Paul E. McKenney, IBM Distinguished Engineer, Linux Technology Center
Member, IBM Academy of Technology

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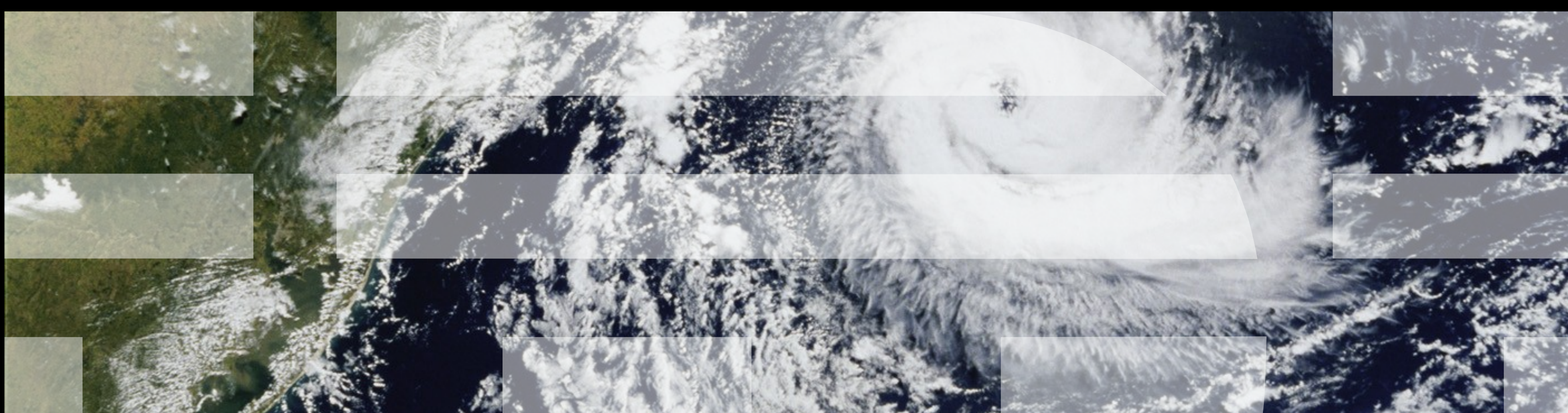
Introduction to RCU Concepts

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

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- 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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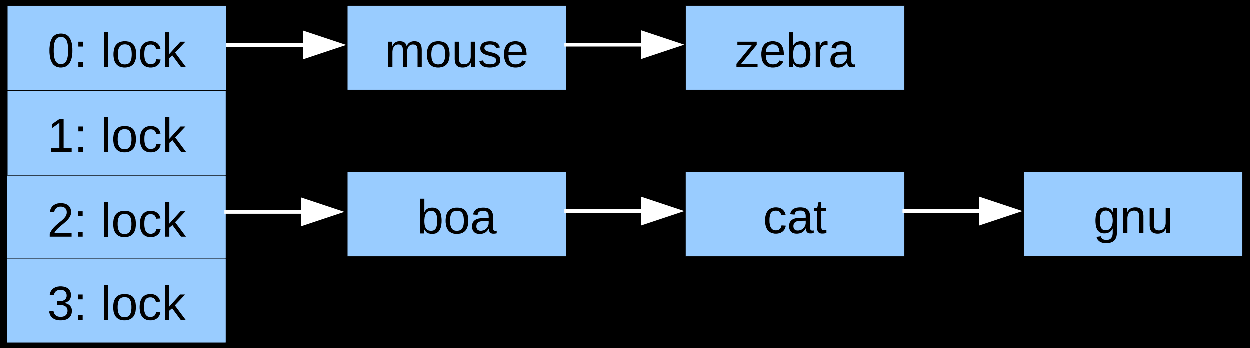
- Simple approach: chained hash table with per-bucket locking



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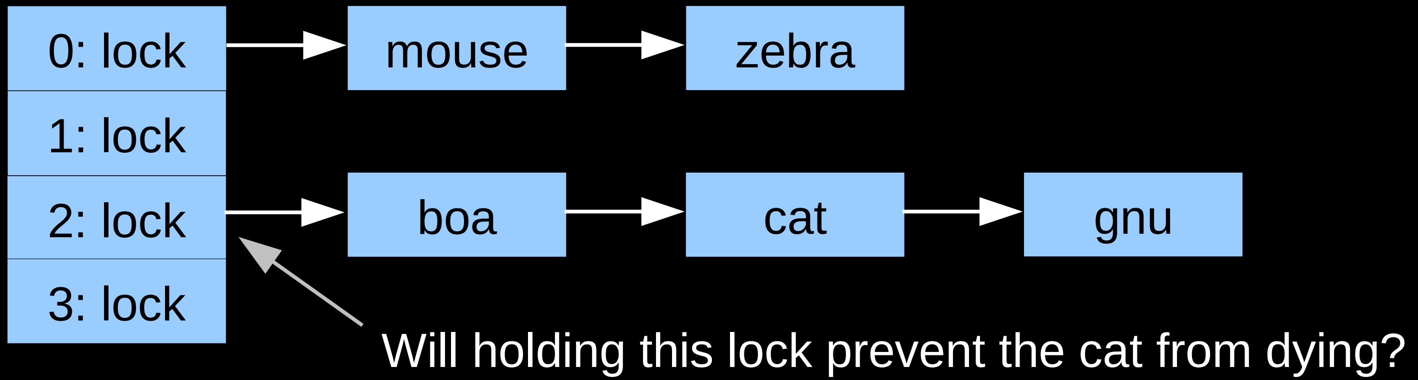

Read-Only Bucket-Locked Hash Table Performance

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

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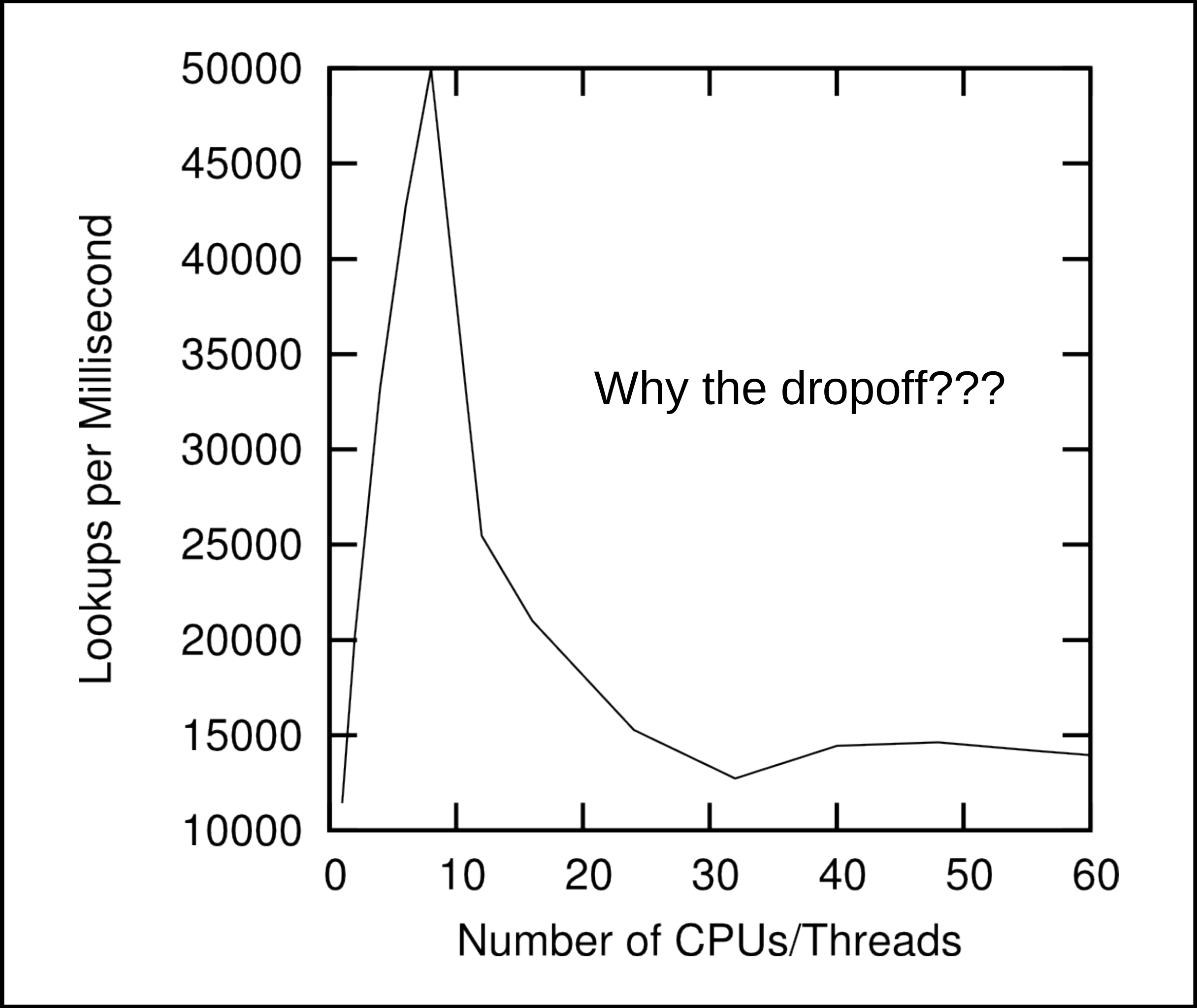
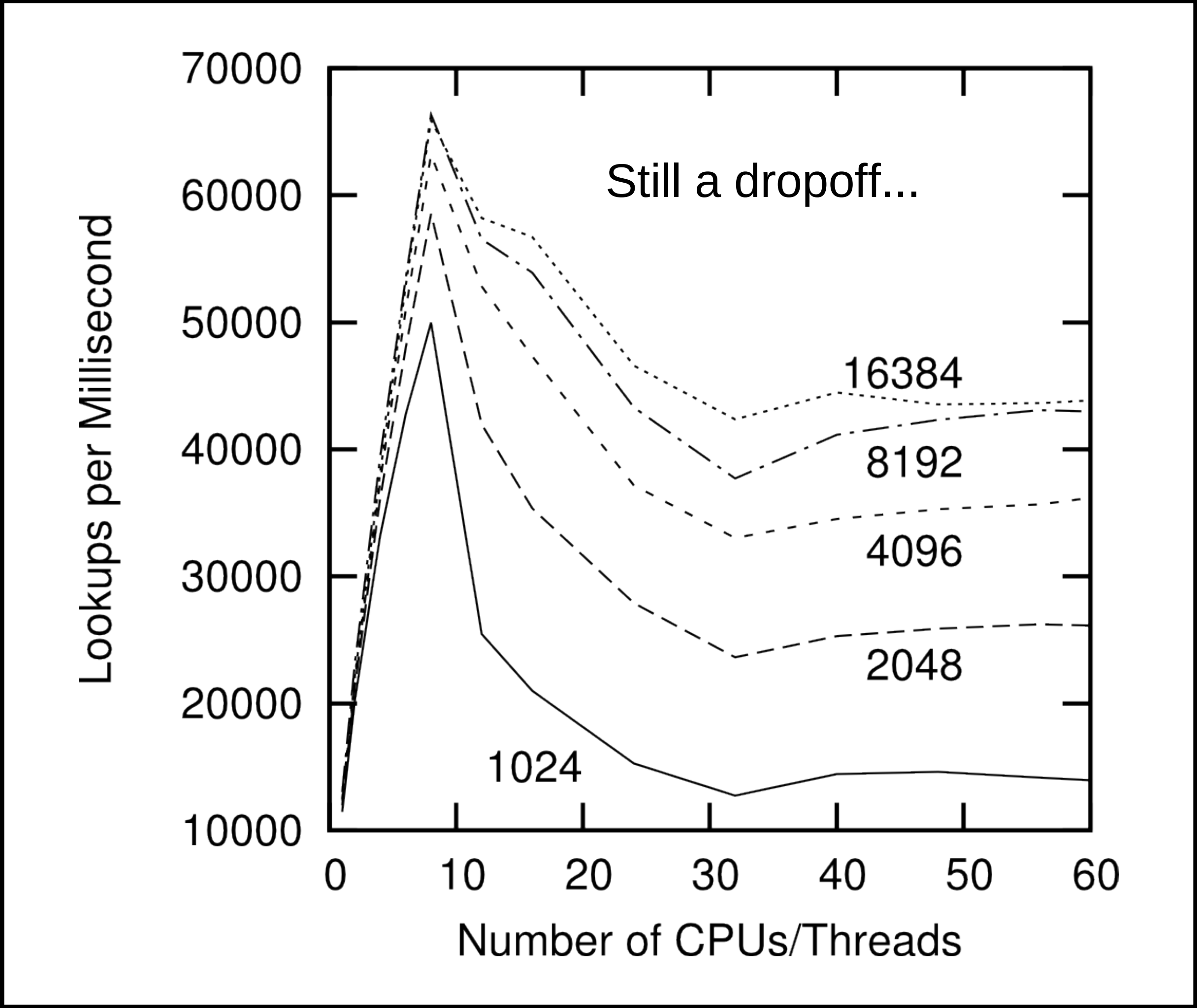


2GHz Intel Xeon Westmere-EX, 1024 hash buckets

Varying Number of Hash Buckets

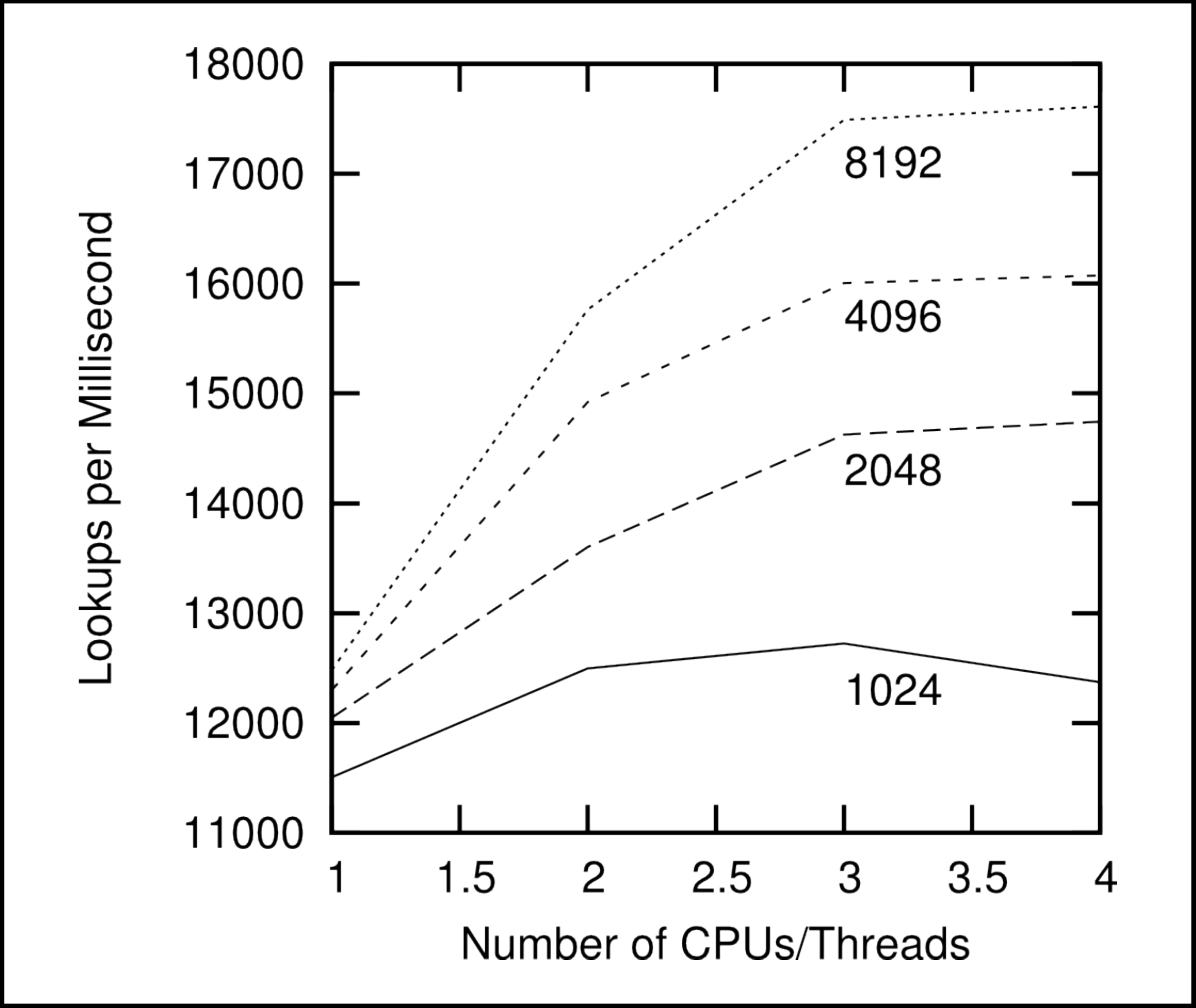


2GHz Intel Xeon Westmere-EX

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

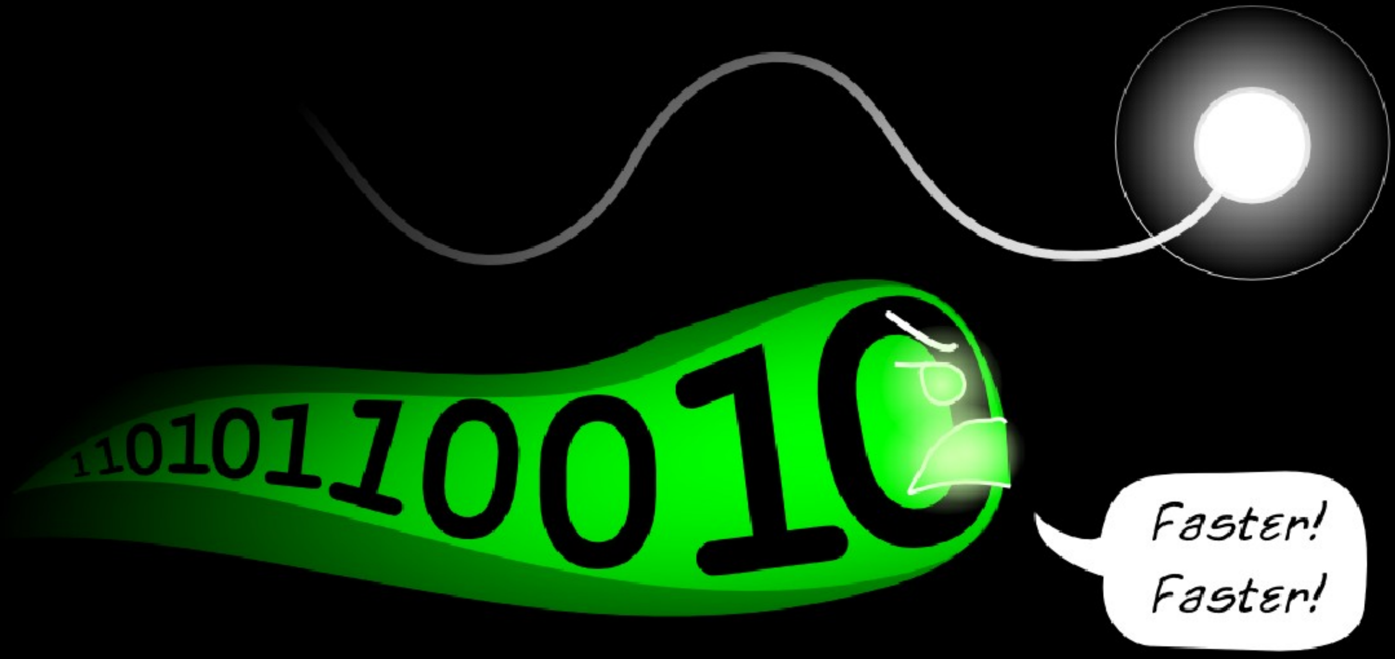
Bucket-Locked Hash Performance: 1 CPU/Socket



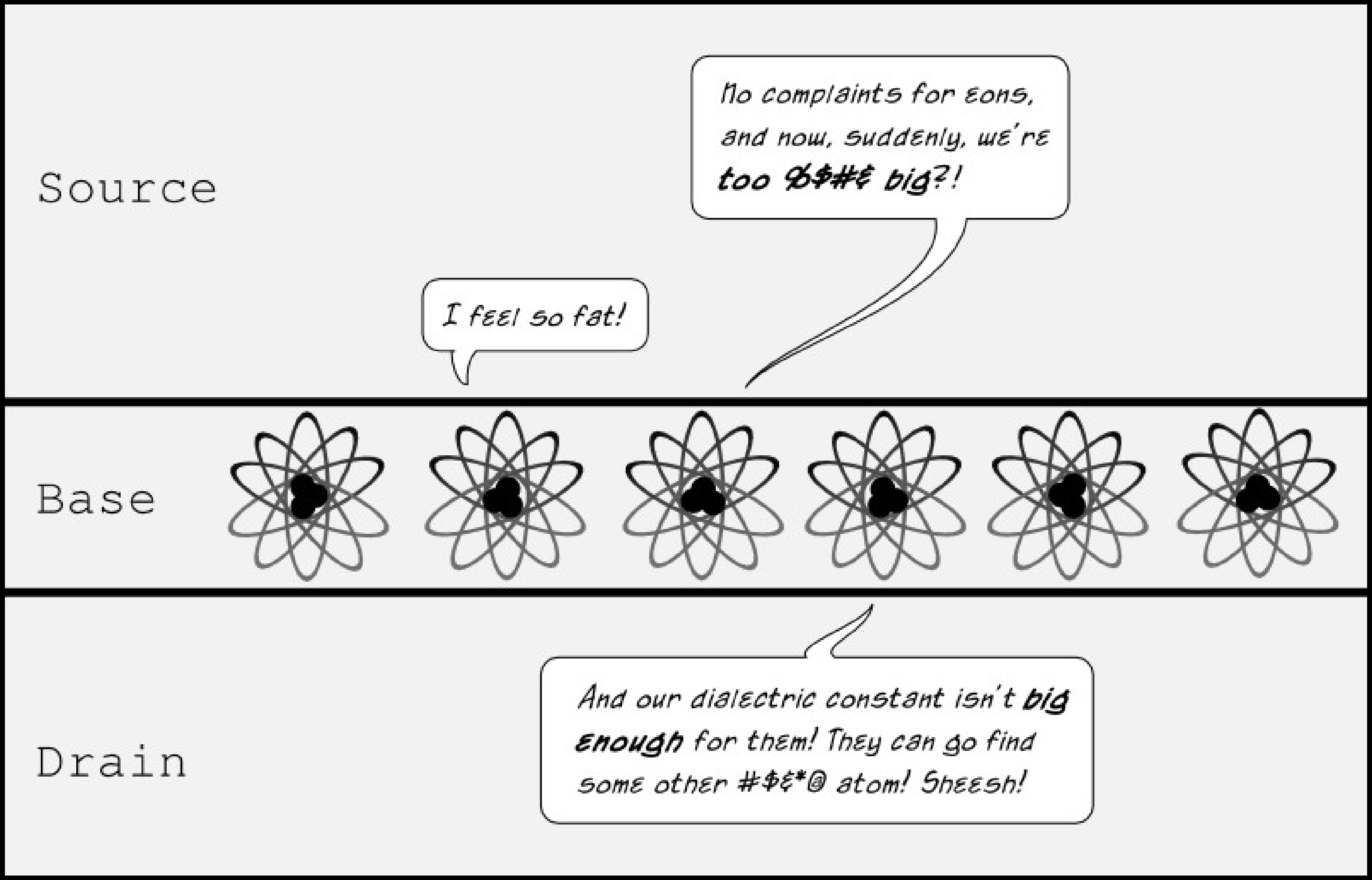
2GHz Intel Xeon Westmere-EX: This is not the sort of scalability Schrödinger requires!!!

Performance of Synchronization Mechanisms

Problem With Physics #1: Finite Speed of Light

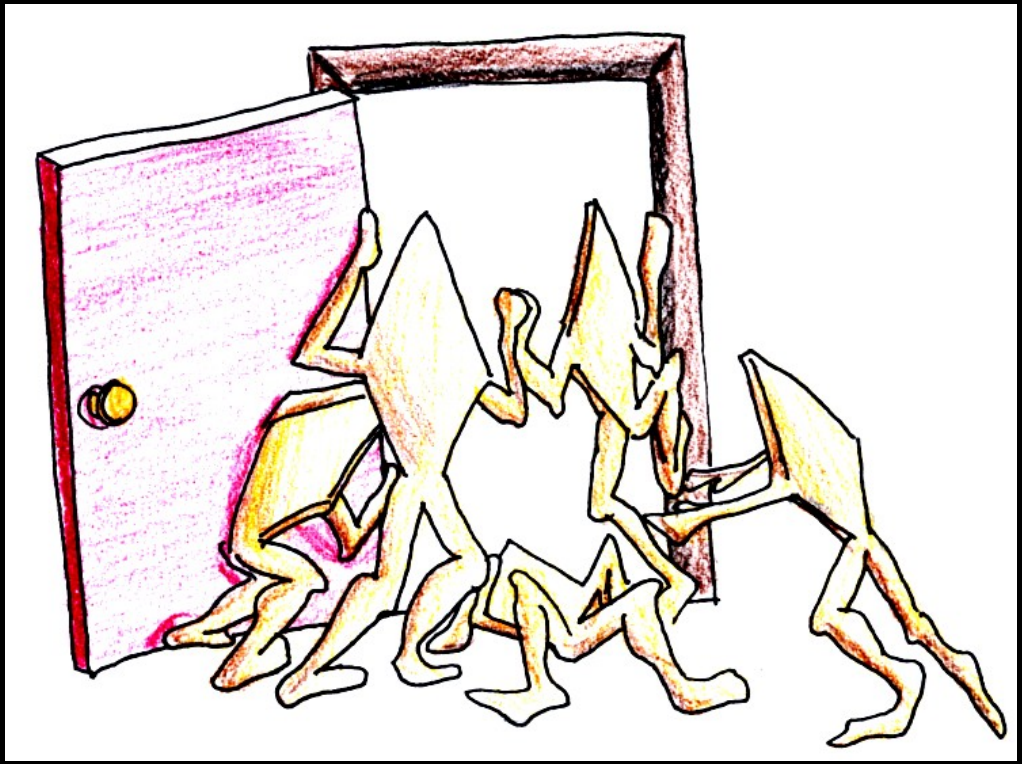


Problem With Physics #2: Atomic Nature of Matter



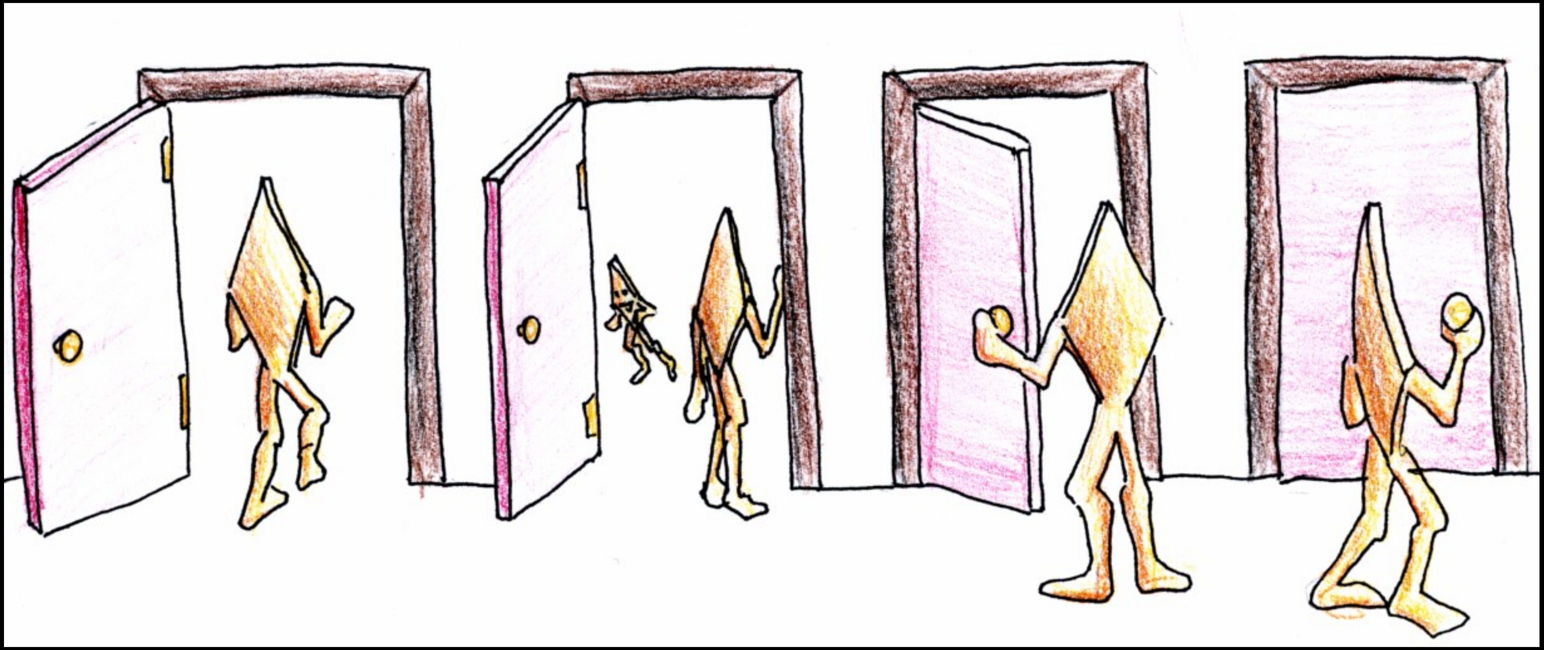
How Can Software Live With This Hardware???

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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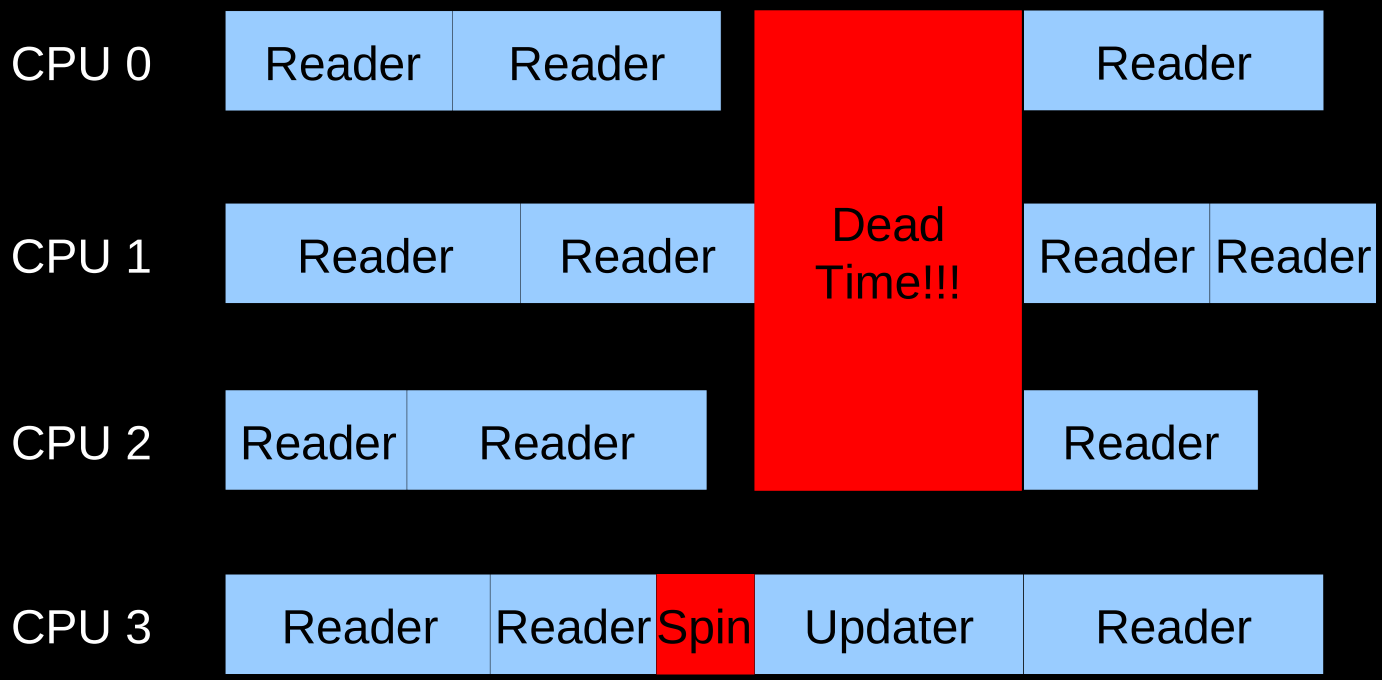
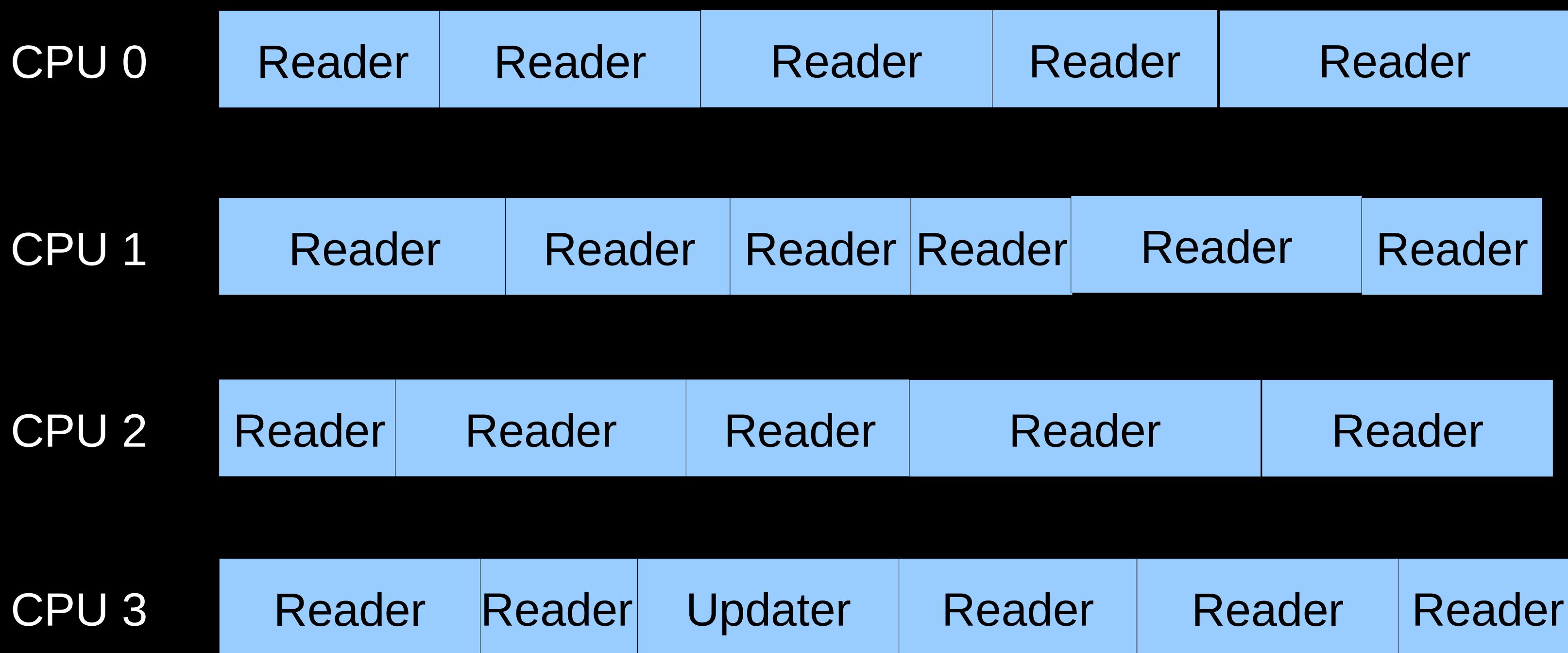
  - Parallelize entire applications rather than low-level algorithms!
  - But the low overhead hash-table insertion/deletion operations do not provide much scope for long critical sections...

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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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

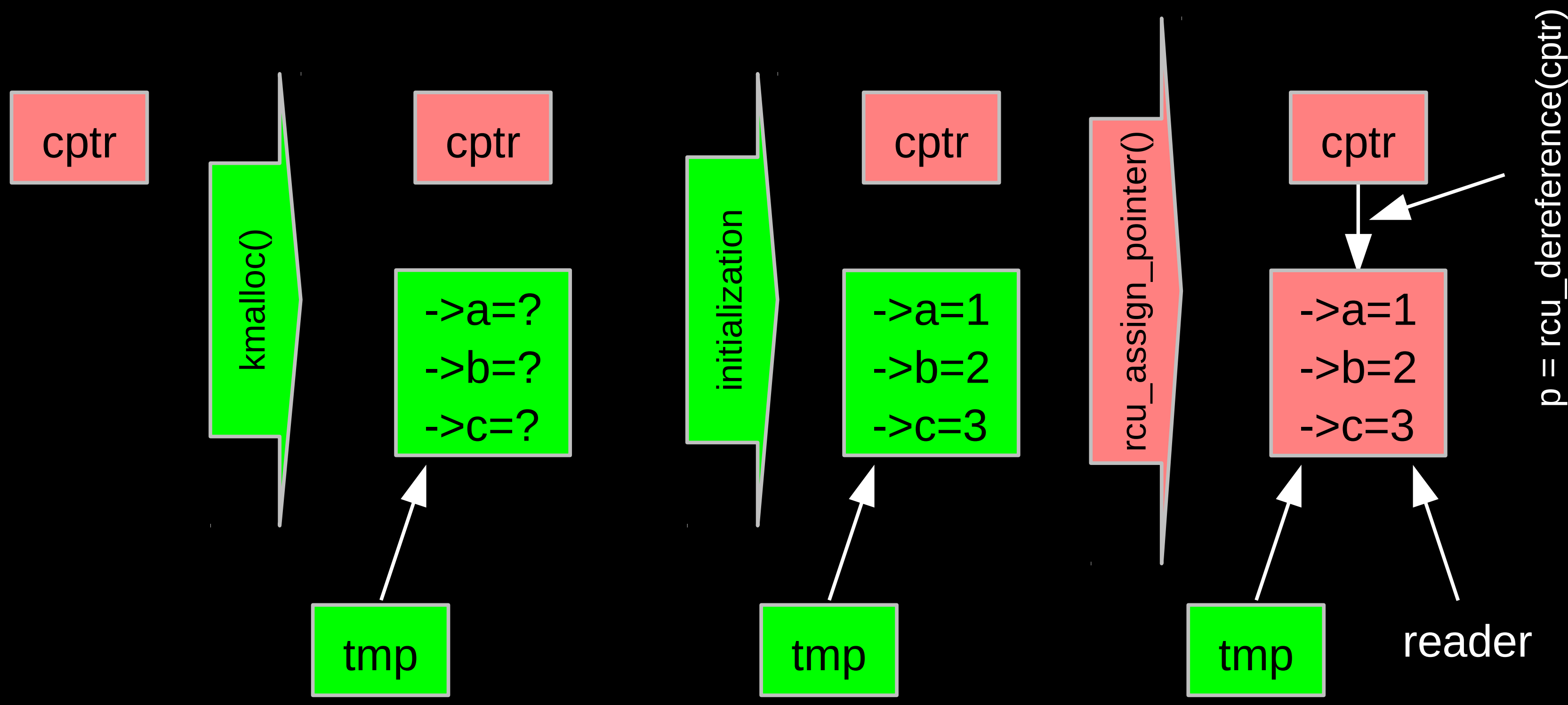
- Updaters must wait for an *RCU grace period* to elapse between making something inaccessible to readers and freeing it

```
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

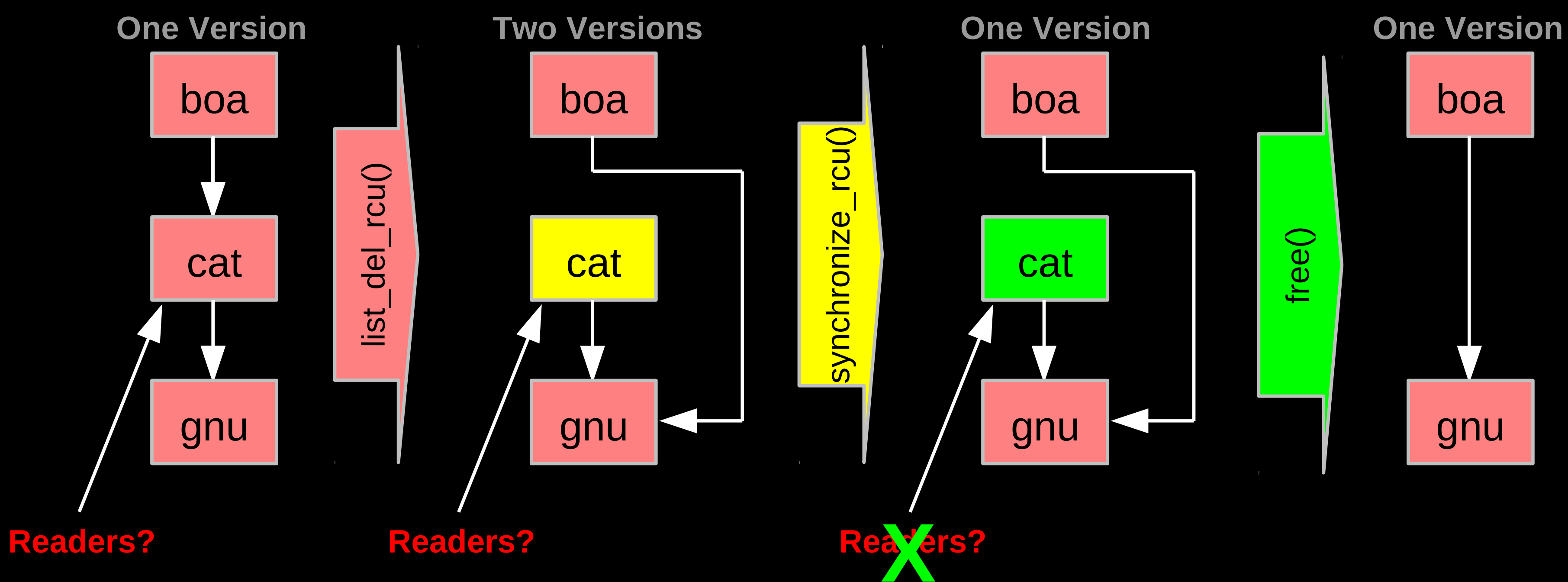
Key:
- Dangerous for updates: all readers can access
- Still dangerous for updates: pre-existing readers can access (next slide)
- Safe for updates: inaccessible to all readers



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

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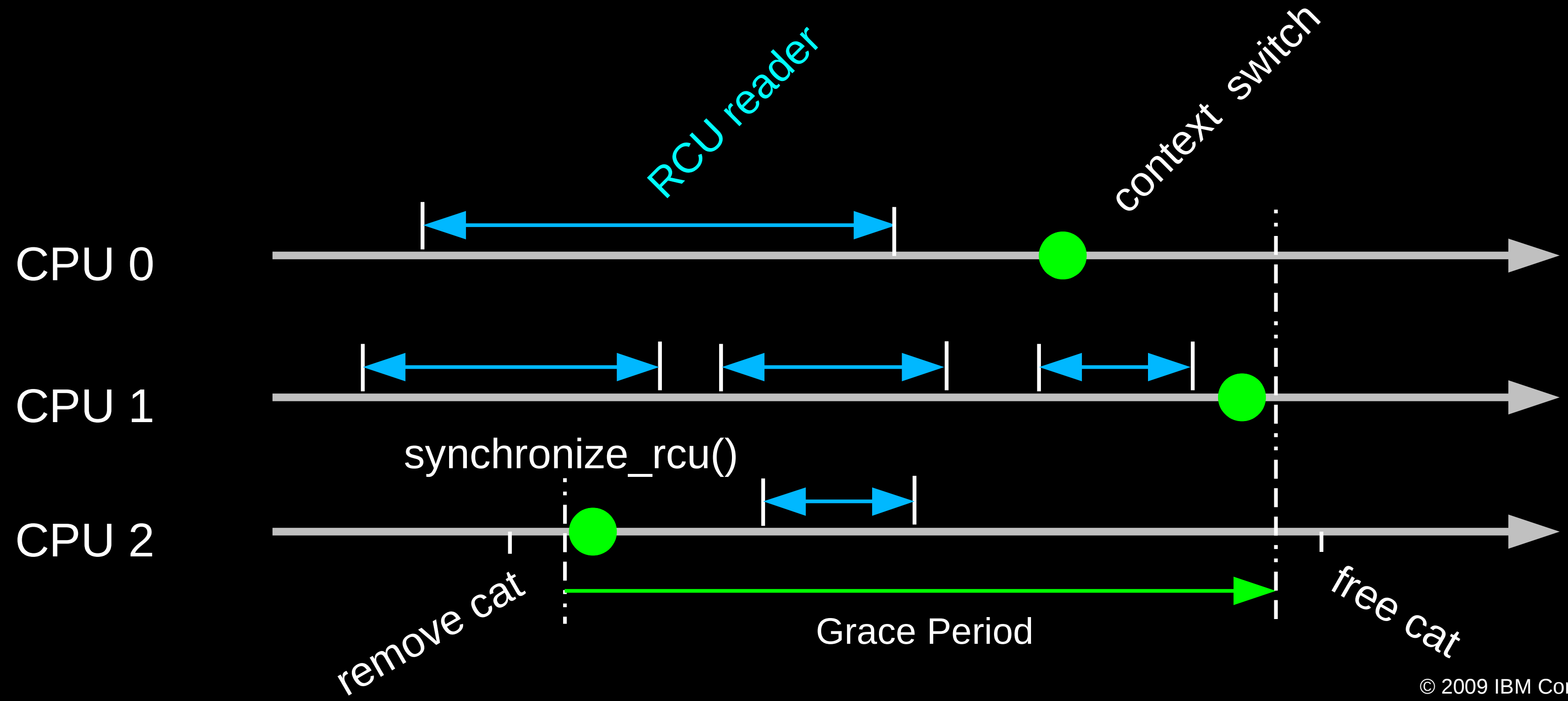
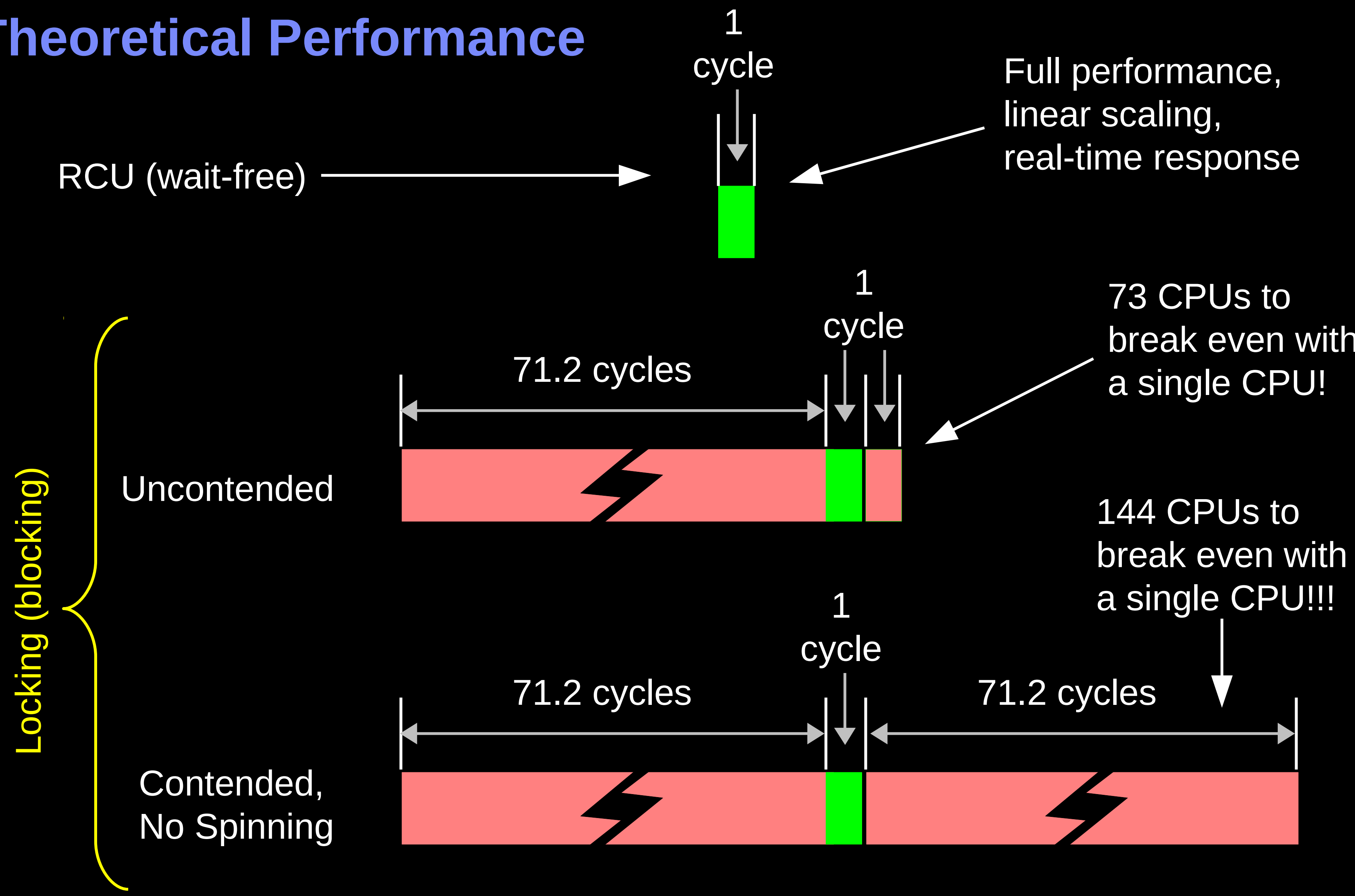
- Non-preemptive environment (CONFIG_PREEMPT=n)
  - RCU readers are not permitted to block
  - Same rule as for tasks holding spinlocks
- CPU context switch means all that CPU's readers are done
- *Grace period* begins after synchronize_rcu() call and ends after all CPUs execute a context switch



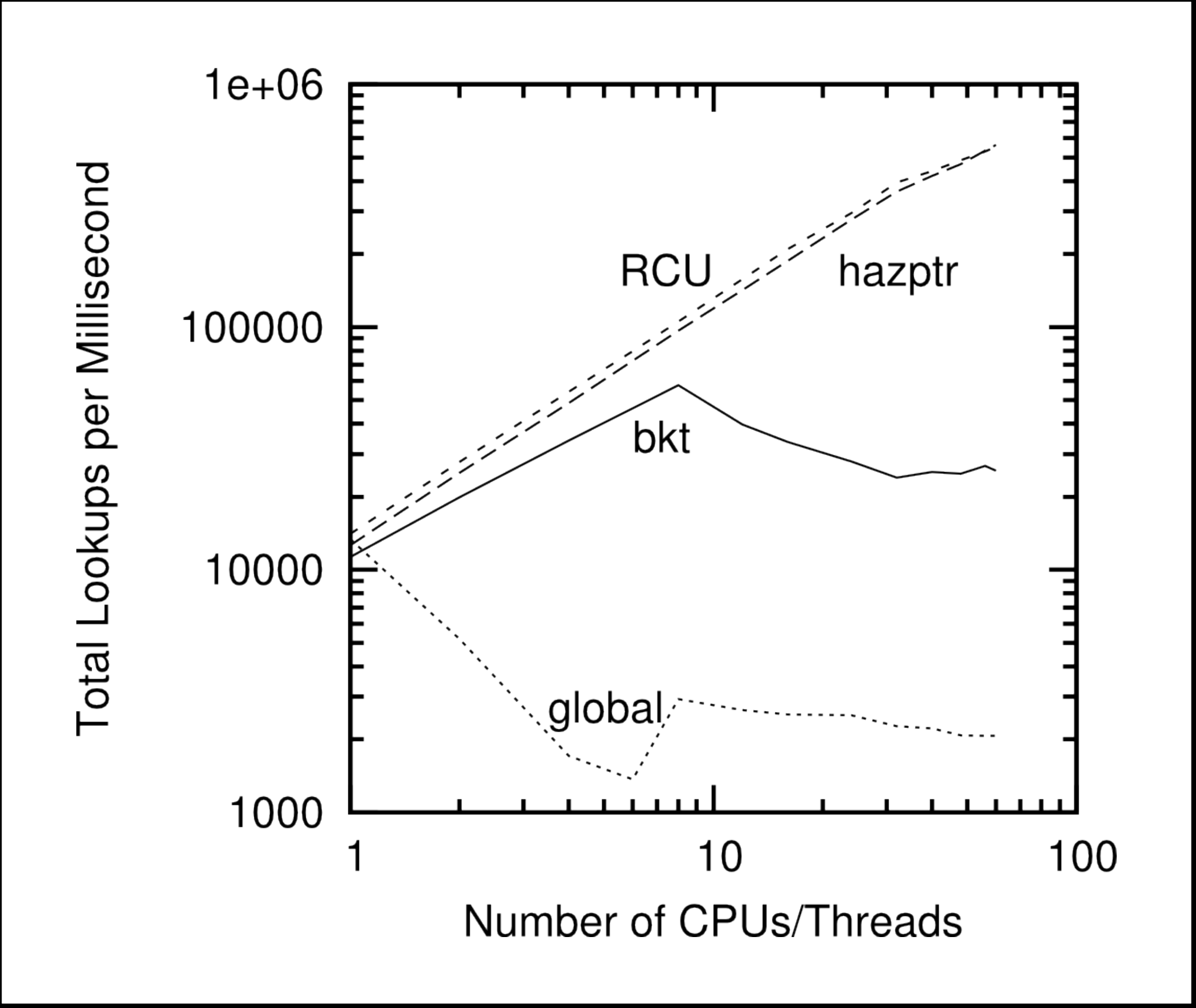
Performance

Theoretical Performance



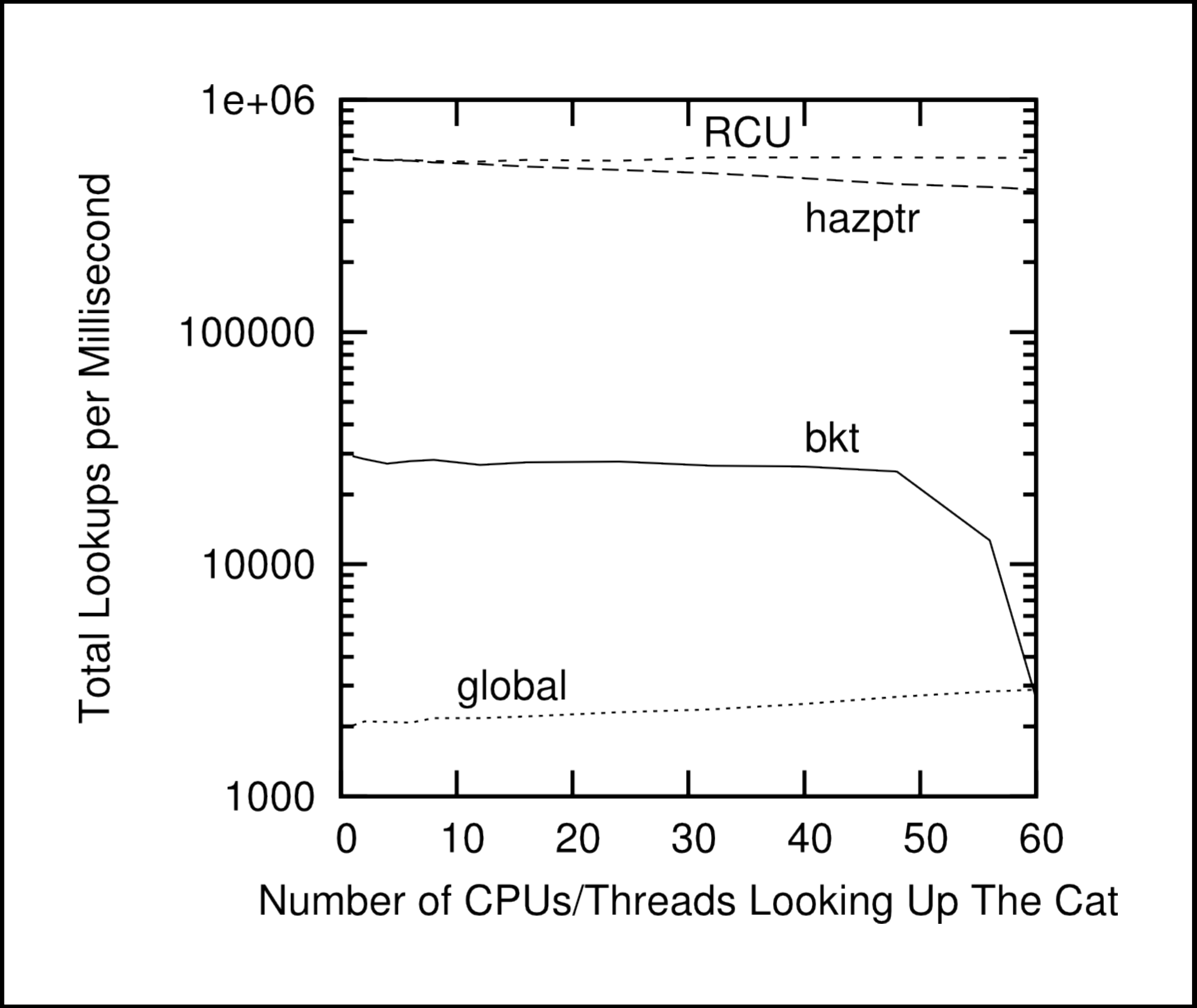
Measured Performance

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!!!)

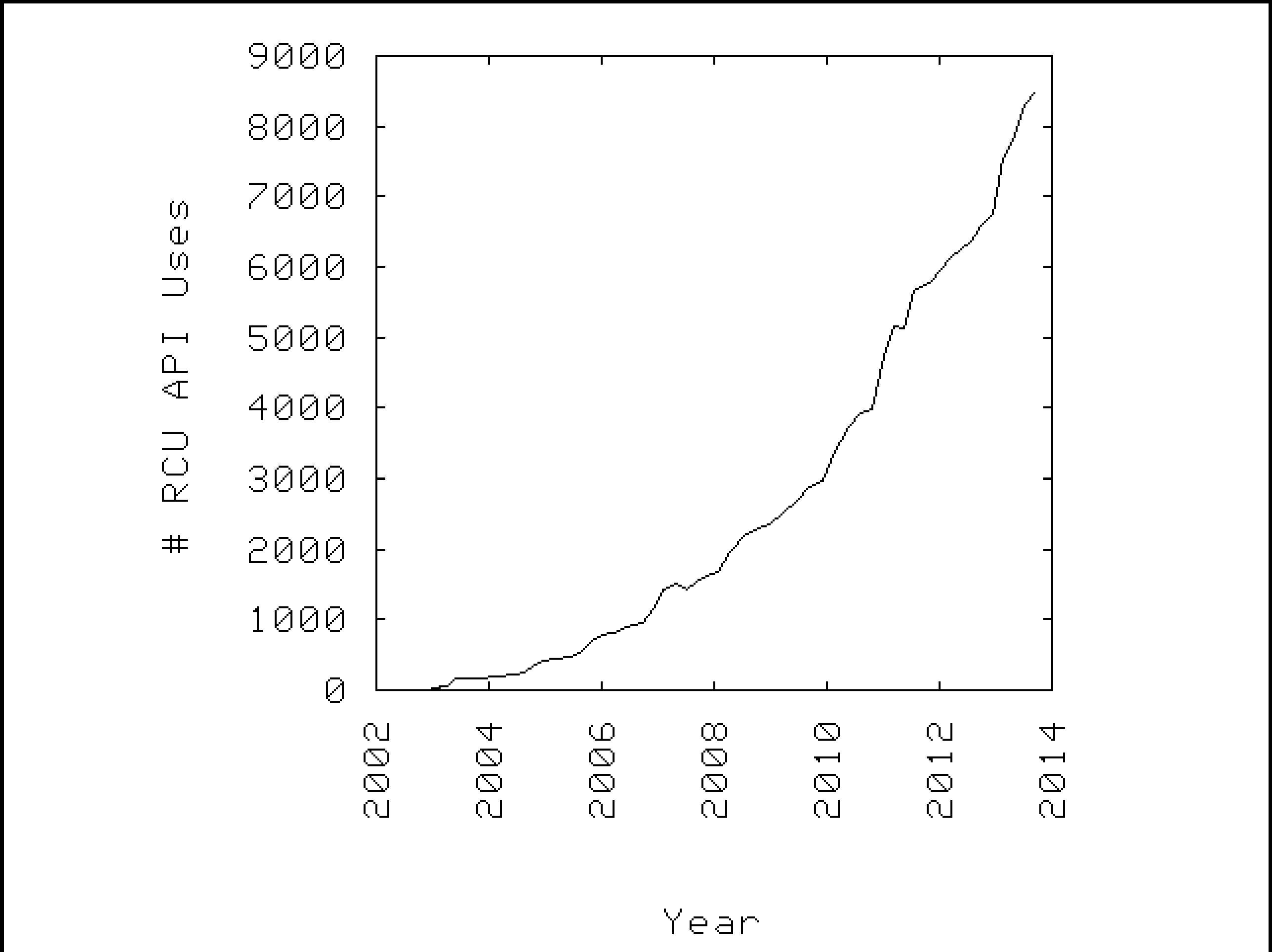
Read-Mostly, Need Consistent Data
(RCU Works OK)

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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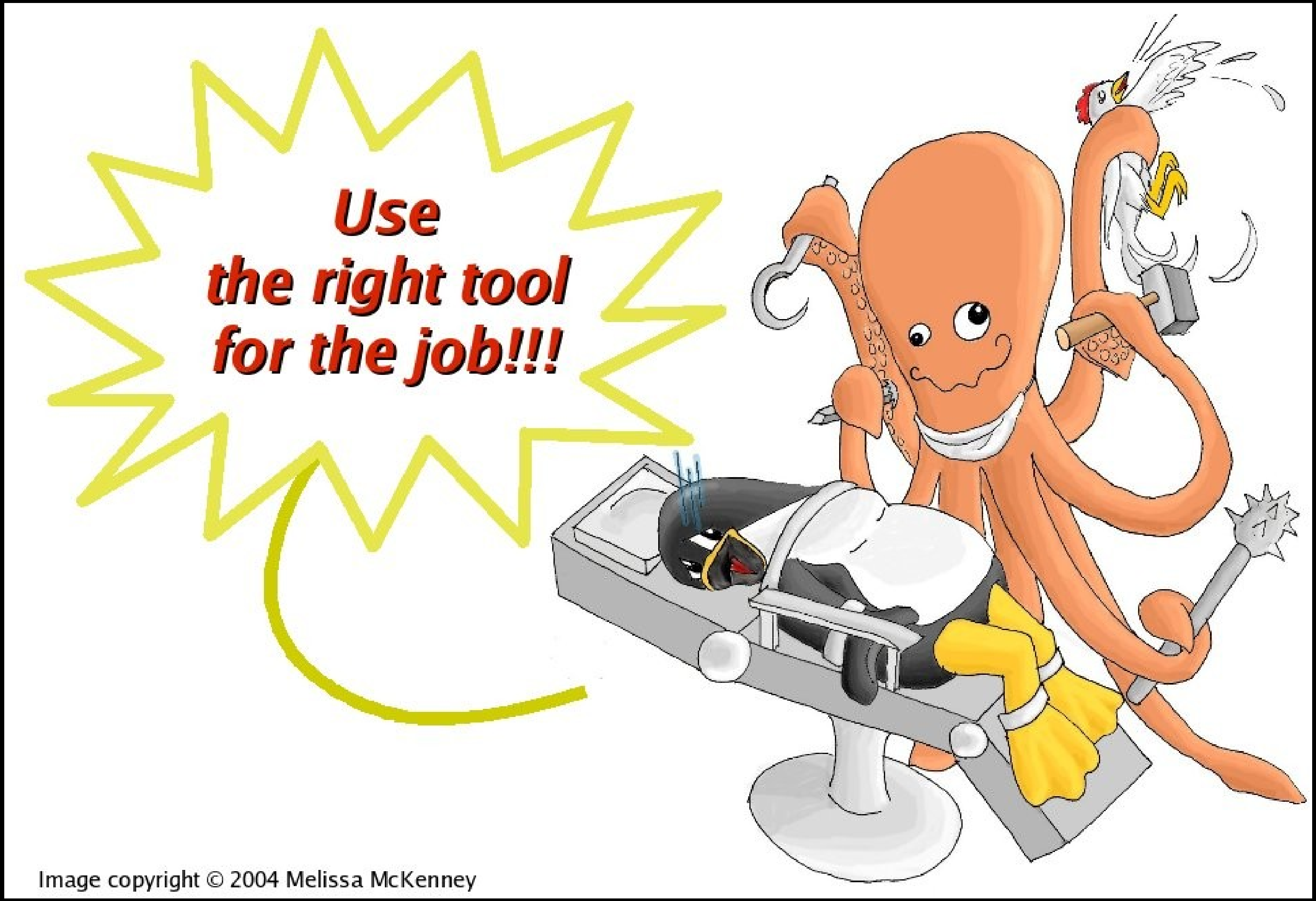
Questions?


Use
the right tool
for the job!!!
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