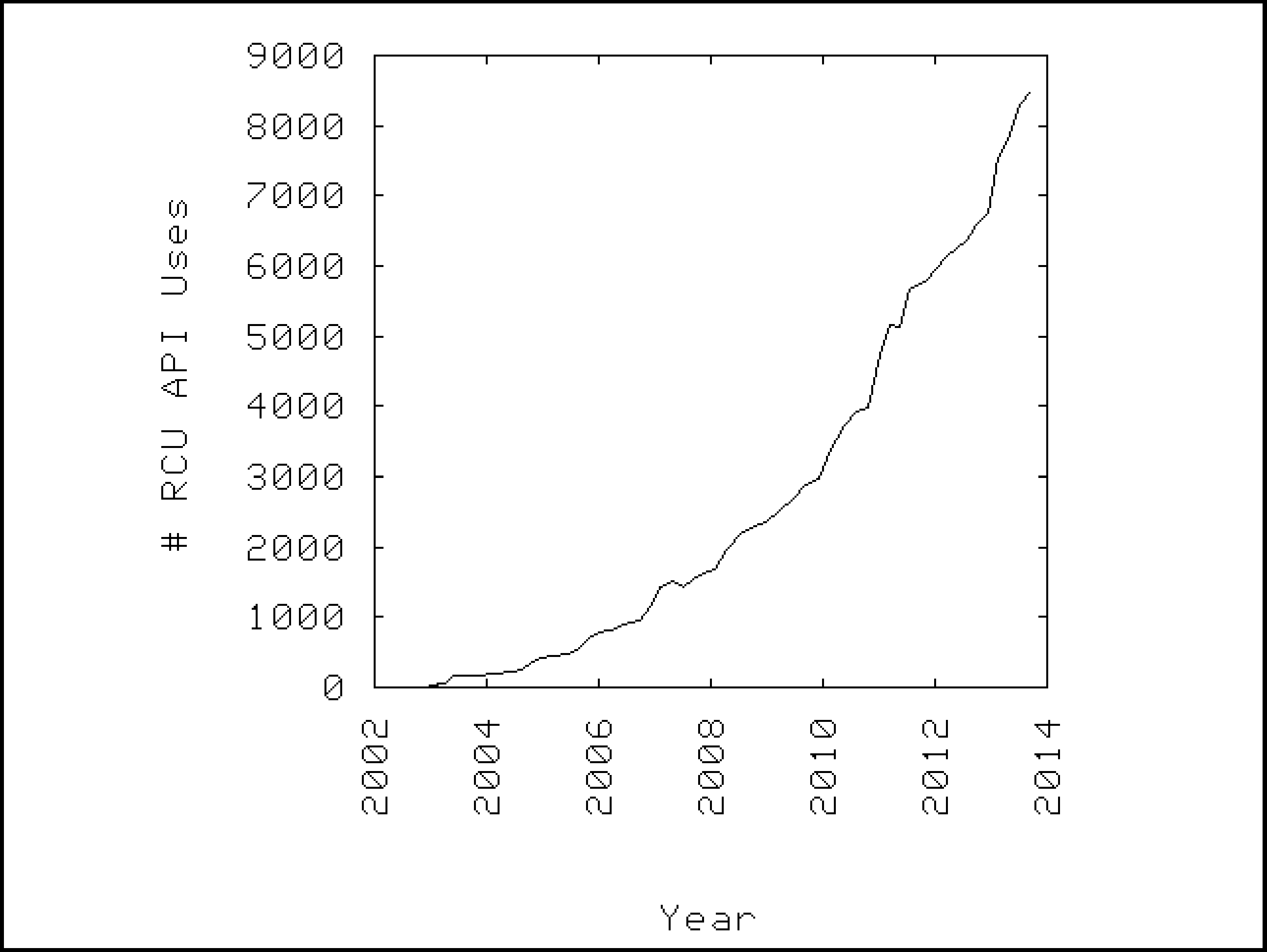
Read-Mostly, Need Consistent Data
(RCU Works OK)

Read-Write, Need Consistent Data
(RCU *Might* Be OK...)

Update-Mostly, Need Consistent Data
(RCU is ***Really*** Unlikely to be the Right Tool For The Job, But It Can:
(1) Provide Existence Guarantees For Update-Friendly Mechanisms
(2) Provide Wait-Free Read-Side Primitives for Real-Time Use)

Schrodinger's zoo is in blue: Can't tell exactly when an animal is born
or dies anyway! Plus, no lock you can hold will prevent an animal's death...

RCU Applicability to the Linux Kernel



Summary

Summary

- Synchronization overhead is a big issue for parallel programs
- Straightforward design techniques can avoid this overhead
  - Partition the problem: “Many instances of something good!”
  - Avoid expensive operations
  - Avoid mutual exclusion
- RCU is part of the solution, as is hazard pointers
  - Excellent for read-mostly data where staleness and inconsistency OK
  - Good for read-mostly data where consistency is required
  - Can be OK for read-write data where consistency is required
  - Might not be best for update-mostly consistency-required data
    - Provide existence guarantees that are useful for scalable updates
  - Used heavily in the Linux kernel
- Much more information on RCU is available...

Graphical Summary

To Probe Further:

- https://queue.acm.org/detail.cfm?id=2488549
  - "Structured Deferral: Synchronization via Procrastination"
- http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.159 and http://www.computer.org/cms/Computer.org/dl/trans/td/2012/02/extras/ttd2012020375s.pdf
  - "User-Level Implementations of Read-Copy Update"
- git://lttng.org/userspace-rcu.git (User-space RCU git tree)
- http://people.csail.mit.edu/nickolai/papers/clements-bonsai.pdf
  - Applying RCU and weighted-balance tree to Linux mmap_sem.
- http://www.usenix.org/event/atc11/tech/final_files/Triplett.pdf
  - RCU-protected resizable hash tables, both in kernel and user space
- http://www.usenix.org/event/hotpar11/tech/final_files/Howard.pdf
  - Combining RCU and software transactional memory
- http://wiki.cs.pdx.edu/rp/: Relativistic programming, a generalization of RCU
- http://lwn.net/Articles/262464/, http://lwn.net/Articles/263130/, http://lwn.net/Articles/264090/
  - "What is RCU?" Series
- http://www.rdrop.com/users/paulmck/RCU/RCUdissertation.2004.07.14e1.pdf
  - RCU motivation, implementations, usage patterns, performance (micro+sys)
- http://www.livejournal.com/users/james_morris/2153.html
  - System-level performance for SELinux workload: >500x improvement
- http://www.rdrop.com/users/paulmck/RCU/hart_ipdps06.pdf
  - Comparison of RCU and NBS (later appeared in JPDC)
- http://doi.acm.org/10.1145/1400097.1400099
  - History of RCU in Linux (Linux changed RCU more than vice versa)
- http://read.seas.harvard.edu/cs261/2011/rcu.html
  - Harvard University class notes on RCU (Courtesy Eddie Koher)
- http://www.rdrop.com/users/paulmck/RCU/ (More RCU information)

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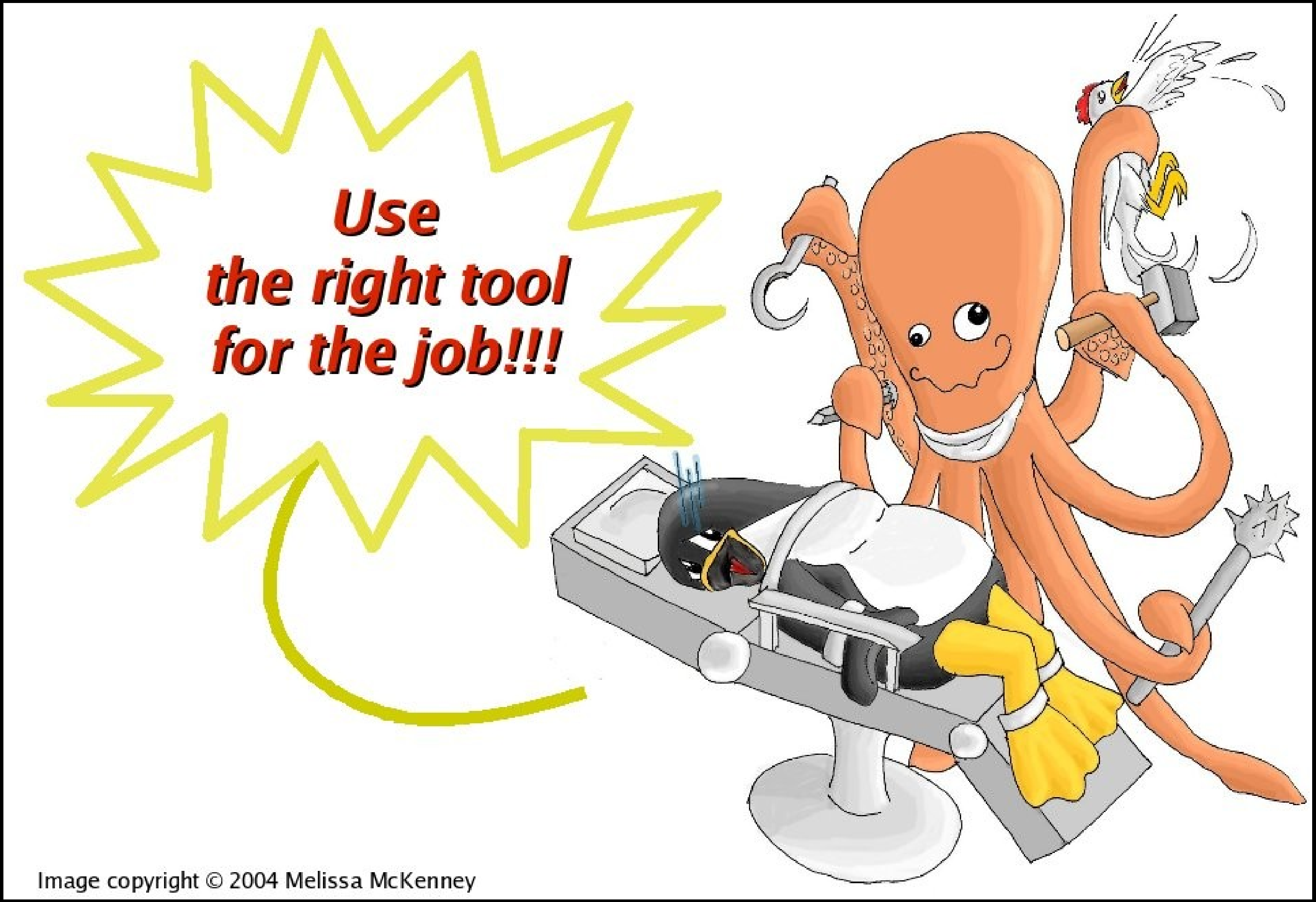
  - This material is based upon work supported by the National Science Foundation under Grant No. CNS-0719851.
  - Joint work with Mathieu Desnoyers, Alan Stern, Michel Dagenais, Manish Gupta, Maged Michael, Phil Howard, Joshua Triplett, Jonathan Walpole, and the Linux kernel community.
  - Additional reviewers: Carsten Weinhold and Mingming Cao.

Questions?


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

Introduction to Userspace RCU Data Structures

EfficiOS

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Presenter

Mathieu Desnoyers

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- http://www.efficios.com

Author/Maintainer of

- Userspace RCU,
- LTTng kernel and user-space tracers,
- Babeltrace.

Content

- Introduction to major Userspace RCU (URCU) concepts,
- URCU memory model,
- URCU APIs
  - Atomic operations, helpers, reference counting,
- URCU Concurrent Data Structures (CDS)
  - Lists,
  - Stacks,
  - Queues,
  - Hash tables.

Content (cont.)

- Userspace RCU hands-on tutorial

Data Structure Characteristics

- Scalability
- Real-Time Response
- Performance

Non-Blocking Algorithms

- Progress Guarantees
  - Lock-free
    - guarantee of *system* progress.
  - Wait-free
    - also guarantee *per-thread* progress.

Memory Model

- Weakly ordered architectures can reorder memory accesses

Initial conditions
x = 0
y = 0

CPU 0	**CPU 1**
x = 1;	r1 = y;
y = 1;	r2 = x;

If r2 loads 0, can r1 have loaded 1 ?

Memory Model

- Weakly ordered architectures can reorder memory accesses

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x = 0
y = 0

CPU 0	**CPU 1**
x = 1;	r1 = y;
y = 1;	r2 = x;

If r2 loads 0, can r1 have loaded 1 ?

YES, at leasts on many weakly-ordered architectures.

Memory Model

	Loads Reordered After Loads?	Loads Reordered After Stores?	Stores Reordered After Stores?	Stores Reordered After Loads?	Atomic Instructions Reordered With Loads?	Atomic Instructions Reordered With Stores?	Dependent Loads Reordered?	Incoherent Instruction Cache/Pipeline?
Alpha	Y	Y	Y	Y	Y	Y	Y	Y
AMD64	Y			Y				
IA64	Y	Y	Y	Y	Y	Y		Y
(PA–RISC)	Y	Y	Y	Y				
PA–RISC CPUs								
POWER	Y	Y	Y	Y	Y	Y		Y
SPARC RMO	Y	Y	Y	Y	Y	Y		Y
(SPARC PSO)			Y	Y		Y		Y
SPARC TSO				Y				Y
x86	Y	Y		Y				Y
(x86 OOStore)	Y	Y	Y	Y				Y
zSeries				Y				Y

Summary of Memory Ordering
Paul E. McKenney, Memory Ordering in Modern Microprocessors, Part II,
http://www.linuxjournal.com/article/8212

Memory Model

- But how comes we can usually expect those accesses to be ordered ?
  - Mutual exclusion (locks) are the answer,
  - They contain the appropriate memory barriers.
- But what happens if we want to do synchronization without locks ?
  - Need to provide our own memory ordering guarantees.

Memory Model

- Userspace RCU
  - Similar memory model as the Linux kernel, for user-space.
  - For details, see Linux Documentation/memory-barriers.txt

Userspace RCU Memory Model

- urcu/arch.h
  - memory ordering between processors
    - cmm_smp_{mb,rmb,wmb}()
  - memory mapped I/O, SMP and UP
    - cmm_{mb,rmb,wmb}()
  - eventual support for architectures with incoherent caches
    - cmm_smp_{mc,rmc,wmc}()
- urcu/compiler.h
  - compiler-level memory access optimisation barrier
    - cmm_barrier()

Userspace RCU Memory Model (cont.)

- urcu/system.h
  - Inter-thread load and store
    - CMM_LOAD_SHARED(),
    - CMM_STORE_SHARED(),
  - Semantic:
    - Ensures aligned stores and loads to/from word-sized, word-aligned data are performed atomically,
    - Prevents compiler from merging and refetching accesses.
    - Deals with architectures with incoherent caches,

Userspace RCU Memory Model (cont.)

- Atomic operations and data structure APIs have their own memory ordering semantic documented.

Userspace RCU Atomic Operations

- Similar to the Linux kernel atomic operations,
- urcu/uatomic.h
  - uatomic_{add,sub,dec,inc)_return(), uatomic_cmpxchg(), uatomic_xchg() imply full memory barrier (smp_mb()).
  - uatomic_{add,sub,dec,inc,or,and,read,set}() imply no memory barrier.
  - cmm_smp_mb__{before,after}_uatomic_*() provide associated memory barriers.

Userspace RCU Helpers

- urcu/compiler.h
    - Get pointer to structure containing a given field from pointer to field.
        - caa_container_of()
- urcu/compat-tls.h
    - Thread-Local Storage
        - Compiler __thread when available,
        - Fallback on pthread keys,
        - DECLARE_URCU_TLS(),
        - DEFINE_URCU_TLS(),
        - URCU_TLS().

Userspace RCU Reference Counting

- Reference counting based on Userspace RCU atomic operations,
- urcu/ref.h
    - urcu_ref_{set,init,get,put}()

URCU Concurrent Data Structures

- Navigating through URCU CDS API and implementation
- Example of wait-free concurrent queue
    - urcu/wfcqueue.h: header to be included be applications,
        - If _LGPL_SOURCE is defined before include, functions are inlined, else implementation in liburcu-cds.so is called,
    - urcu/wfcqueue.h and wfcqueue.c implement exposed declarations and LGPL wrapping logic,
    - Implementation is found in urcu/static/wfcqueue.h.

URCU lists

- Circular doubly-linked lists,
- Linux kernel alike list API
    - urcu/list.h
    - cds_list_{add,add_tail,del,empty,replace,splice}()
    - cds_list_for_each*()
- Linux kernel alike RCU list API
    - Multiple RCU readers concurrent with single updater.
    - urcu/rculist.h
    - cds_list_{add,add_tail,del,replace,for_each*}_rcu()

URCU hlist

- Linear doubly-linked lists,
- Similar to Linux kernel hlists,
- Meant to be used in hash tables, where size of list head pointer matters,
- urcu/hlist.h
    - cds_hlist_{add_head,del,for_each*}()
- urcu/rcuhlist.h
    - cds_hlist_{add_head,del,for_each*}_rcu()

Stack (Wait-Free Push, Blocking Pop)

- urcu/wfstack.h
  - N push / N pop
  - Wait-free push
    - cds_wfs_push()
  - Wait-free emptiness check
    - cds_wfs_empty()
  - Blocking/nonblocking pop
    - __cds_wfs_pop_blocking()
    - __cds_wfs_pop_nonblocking()
    - subject to existence guarantee constraints
      - Can be provided by either RCU or mutual exclusion on pop and pop all.

Stack (Wait-Free Push, Blocking Pop)

- urcu/wfstack.h (cont.)
  - Wait-free pop all
    - __cds_wfs_pop_all()
    - subject to existence guarantee constraints
      - Can be provided by either RCU or mutual exclusion on pop and pop all.
  - Blocking/nonblocking iteration on stack returned by pop all
    - cds_wfs_for_each_blocking*()
    - cds_wfs_first(), cds_wfs_next_blocking(), cds_wfs_next_nonblocking()

Lock-Free Stack

- urcu/lfstack.h
  - N push / N pop
  - Wait-free emptiness check
    - cds_lfs_empty()
  - Lock-free push
    - cds_lfs_push()
  - Lock-free pop
    - __cds_lfs_pop()
    - subject to existence guarantee constraints
      - Can be provided by either RCU or mutual exclusion on pop and pop all.

Lock-Free Stack

- urcu/lfstack.h (cont.)
  - Lock-free pop all and iteration on the returned stack
    - __cds_lfs_pop_all()
    - subject to existence guarantee constraints
      - Can be provided by either RCU or mutual exclusion on pop and pop all.
    - cds_lfs_for_each*()

Wait-Free Concurrent Queue

- urcu/wfcqueue.h
    - N enqueue / 1 dequeue
    - Wait-free enqueue
        - cds_wfcq_enqueue()
    - Wait-free emptiness check
        - cds_wfcq_empty()
    - Blocking/nonblocking dequeue
        - __cds_wfcq_dequeue_blocking()
        - __cds_wfcq_dequeue_nonblocking()
            - Mutual exclusion of dequeue, splice and iteration required.

Wait-Free Concurrent Queue

- urcu/wfcqueue.h (cont.)
  - Blocking/nonblocking splice (dequeue all)
    - __cds_wfcq_splice_blocking()
    - __cds_wfcq_splice_nonblocking()
      - Mutual exclusion of dequeue, splice and iteration required.

Wait-Free Concurrent Queue

- urcu/wfcqueue.h (cont.)
  - Blocking/nonblocking iteration
    - __cds_wfcq_first_blocking()
    - __cds_wfcq_first_nonblocking()
    - __cds_wfcq_next_blocking()
    - __cds_wfcq_next_nonblocking()
    - __cds_wfcq_for_each_blocking*()
      - Mutual exclusion of dequeue, splice and iteration required.

Wait-Free Concurrent Queue

- urcu/wfcqueue.h (cont.)
  - Splice operations can be chained, so N queues can be merged in N operations.
    - Independent of the number of elements in each queue.

Lock-Free Queue

- urcu/rculfqueue.h
- Requires RCU synchronization for queue nodes
- Lock-Free RCU enqueue
    - cds_lfq_enqueue_rcu()
- Lock-Free RCU dequeue
    - cds_lfq_dequeue_rcu()
- ***No*** splice (dequeue all) operation
- Requires a destroy function to dispose of queue internal structures when queue is freed.
    - cds_lfq_destroy_rcu()

RCU Lock-Free Hash Table

- urcu/rculfhash.h
- Wait-free lookup
    - Lookup by key,
    - cds_lfht_lookup()
- Wait-free iteration
    - Iterate on key duplicates
        - cds_lfht_next_duplicate()
    - Iterate on entire hash table
        - cds_lfht_first()
        - cds_lfht_next()
        - cds_lfht_for_each*()

RCU Lock-Free Hash Table

- Lock-Free add
  - Allows duplicate keys
  - cds_lfht_add().
- Lock-Free del
  - Remove a node.
  - cds_lfht_del().
- Wait-Free check if deleted
  - cds_lfht_is_node_deleted().

RCU Lock-Free Hash Table

- Lock-Free add_unique
    - Add node if node's key was not present, return added node,
    - Acts as a lookup if key was present, return existing node,
    - cds_lfht_add_unique().

RCU Lock-Free Hash Table

- Lock-Free replace
    - Replace existing node if key was present, return replaced node,
    - Return failure if not present,
    - cds_lfht_replace().
- Lock-Free add_replace
    - Replace existing node if key was present, return replaced node,
    - Add new node if key was not present.
    - cds_lfht_add_replace().

RCU Lock-Free Hash Table

- Uniqueness guarantee
  - Lookups/traversals executing concurrently with add_unique, add_replace, replace and del will never see duplicate keys.
- Automatic resize and node accounting
  - Pass flags to cds_lfht_new()
    - CDS_LFHT_AUTO_RESIZE
    - CDS_LFHT_ACCOUNTING
  - Node accounting internally performed with split-counters, resize performed internally by call_rcu worker thread.

RCU Island Game

http://urcu.so

Userspace RCU Hands-on Tutorial

- Downloads required
  - Userspace RCU library 0.8.0
    - http://urcu.so
    - Follow README file to install
  - RCU Island game
    - git clone git://github.com/efficios/urcu-tutorial
    - Run ./bootstrap
    - Solve exercises in exercises/questions.txt

Thank you!

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