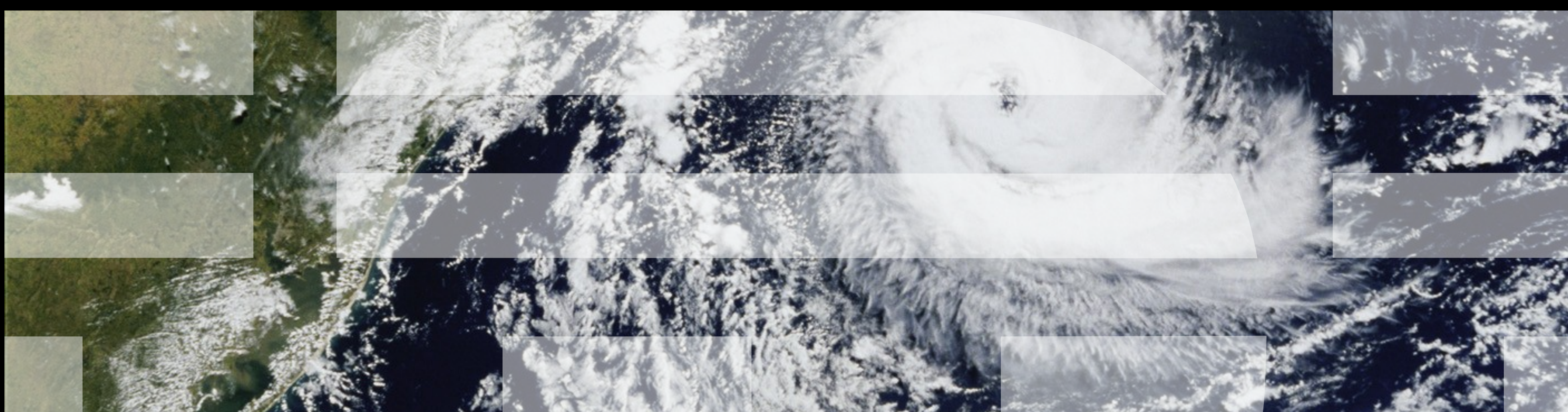
Paul E. McKenney, IBM Distinguished Engineer, Linux Technology Center

3 June 2013

# What Is RCU?

*Distributed OS Lecture, TU Dresden*



# Overview

- Mutual Exclusion
- Example Application
- Performance of Synchronization Mechanisms
- Making Software Live With Current (and Future) Hardware
- Implementing RCU
- RCU Grace Periods: Conceptual and Graphical Views
- Performance
- RCU Area of Applicability
- Summary

# Mutual Exclusion

# Mutual Exclusion

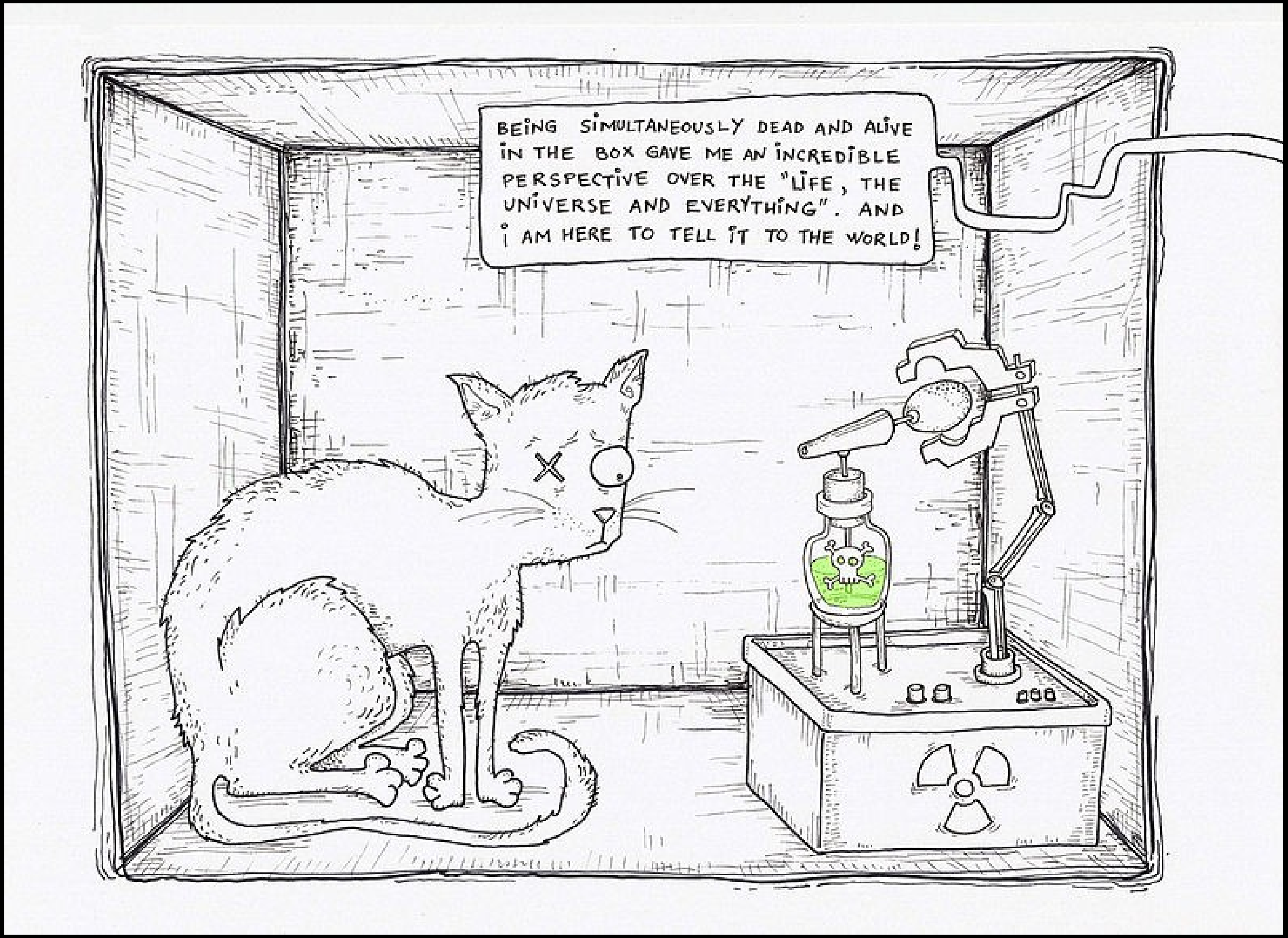
- “We simply do not have a synchronization mechanism that can enforce mutual exclusion”
- True or false?

# Example Application

# Example Application

- Schrödinger wants to construct an in-memory database for the animals in his zoo (example in upcoming ACM Queue)
  - 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?)

# Example Application: Schrödinger's Cat



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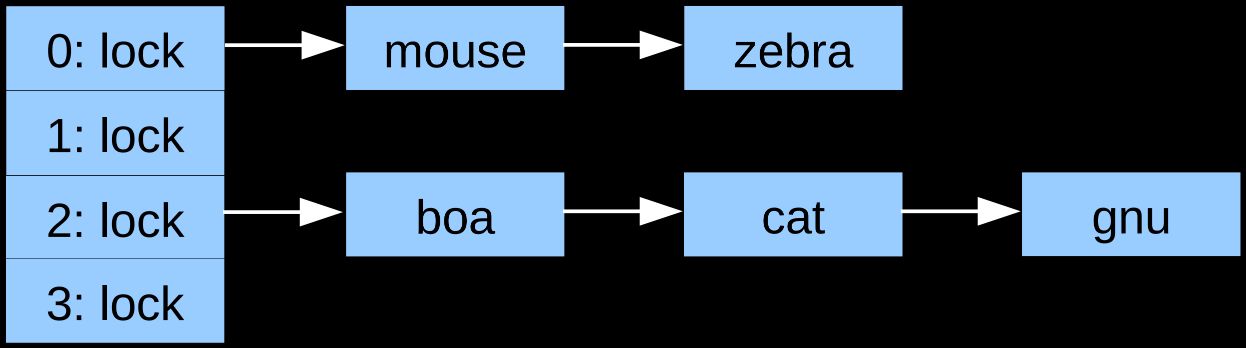
- Simple approach: chained hash table with per-bucket locking



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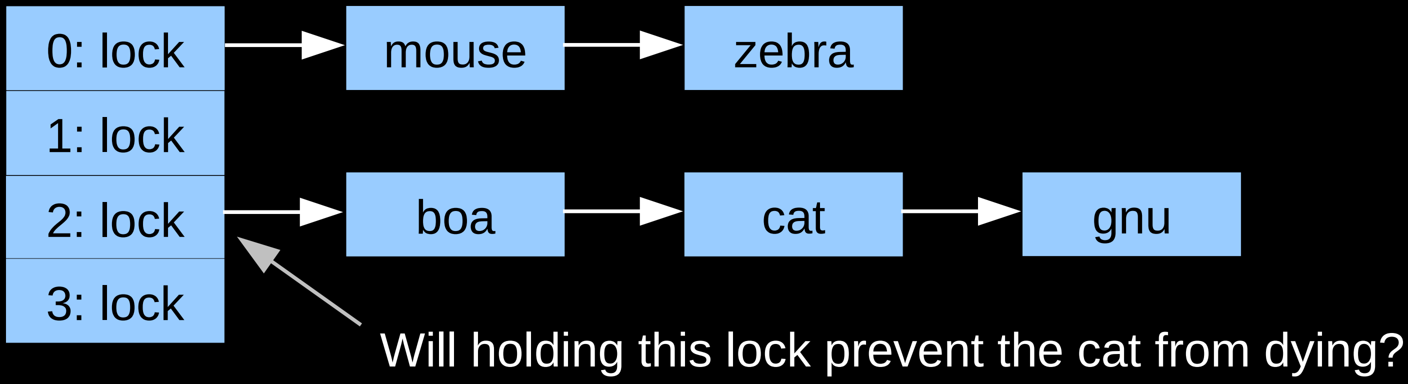
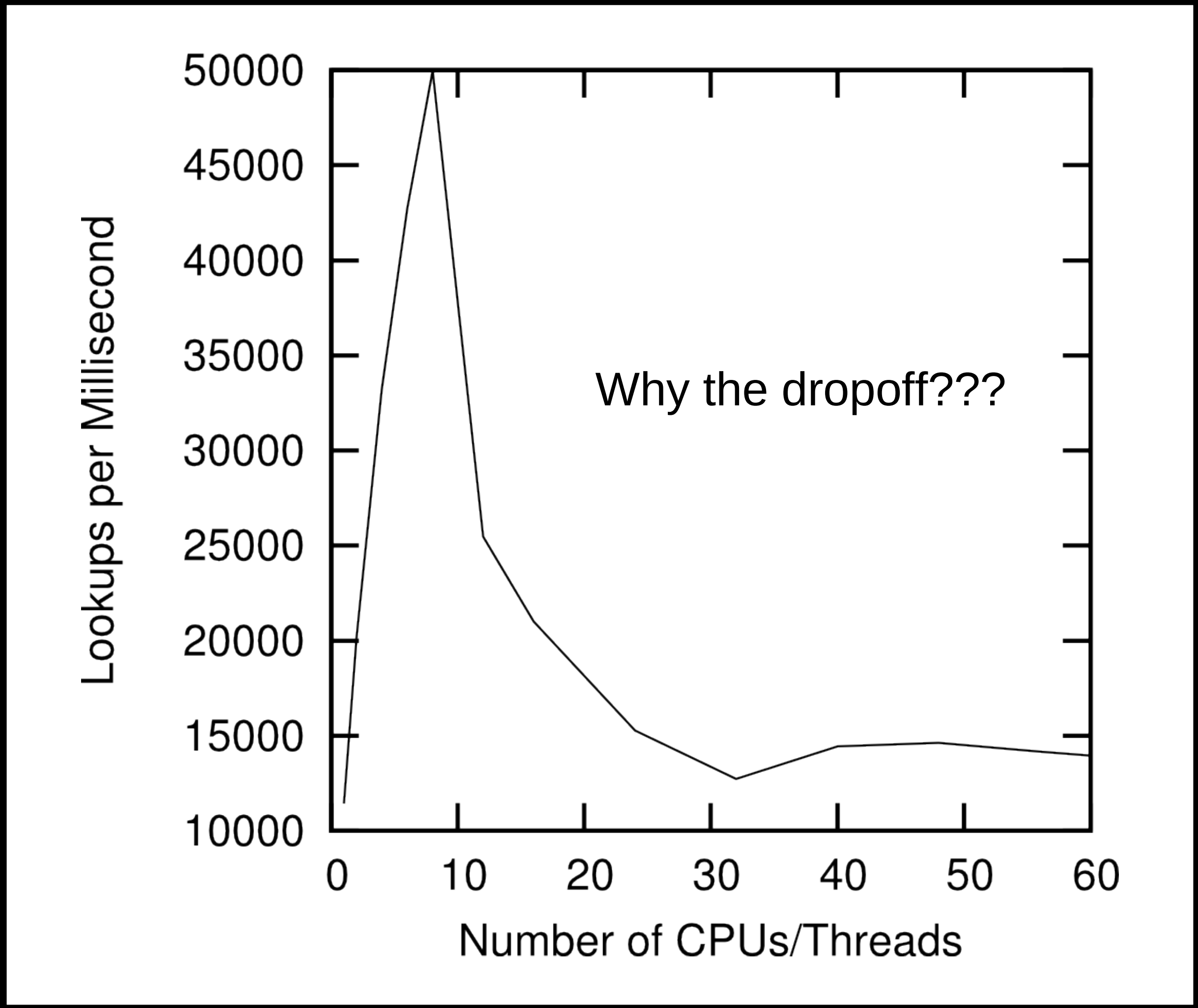
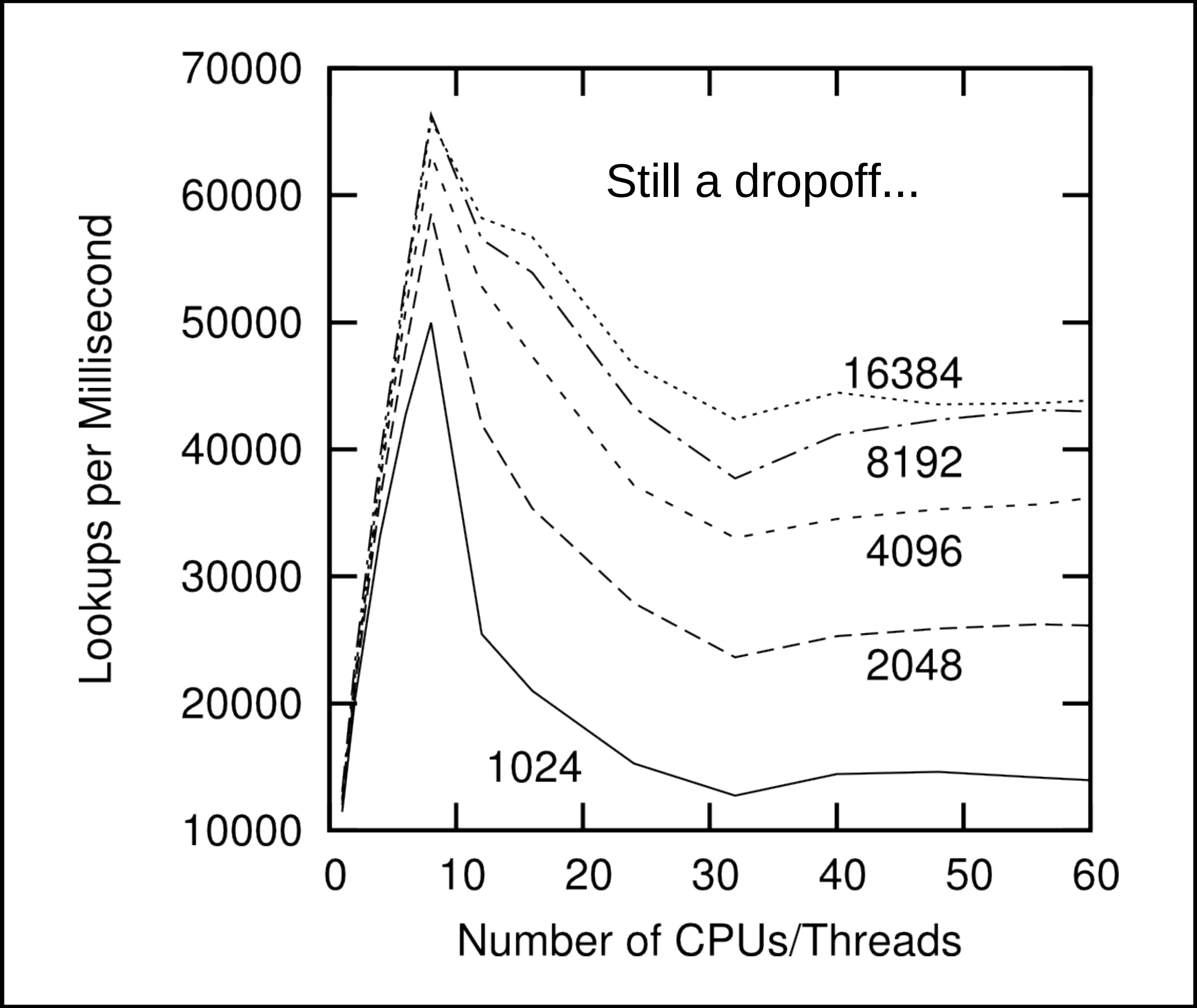


# Read-Only Bucket-Locked Hash Table Performance




2GHz Intel Xeon Westmere-EX, 1024 hash buckets

# Varying Number of Hash Buckets

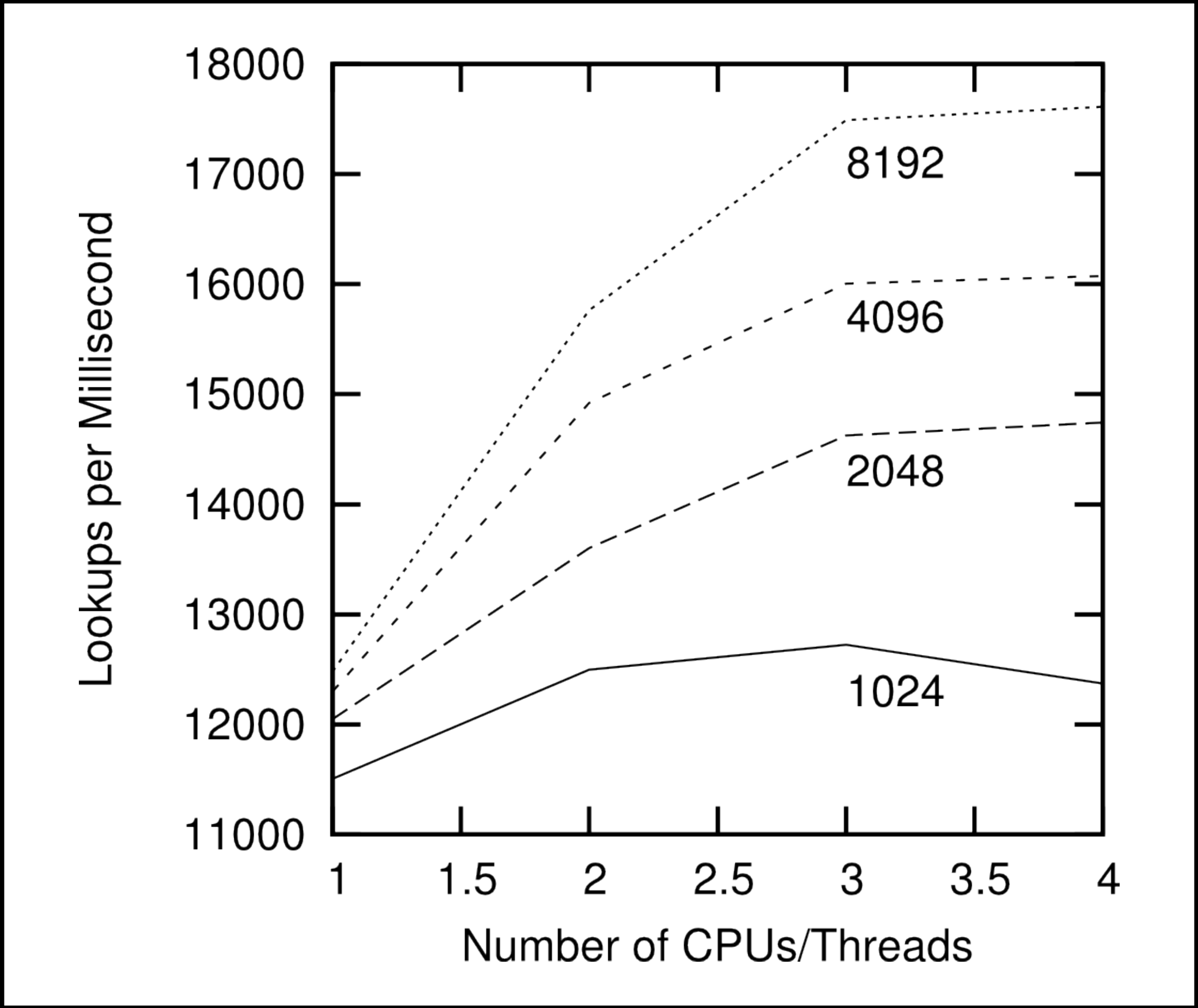



2GHz Intel Xeon Westmere-EX

# 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

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**16-CPU 2.8GHz Intel X5550 (Nehalem) System**

| Operation | Cost (ns) | Ratio |
|---|---|---|
| Clock period | 0.4 | 1 |
| “Best-case” CAS | 12.2 | 33.8 |
| Best-case lock | 25.6 | 71.2 |
| Single cache miss | 12.9 | 35.8 |
| CAS cache miss | 7.0 | 19.4 |
| Single cache miss **(off-core)** | 31.2 | 86.6 |
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| Single cache miss **(off-socket)** | 92.4 | 256.7 |
| CAS cache miss **(off-socket)** | 95.9 | 266.4 |

**And these are best-case values!!! (Why?)**

# Why All These Low-Level Details???

- Would you trust a bridge designed by someone who did not understand strengths of materials?
  - Or a ship designed by someone who did not understand the steel-alloy transition temperatures?
  - Or a house designed by someone who did not understand that unfinished wood rots when wet?
  - Or a car designed by someone who did not understand the corrosion properties of the metals used in the exhaust system?
  - Or a space shuttle designed by someone who did not understand the temperature limitations of O-rings?

- So why trust algorithms from someone ignorant of the properties of the underlying hardware???

# But What Do The Operation Timings Really Mean???

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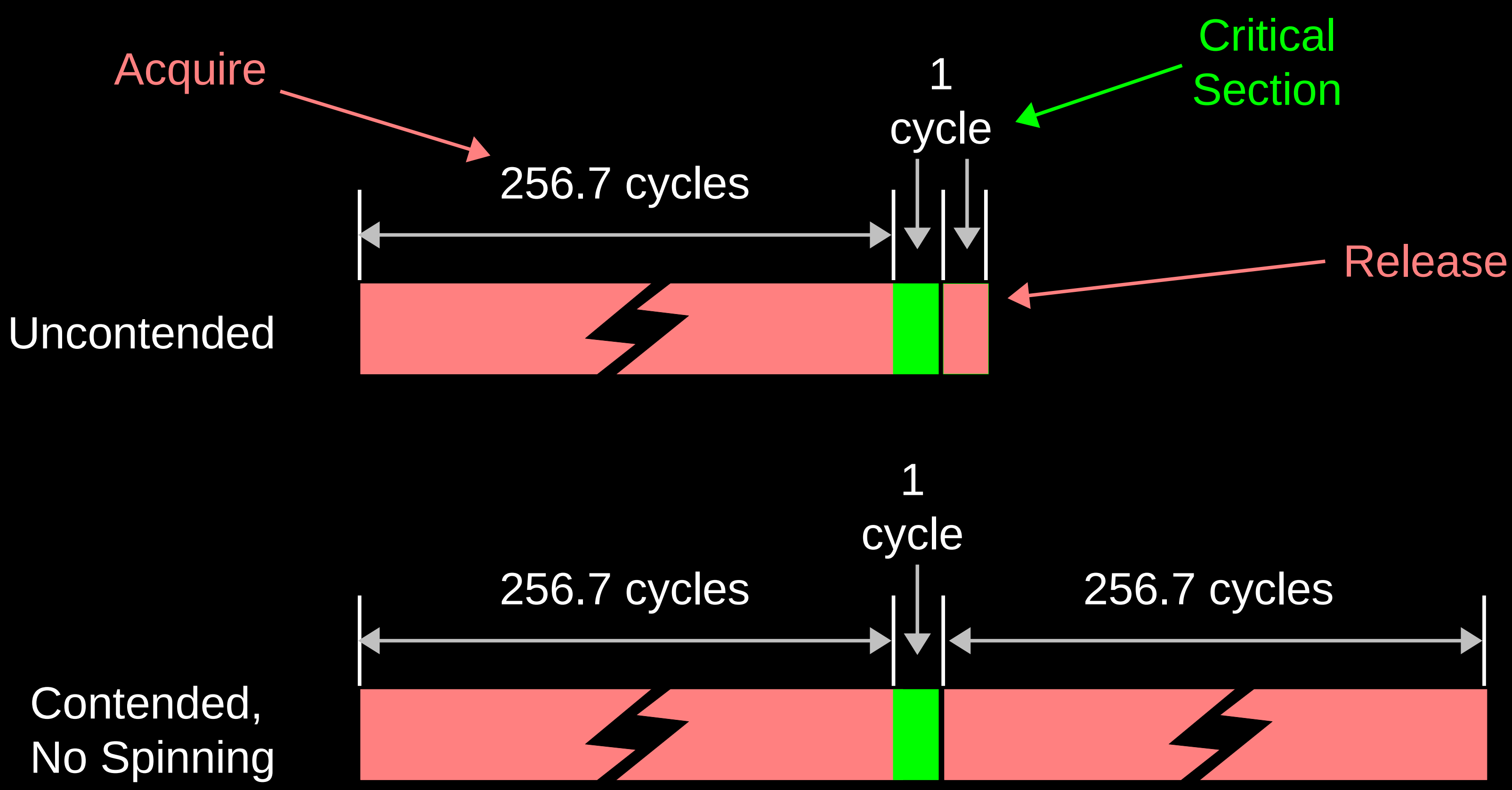
- Single-instruction critical sections protected by multiple locks




So, what *does* this mean?

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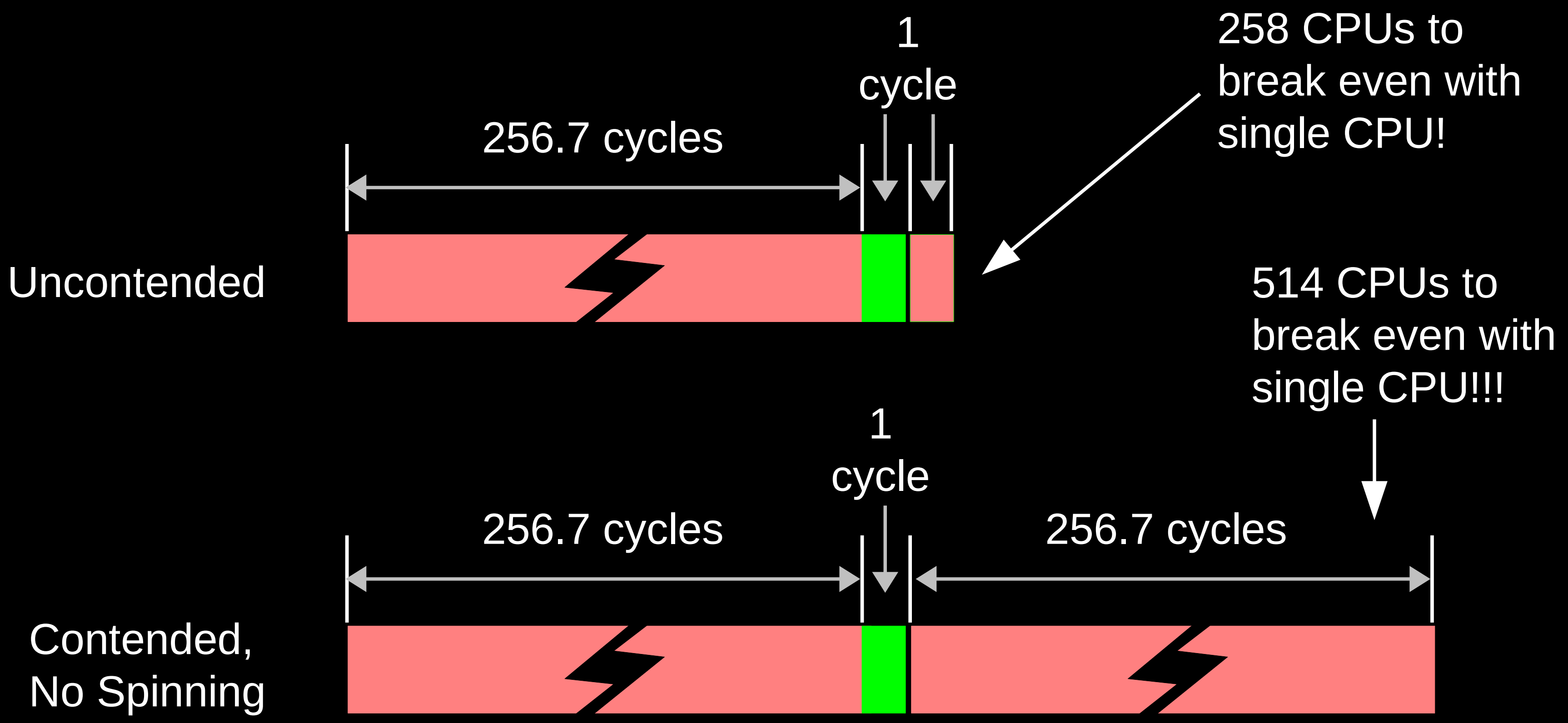

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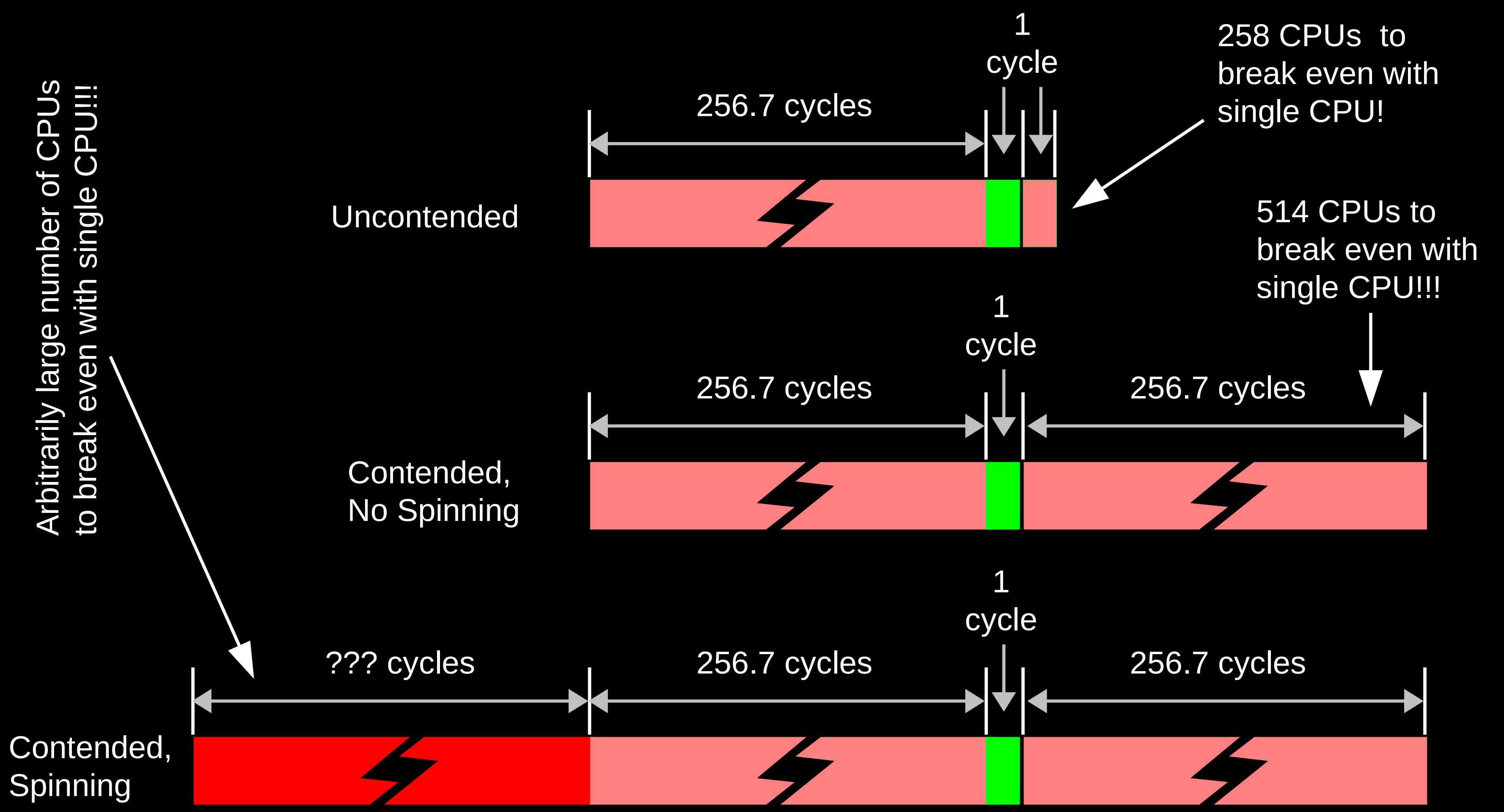

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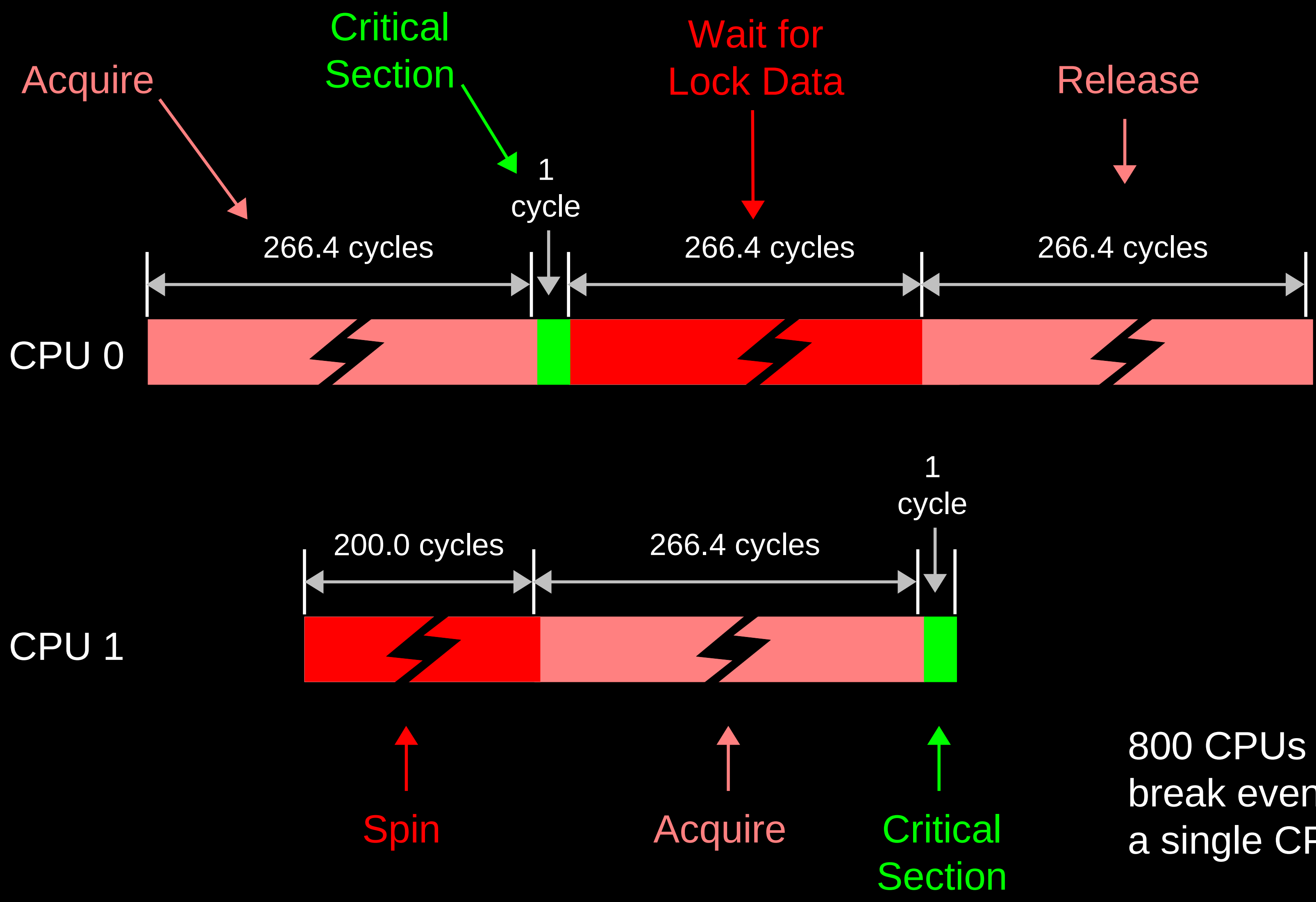
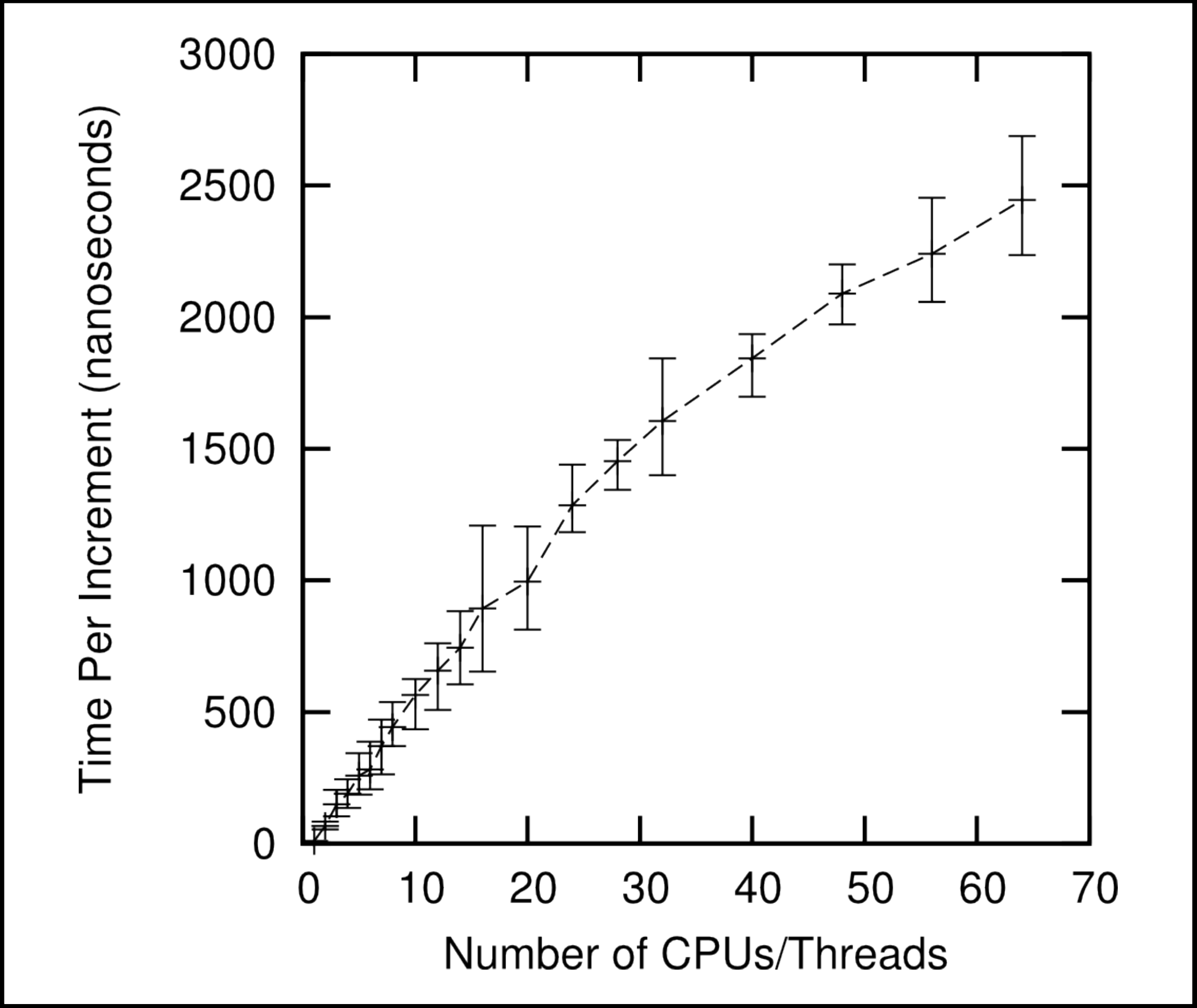



800 CPUs to break even with a single CPU!!!

# But What About Scaling With Atomic Operations?

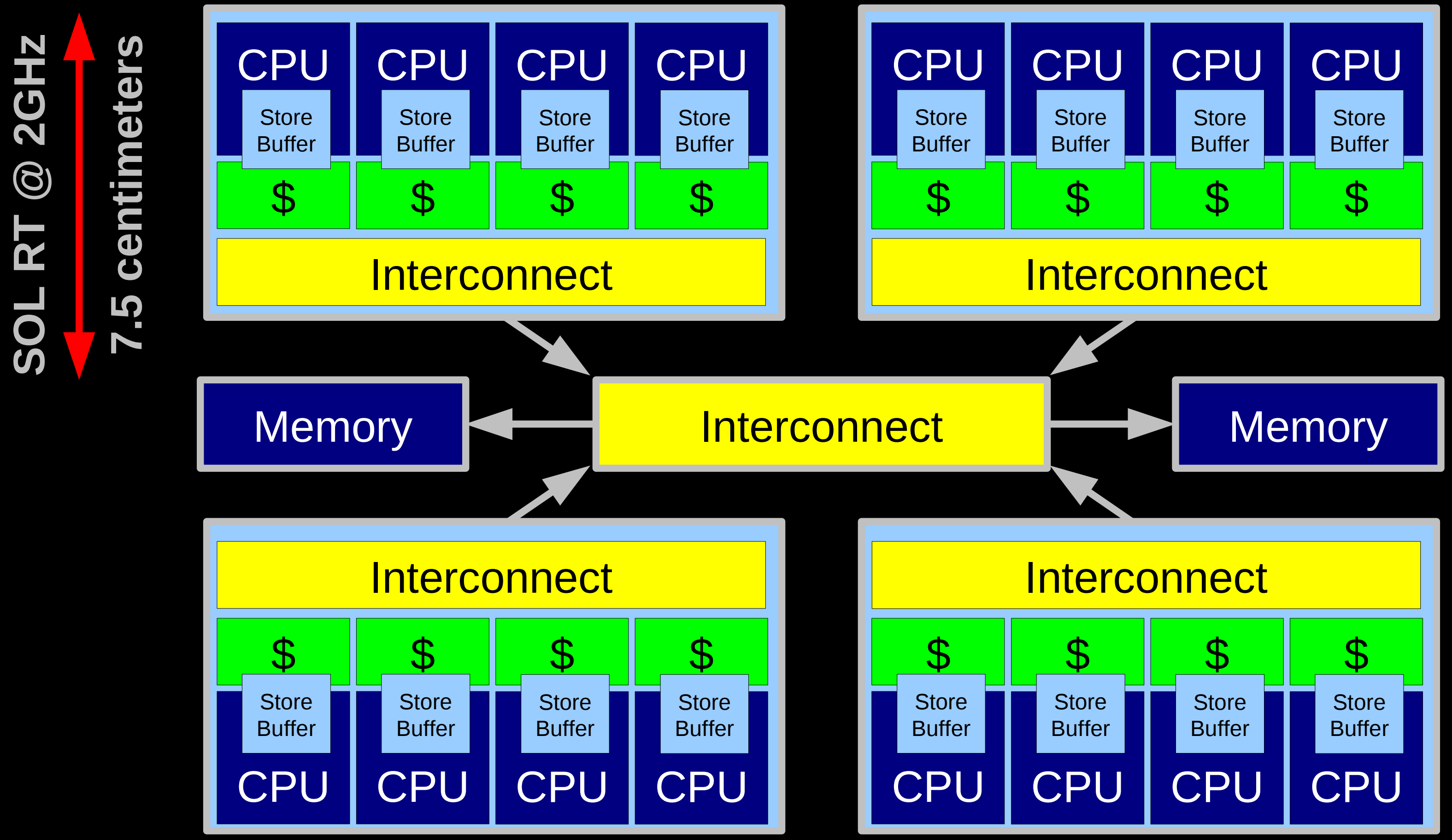
# If You Think Single Atomic is Expensive, Try Lots!!!




2GHz Intel Xeon Westmere-EX

# Why So Slow???

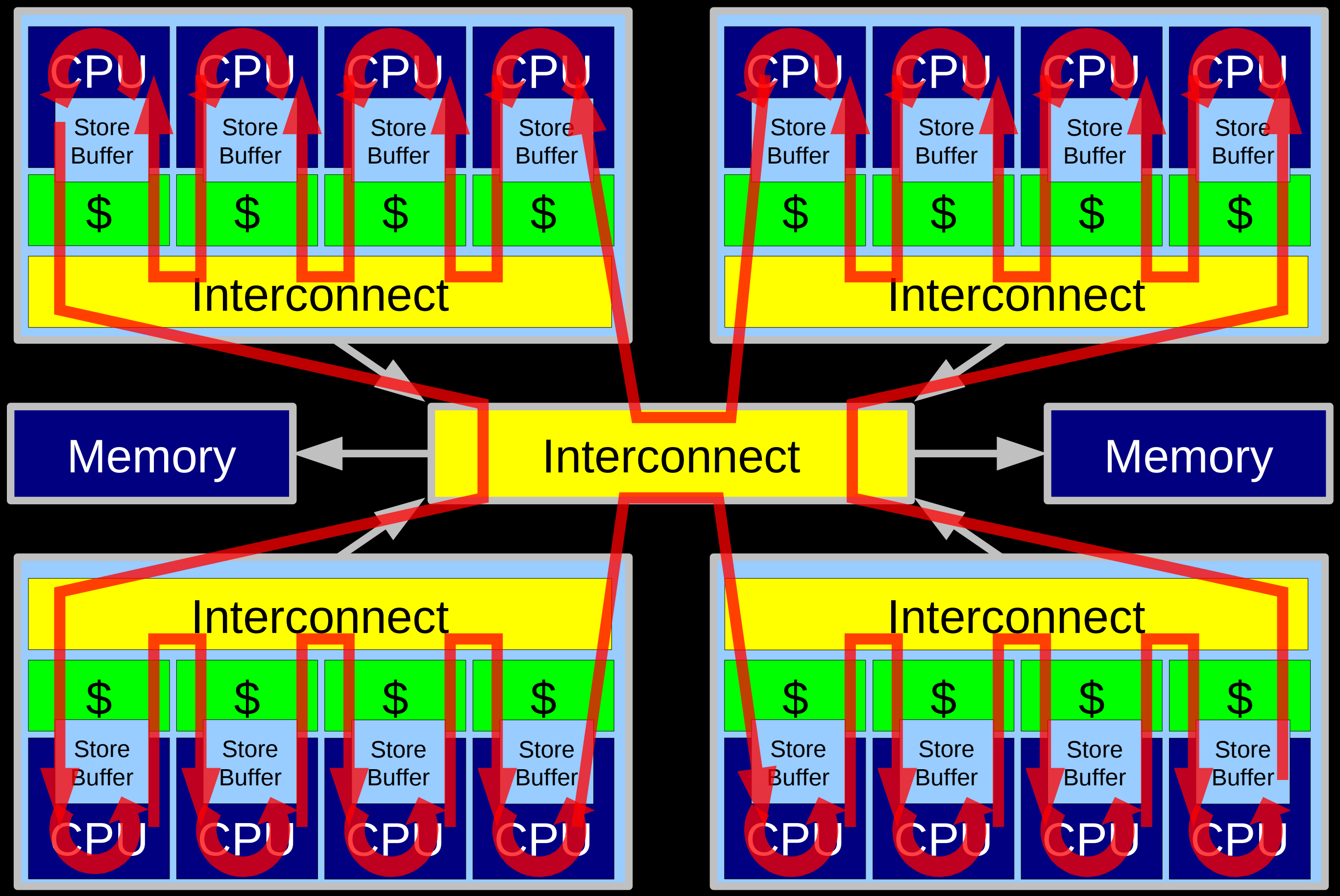
# System Hardware Structure and Laws of Physics




**Electrons move at 0.03C to 0.3C in transistors and, so lots of waiting. 3D???**

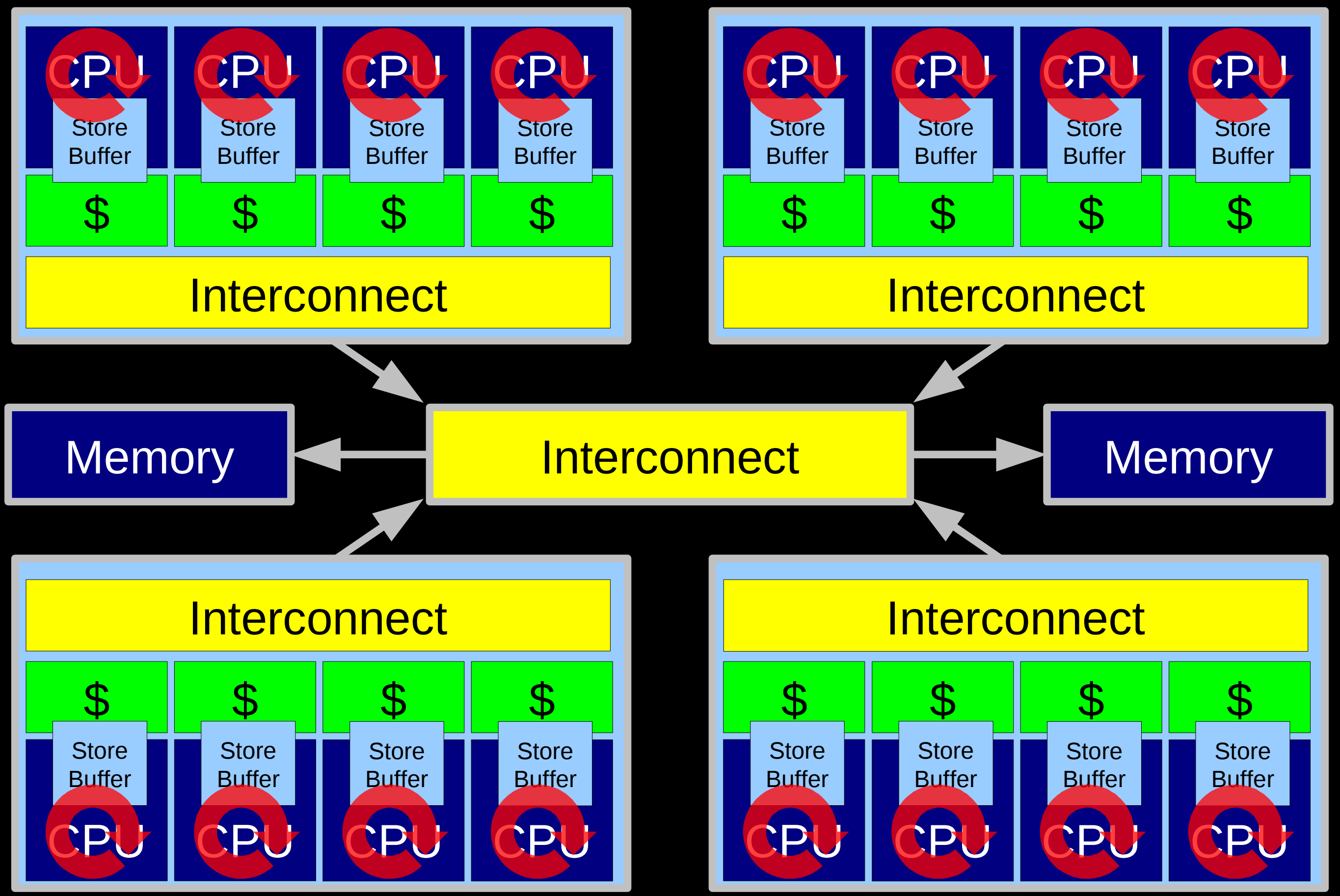
IBM

# Atomic Increment of Global Variable




Lots and Lots of Latency!!!

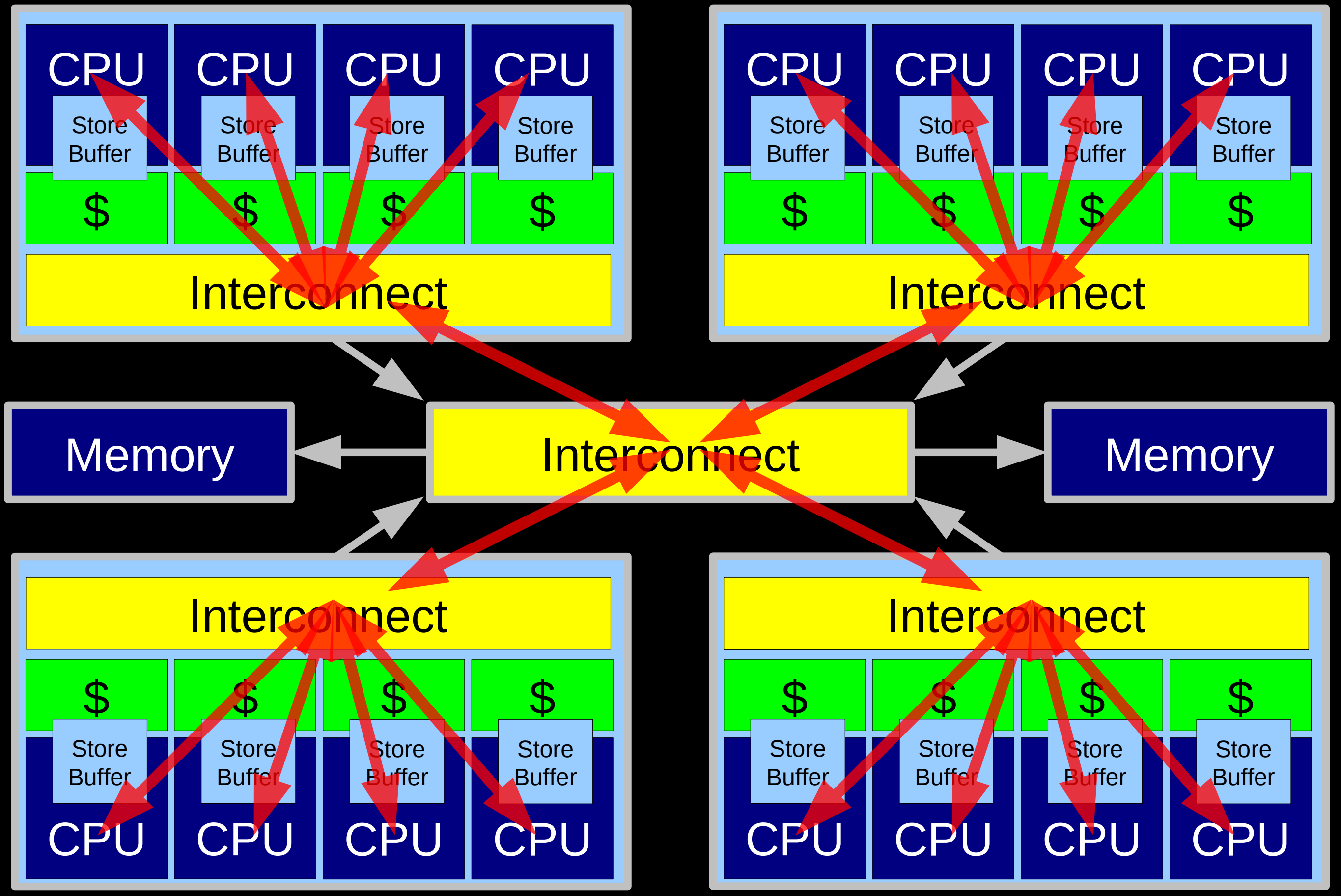
# Atomic Increment of Per-CPU Counter




Little Latency, Lots of Increments at Core Clock Rate

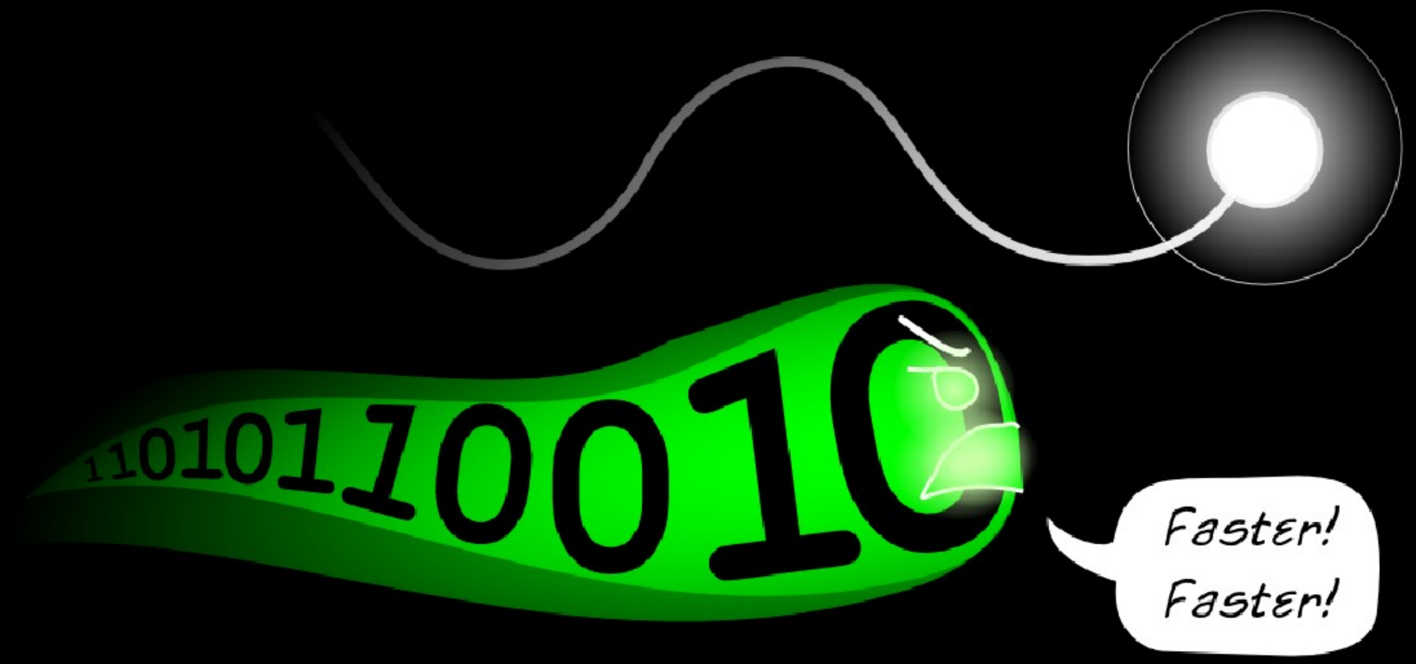
# Can't The Hardware Do Better Than This???

# HW-Assist Atomic Increment of Global Variable

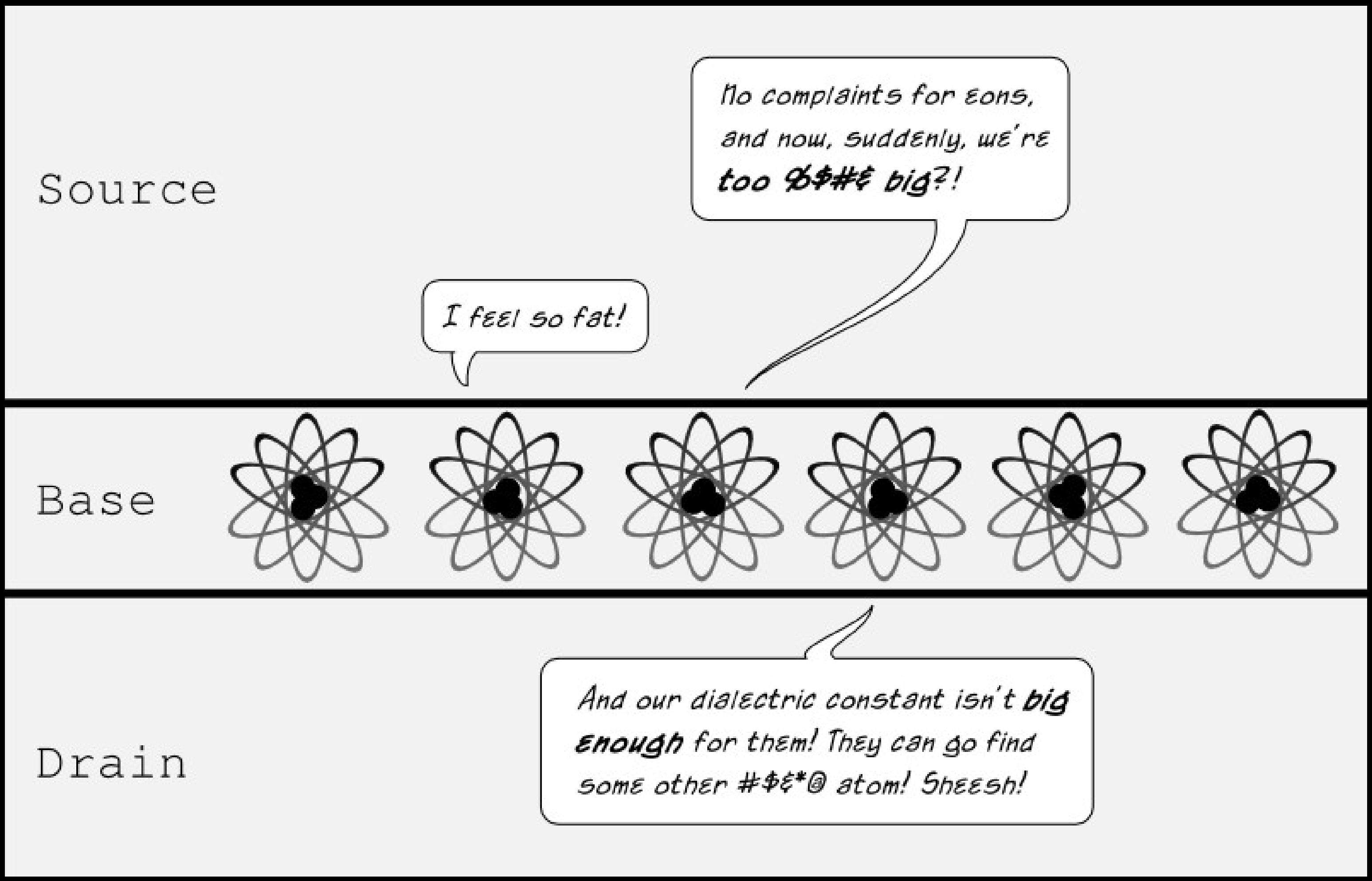



SGI systems used this approach in the 1990s, expect modern micros to pick it up.
Still not as good as per-CPU counters.

# Problem With Physics #1: Finite Speed of Light

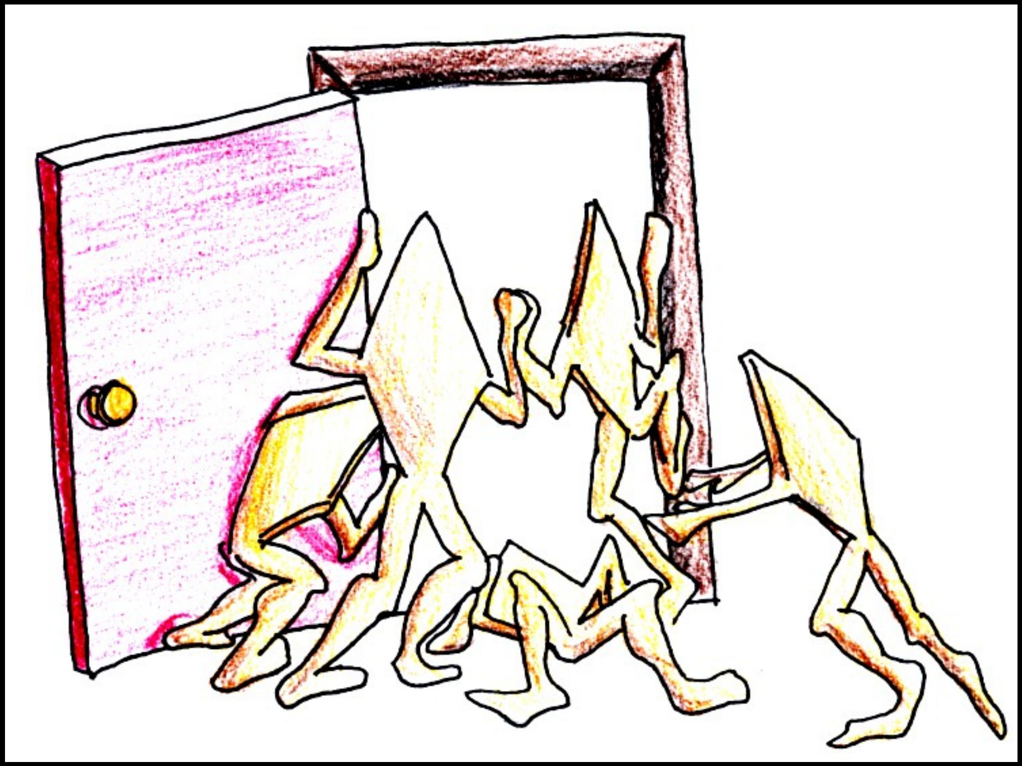


# Problem With Physics #2: Atomic Nature of Matter



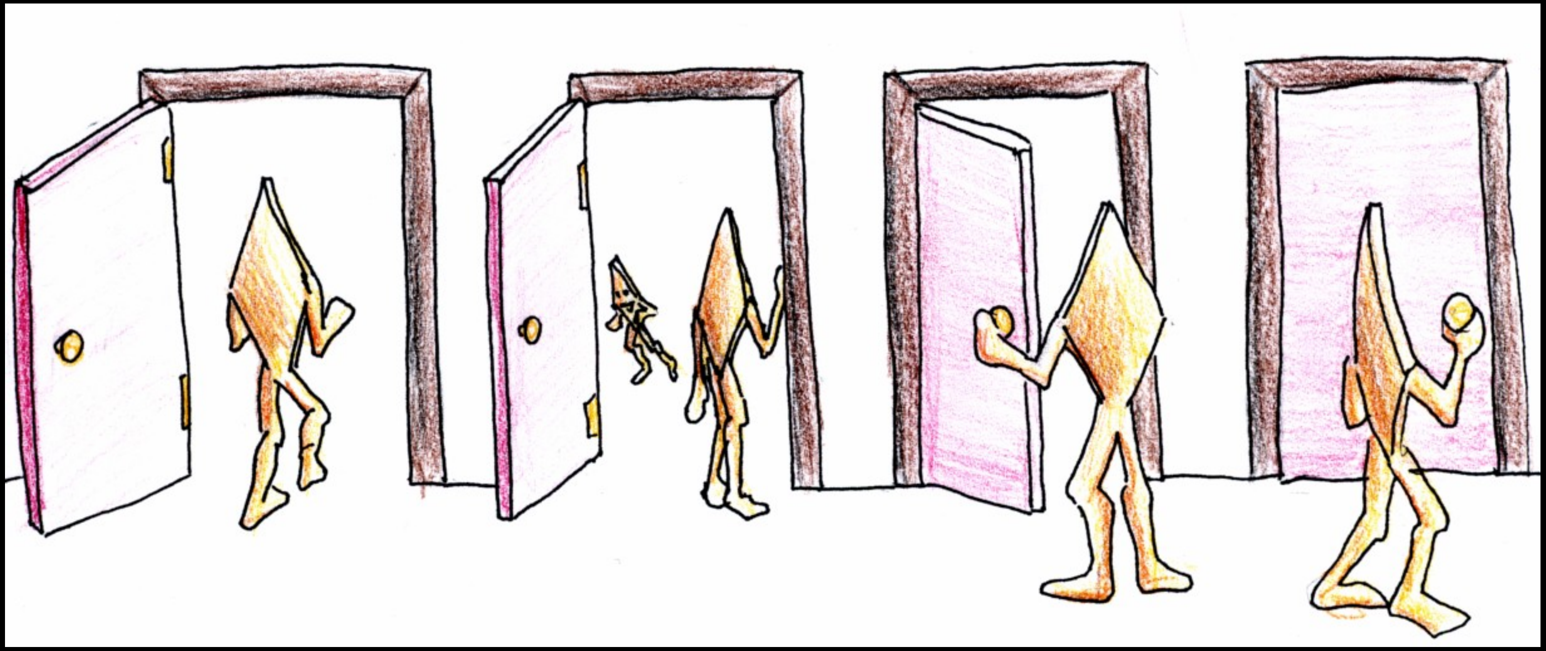
# How Can Software Live With This Hardware???

# 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!**
**Avoiding tightly coupled interactions is an excellent way to avoid bugs.**
**But NUMA effects defeated this for per-bucket locking!!!**

# Design Principle: Avoid Expensive Operations

Need to be here! (Partitioning/RCU)

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| Clock period | 0.4 | 1 |
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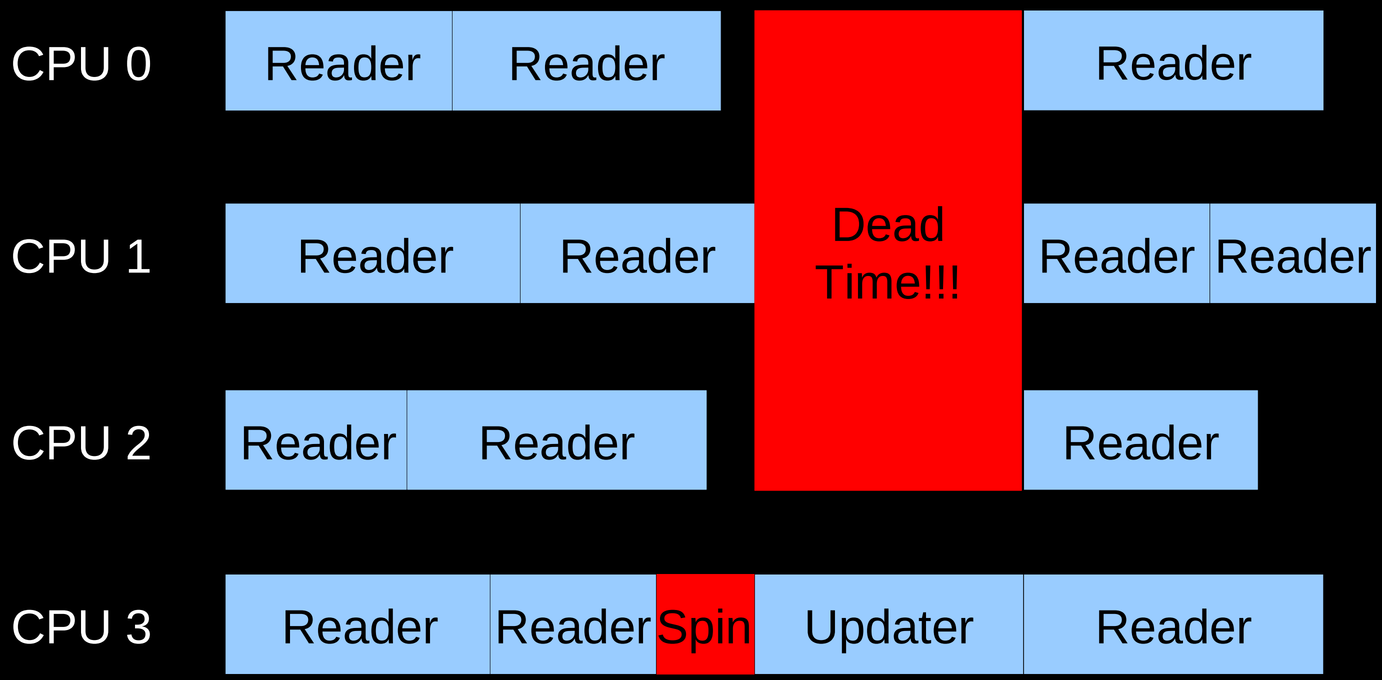
Heavily optimized reader-writer lock might get here for readers (but too bad about those poor writers...)

Typical synchronization mechanisms do this a lot

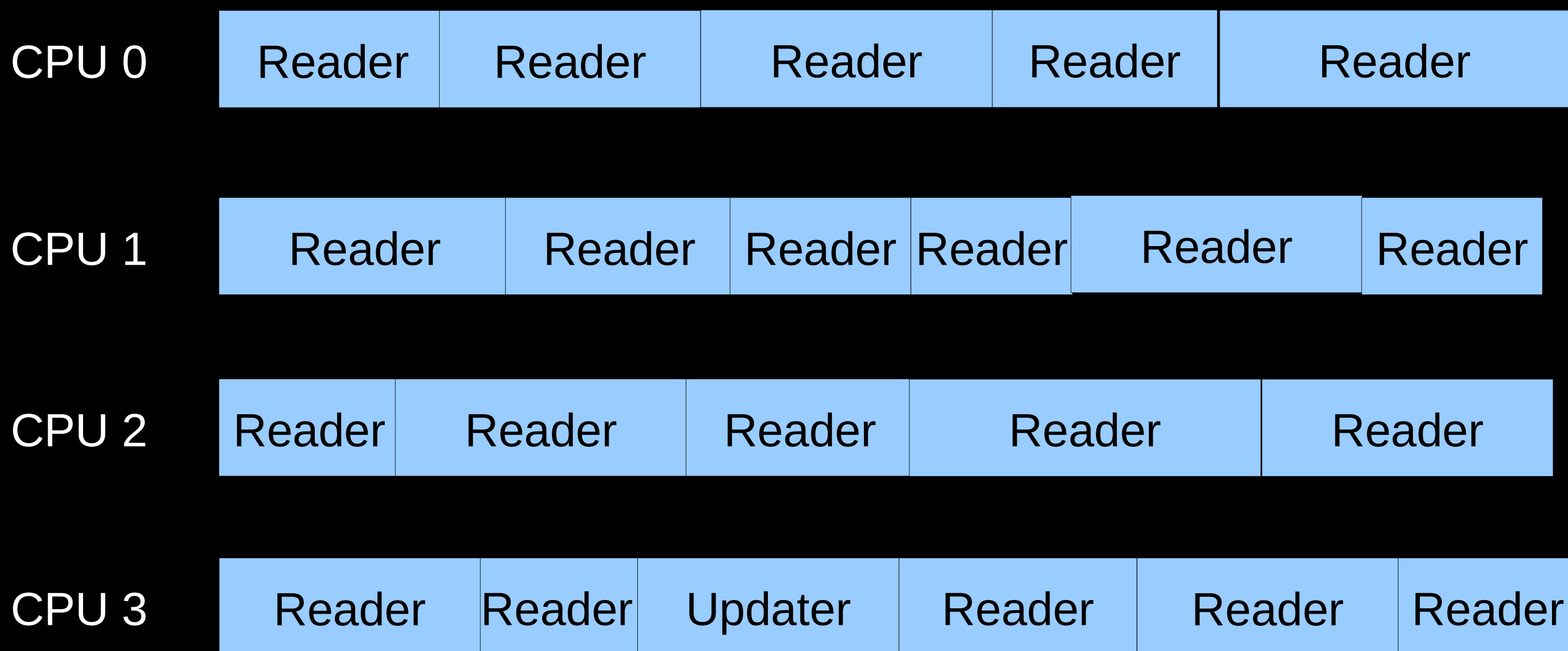
# Design Principle: Get Your Money's Worth

- If synchronization is expensive, use large critical sections
- On Nehalem, off-socket CAS costs about 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!

# Design Principle: Avoid Mutual Exclusion!!!



# Design Principle: Avoiding Mutual Exclusion




**No Dead Time!**

# But How Can This Possibly Be Implemented???

# Implementing RCU

- Lightest-weight conceivable read-side primitives

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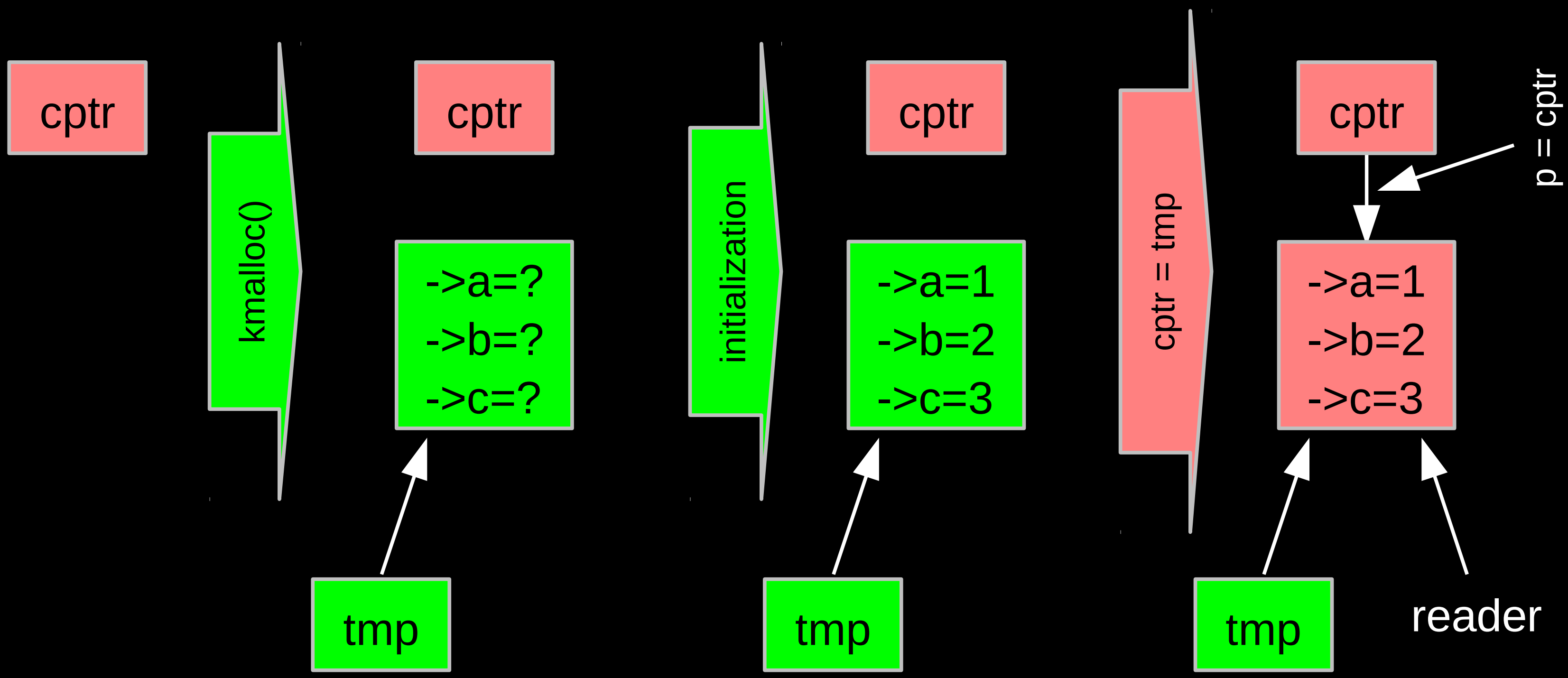
- Best possible performance, scalability, real-time response, wait-freedom, and energy efficiency
- But how can these possibly be useful???
- How can something that does not affect machine state be used as a synchronization primitive???

# What Is RCU?

- Publishing of new data
- Subscribing to the current version of data
- Waiting for pre-existing RCU readers: Avoid disrupting readers by maintaining multiple versions of the data
  - Each *read*er continues traversing its *copy* of the data while a new *copy* might be being created concurrently by each *update*r
    - Hence the name *read-copy update*, or RCU
  - Once all pre-existing RCU readers are done with them, old versions of the data may be discarded

# 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



# Memory Ordering: Mischief From Compiler and CPU

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- Original updater code:

```
p = malloc(sizeof(*p));
p->a = 1;
p->b = 2;
p->c = 3;
cptr = p;
```

- Original reader code:

```
p = cptr;
foo(p->a, p->b, p->c);
```

- Mischievous updater code:

```
p = malloc(sizeof(*p));
cptr = p;
p->a = 1;
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- Mischievous reader code:

```
retry:
p = guess(cptr);
foo(p->a, p->b, p->c);
if (p != cptr)
    goto retry;
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But don't take *my* word for it on HW value speculation:
http://www.openvms.compaq.com/wizard/wiz_2637.html

# Preventing Memory-Order Mischief

- Updater uses rcu_assign_pointer() to publish pointer:

```
#define rcu_assign_pointer(p, v) \
({ \
        smp_wmb(); /* SMP Write Memory Barrier */ \
        (p) = (v); \
})
```

- Reader uses rcu_dereference() to subscribe to pointer:

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

- The Linux-kernel definitions are more ornate: Debugging code

# Preventing Memory-Order Mischief

- “Memory-order-mischief proof” updater code:

```
p = malloc(sizeof(*p));
p->a = 1;
p->b = 2;
p->c = 3;
rcu_assign_pointer(cptr, p);
```

- “Memory-order-mischief proof” reader code:

```
p = rcu_dereference(cptr);
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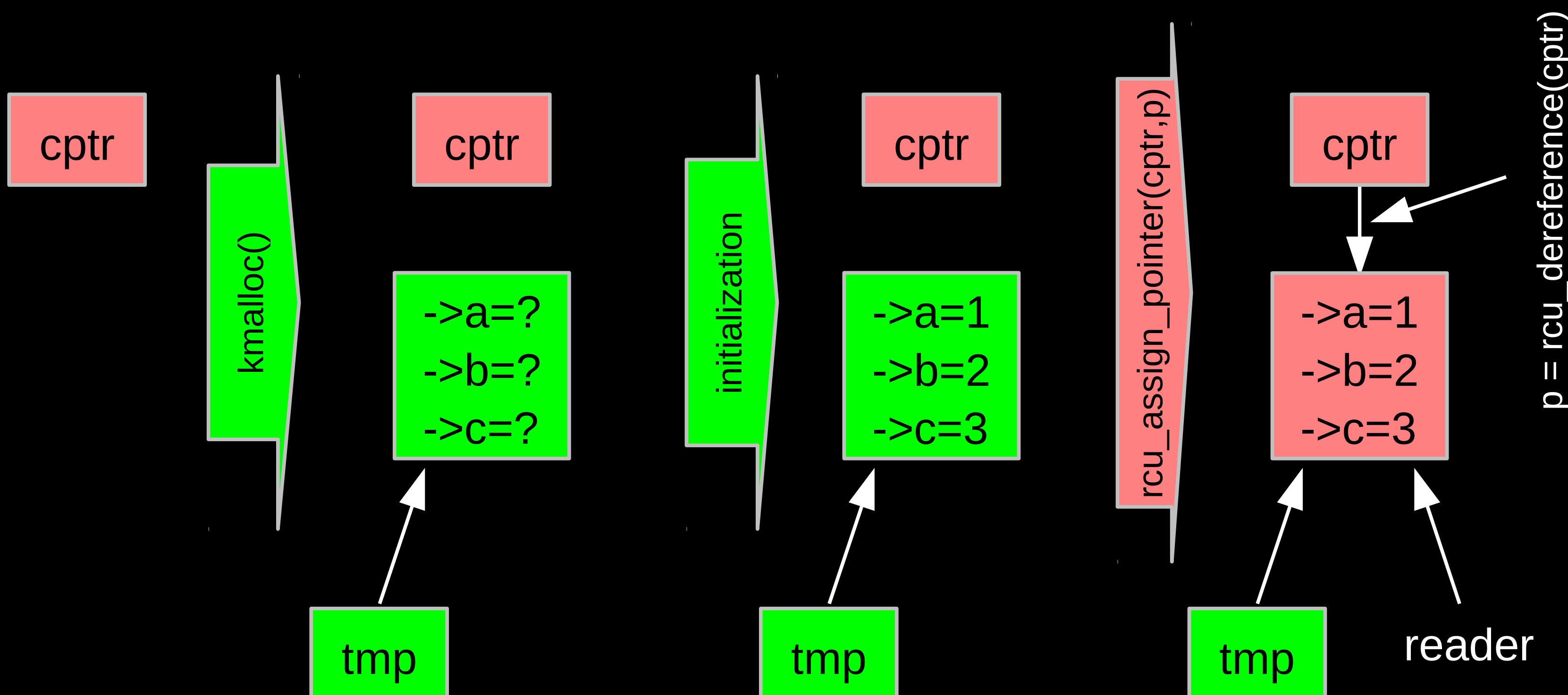
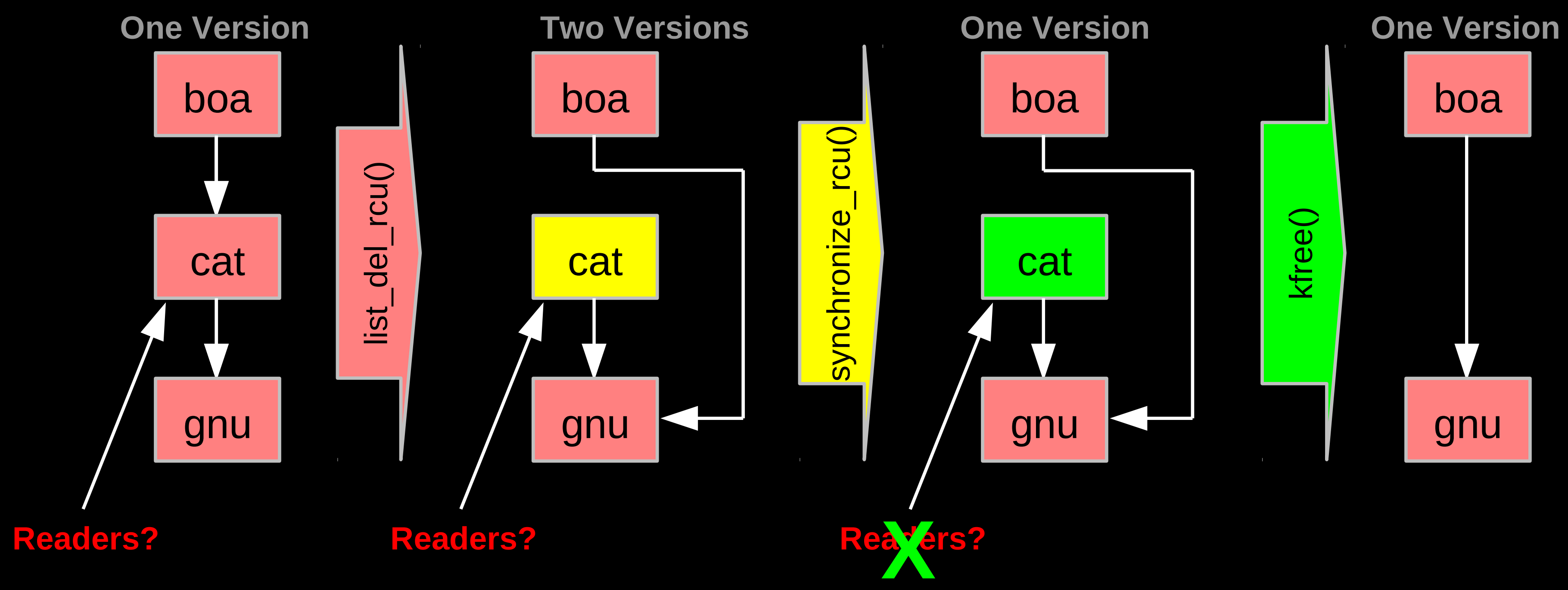



But if all we do is add, we have a big memory leak!!!

# 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())



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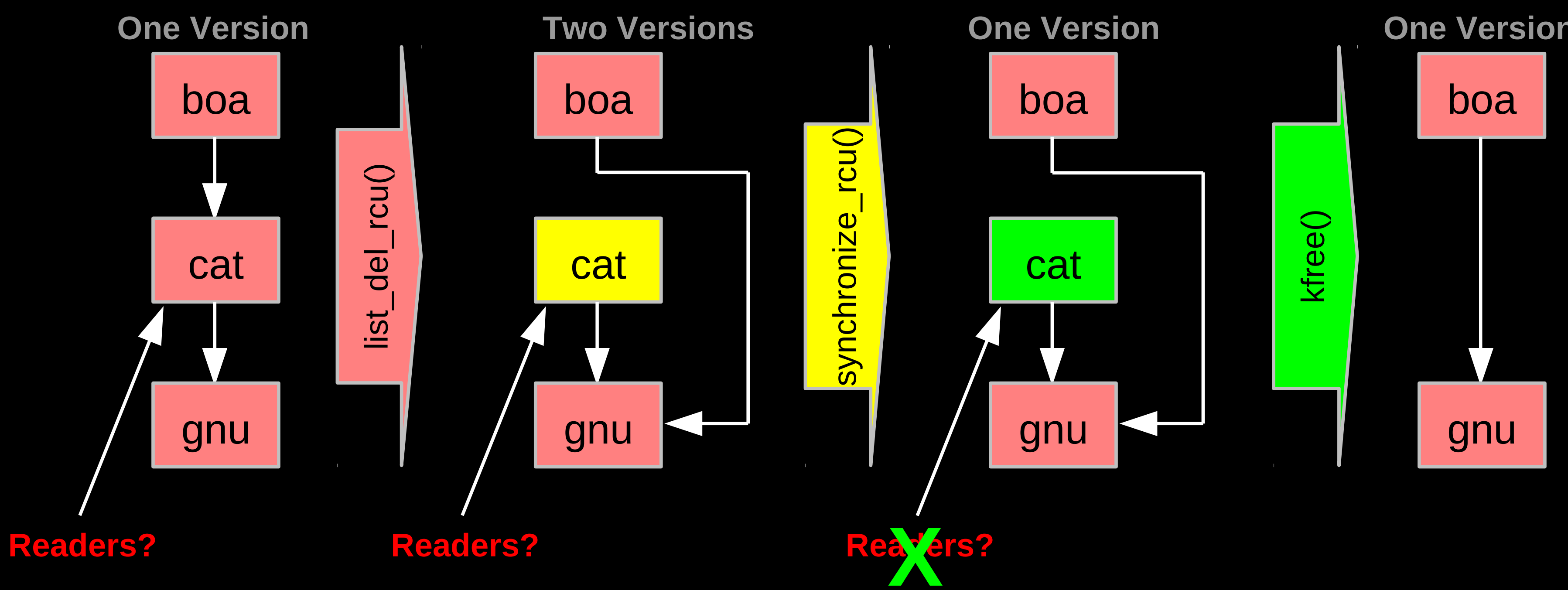


**But if readers leave no trace in memory, how can we possibly tell when they are done???**

# How Can RCU Tell When Readers Are Done???

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**That is, without re-introducing all of the overhead and latency inherent to other synchronization mechanisms...**

# But First, Some RCU Nomenclature

- *RCU read-side critical section*
  - Begins with rcu_read_lock(), ends with rcu_read_unlock(), and may contain rcu_dereference()
- *Quiescent state*
  - Any code that is not in an RCU read-side critical section
- *Extended quiescent state*
  - Quiescent state that persists for a significant time period
- *RCU grace period*
  - Time period when every thread was in at least one quiescent state

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  - Time period when every thread was in at least one quiescent state
- OK, names are nice, but how can you possibly implement this???

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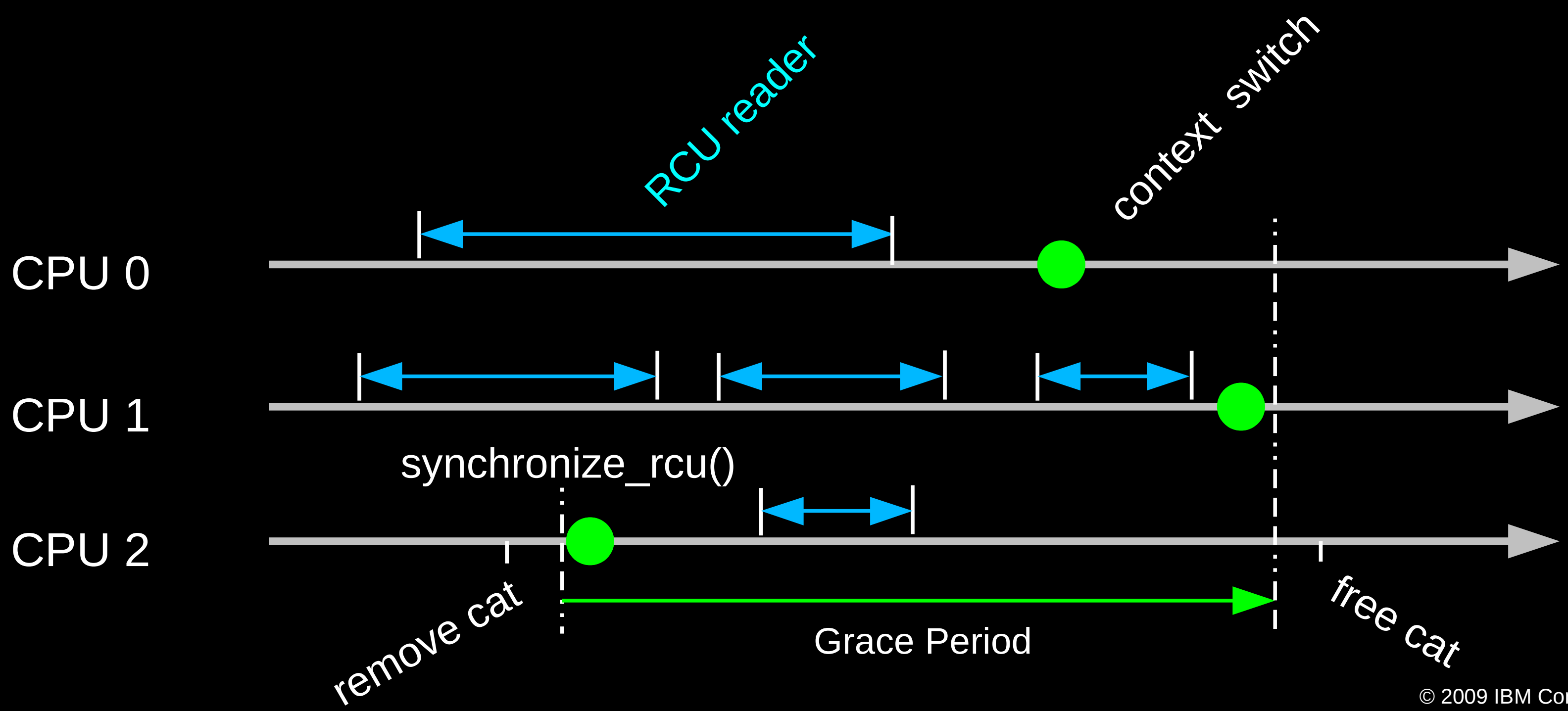
- Non-preemptive environment (CONFIG_PREEMPT=n)
  - RCU readers are not permitted to block
  - Same rule as for tasks holding spinlocks
- CPU context switch means all that CPU's readers are done
- *Grace period* ends after all CPUs execute a context switch



# Synchronization Without Changing Machine State???

- But rcu_read_lock() does not need to change machine state
  - Instead, it acts on the developer, who must avoid blocking within RCU read-side critical sections
  - Or, more generally, avoid quiescent states within RCU read-side critical sections

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  - Instead, it acts on the developer, who must avoid blocking within RCU read-side critical sections
  - Or, more generally, avoid quiescent states within RCU read-side critical sections
- RCU is therefore synchronization via social engineering
- Just as is the case for most synchronization mechanisms
  - “Avoid data races”
  - “Protect specified variables with the corresponding lock”
  - “Access shared variables only within transactions”

# Toy Implementation of RCU: 20 Lines of Code

- 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);
}
```

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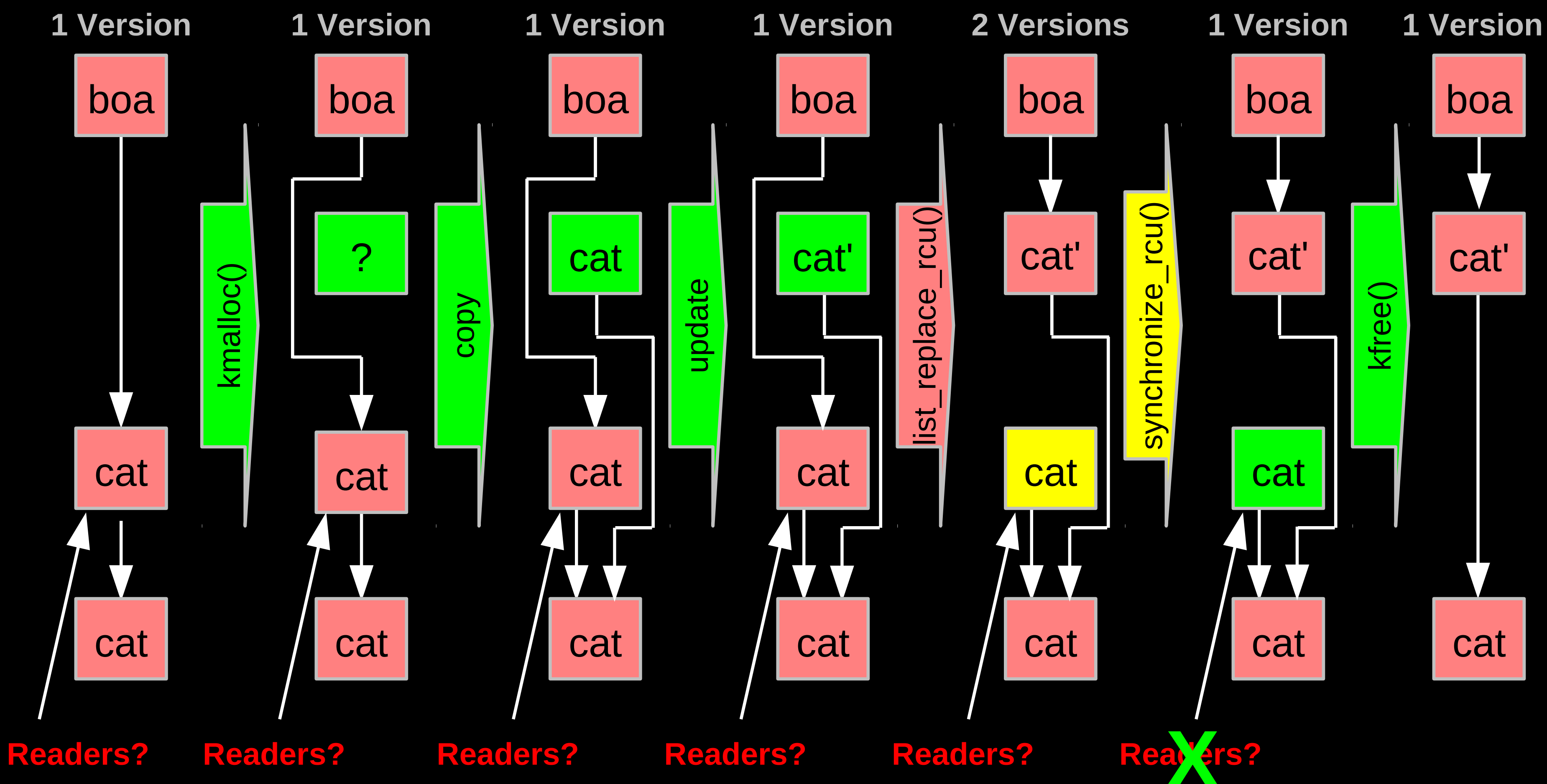
Only 9 of which are needed on SC systems...
And some people still insist that RCU is complicated... ;-)

# Complex Atomic-To-Reader Updates

# RCU Replacement Of Item In Linked List



# RCU Grace Periods: Conceptual and Graphical Views

# RCU Grace Periods: A Conceptual View

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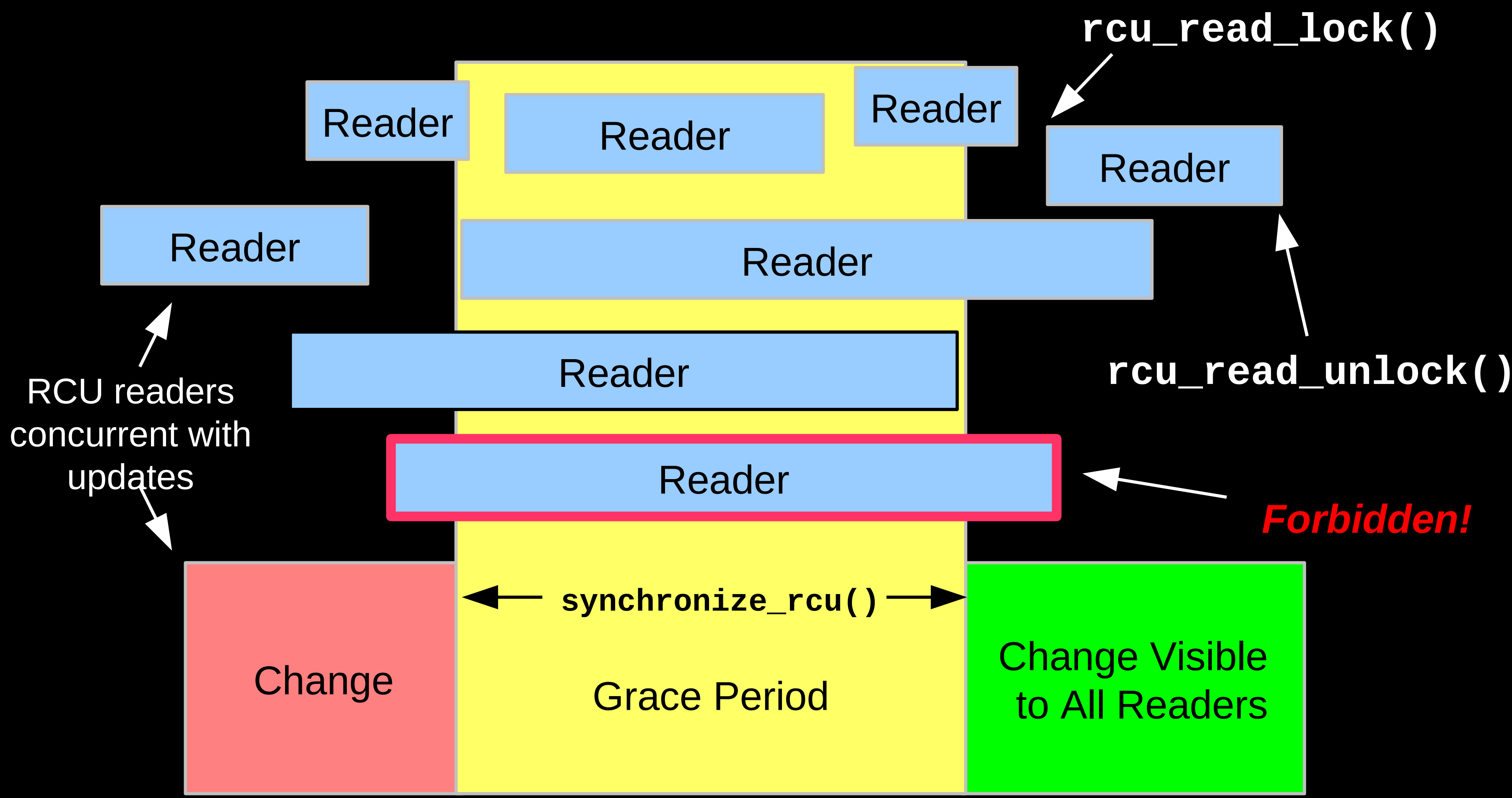
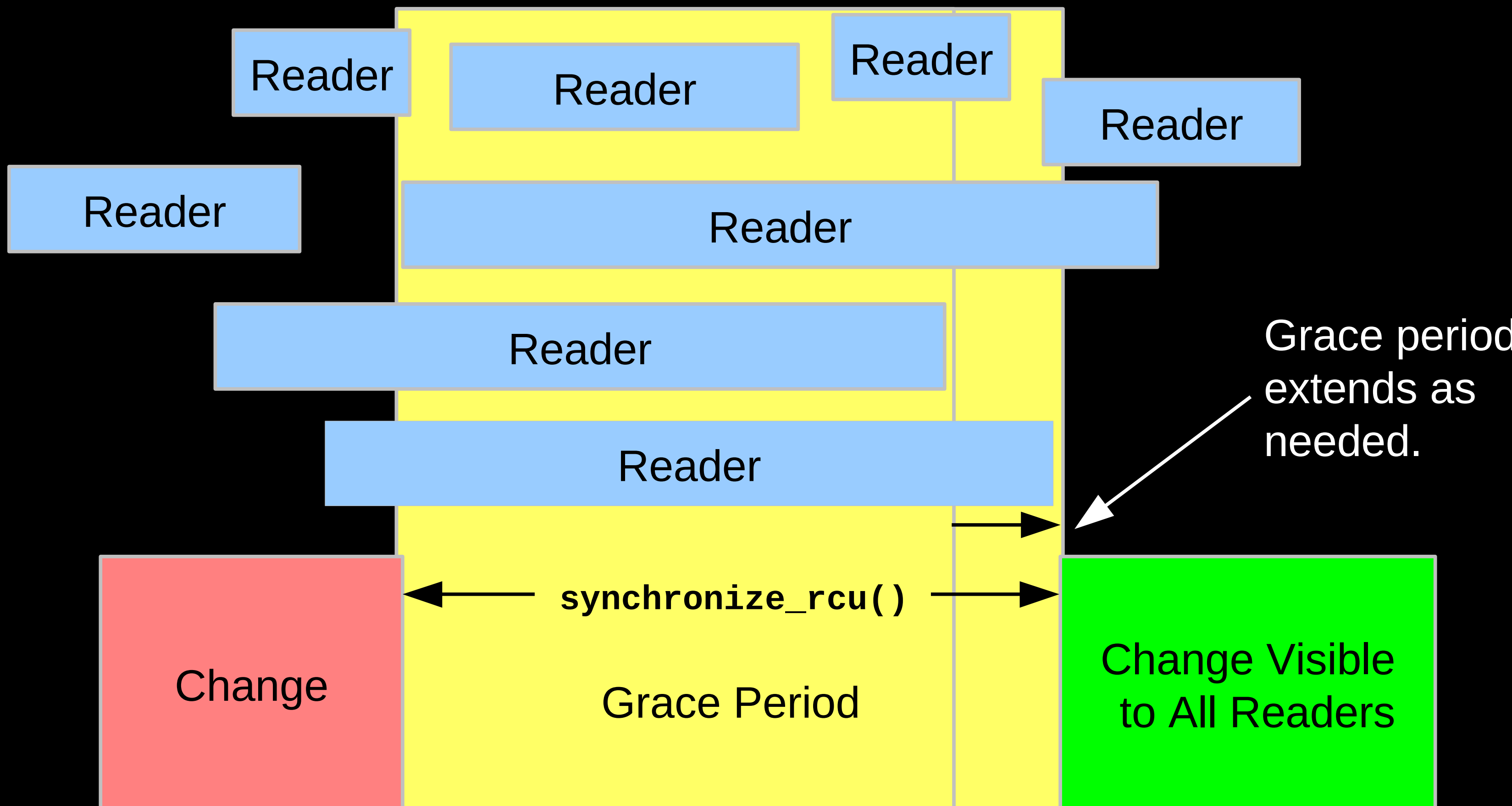
- *RCU grace period*
  - Time period when every thread is in at least one quiescent state
  - Ends when all pre-existing readers complete
  - Guaranteed to complete in finite time iff all RCU read-side critical sections are of finite duration
- But what happens if you try to extend an RCU read-side critical section across a grace period?

# RCU Grace Periods: A Graphical View



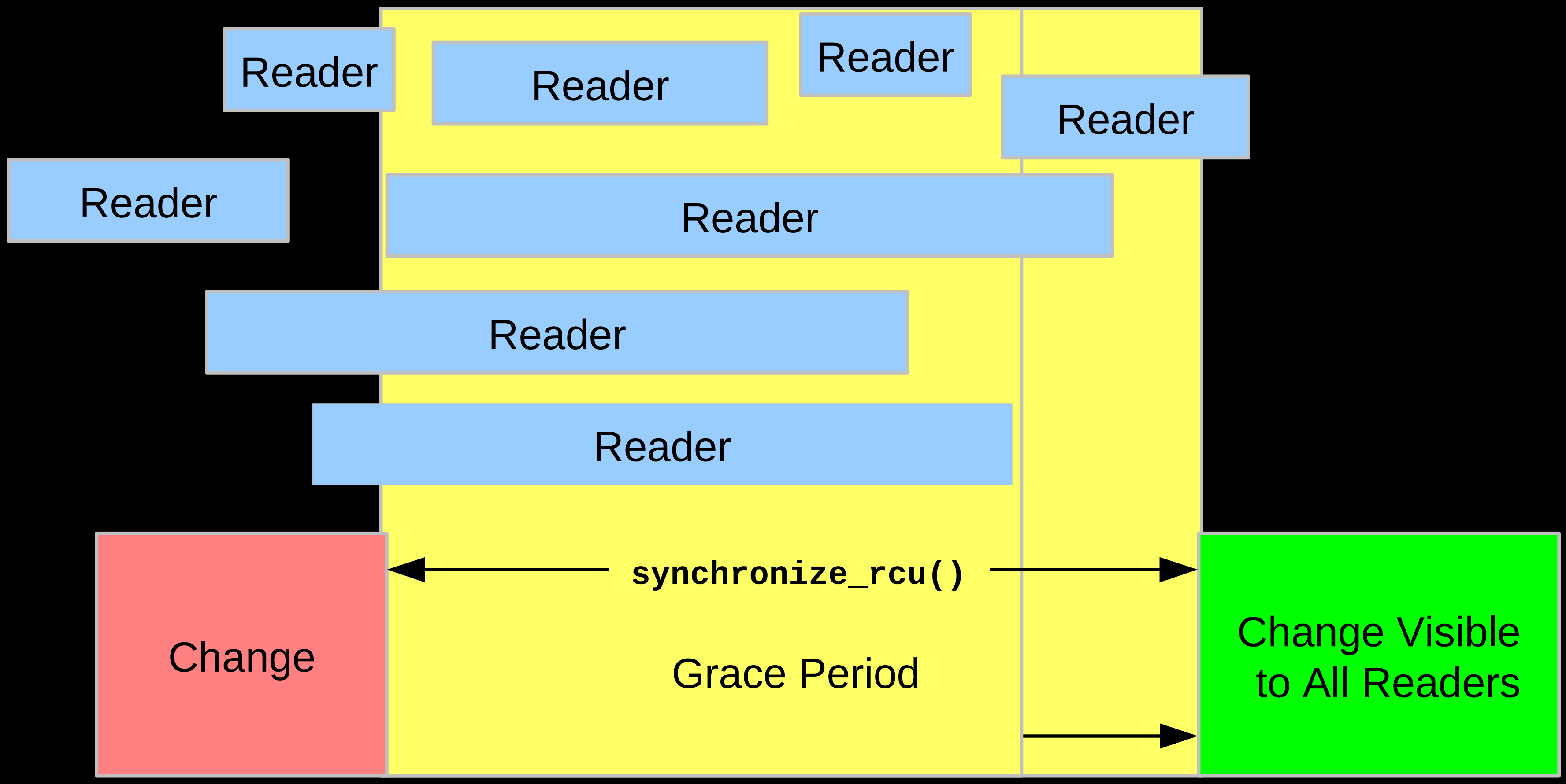

So what happens if you try to extend an RCU read-side critical section across a grace period?

# RCU Grace Period: A Self-Repairing Graphical View



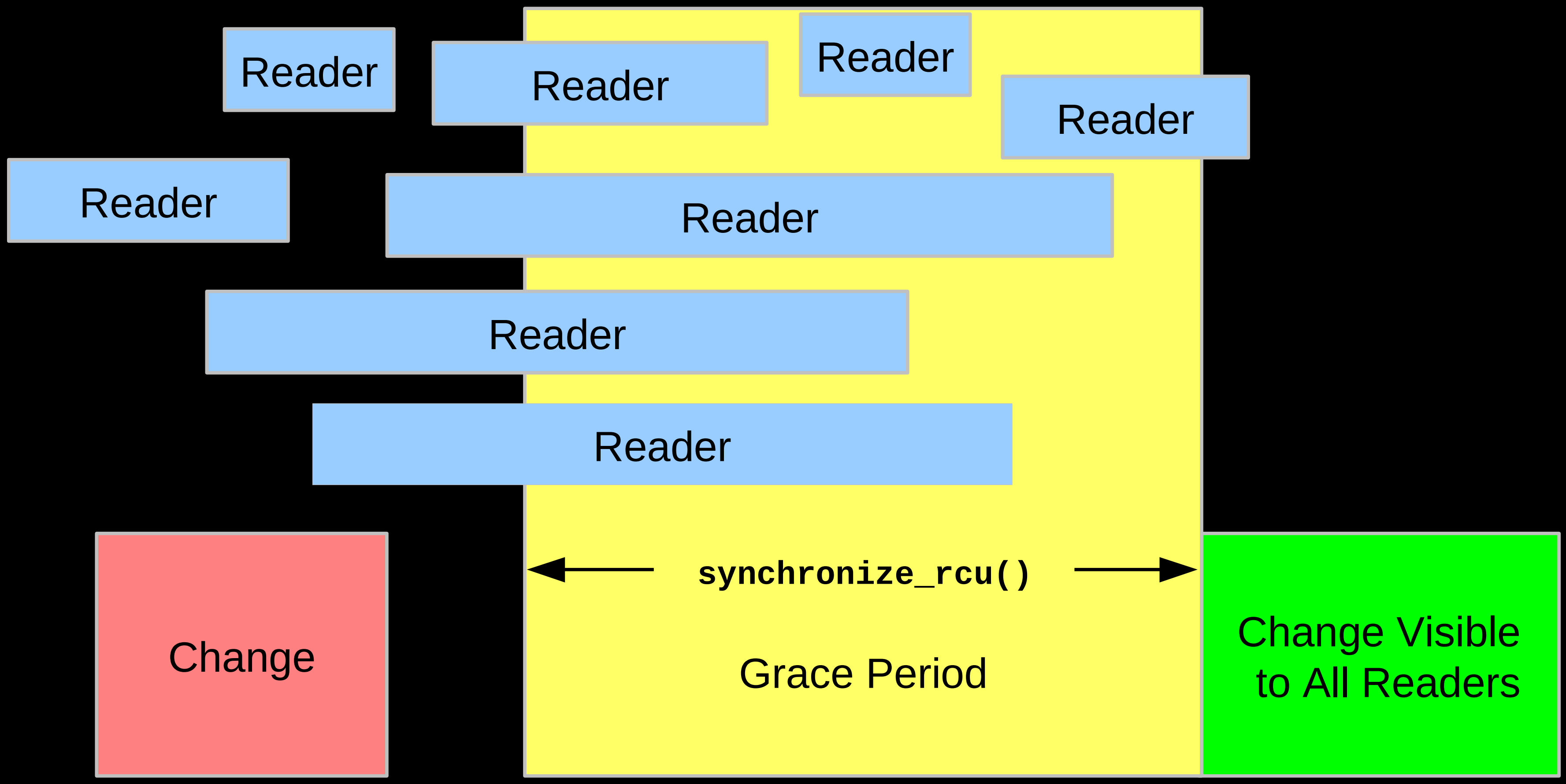

A grace period is not permitted to end until all pre-existing readers have completed.

# RCU Grace Period: A Lazy Graphical View



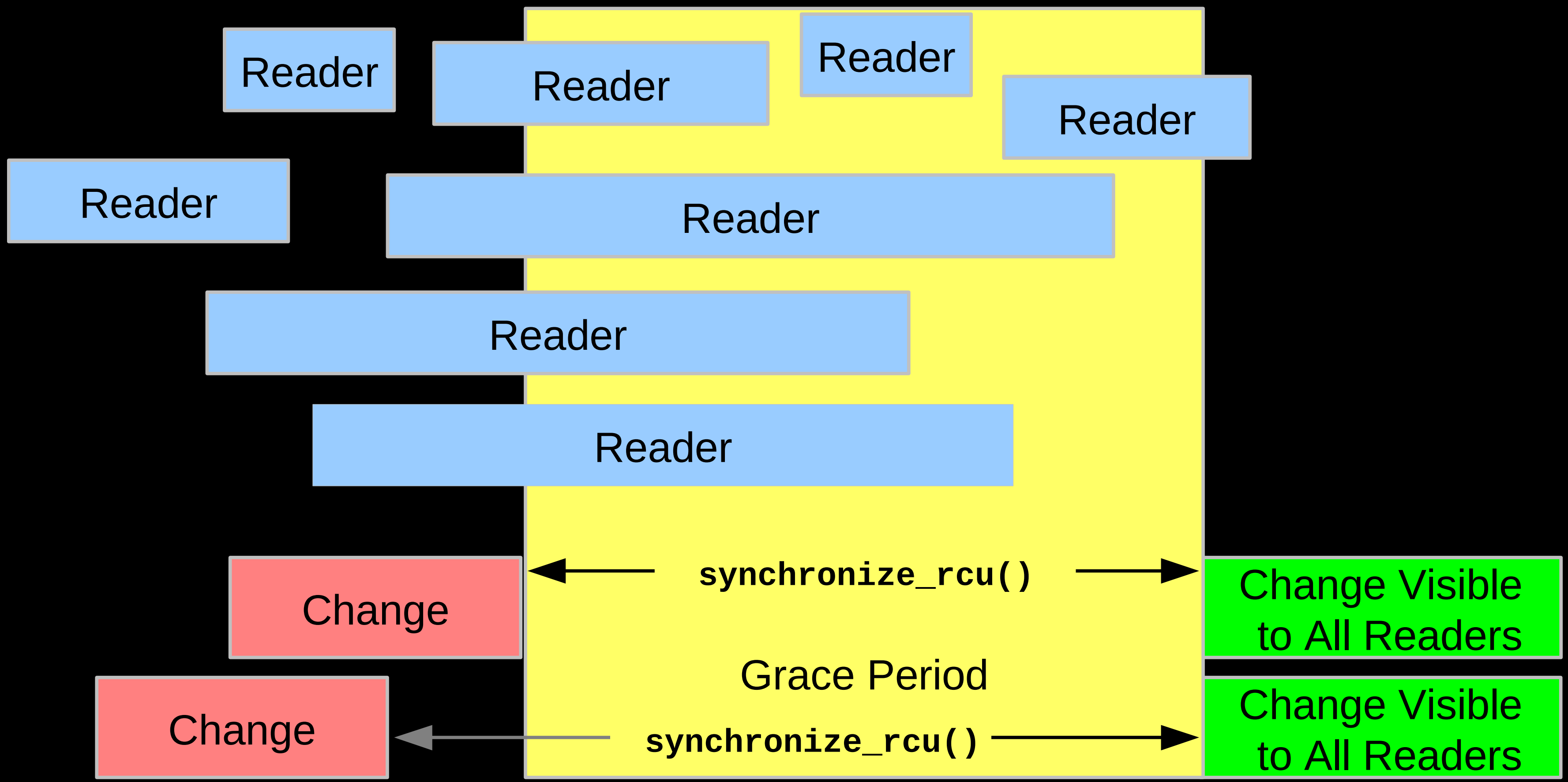

But it is OK for RCU to be lazy and allow a grace period to extend longer than necessary

# RCU Grace Period: A *Really* Lazy Graphical View




And it is also OK for RCU to be even more lazy and start a grace period later than necessary
But why is this useful?

# RCU Grace Period: A Usefully Lazy Graphical View

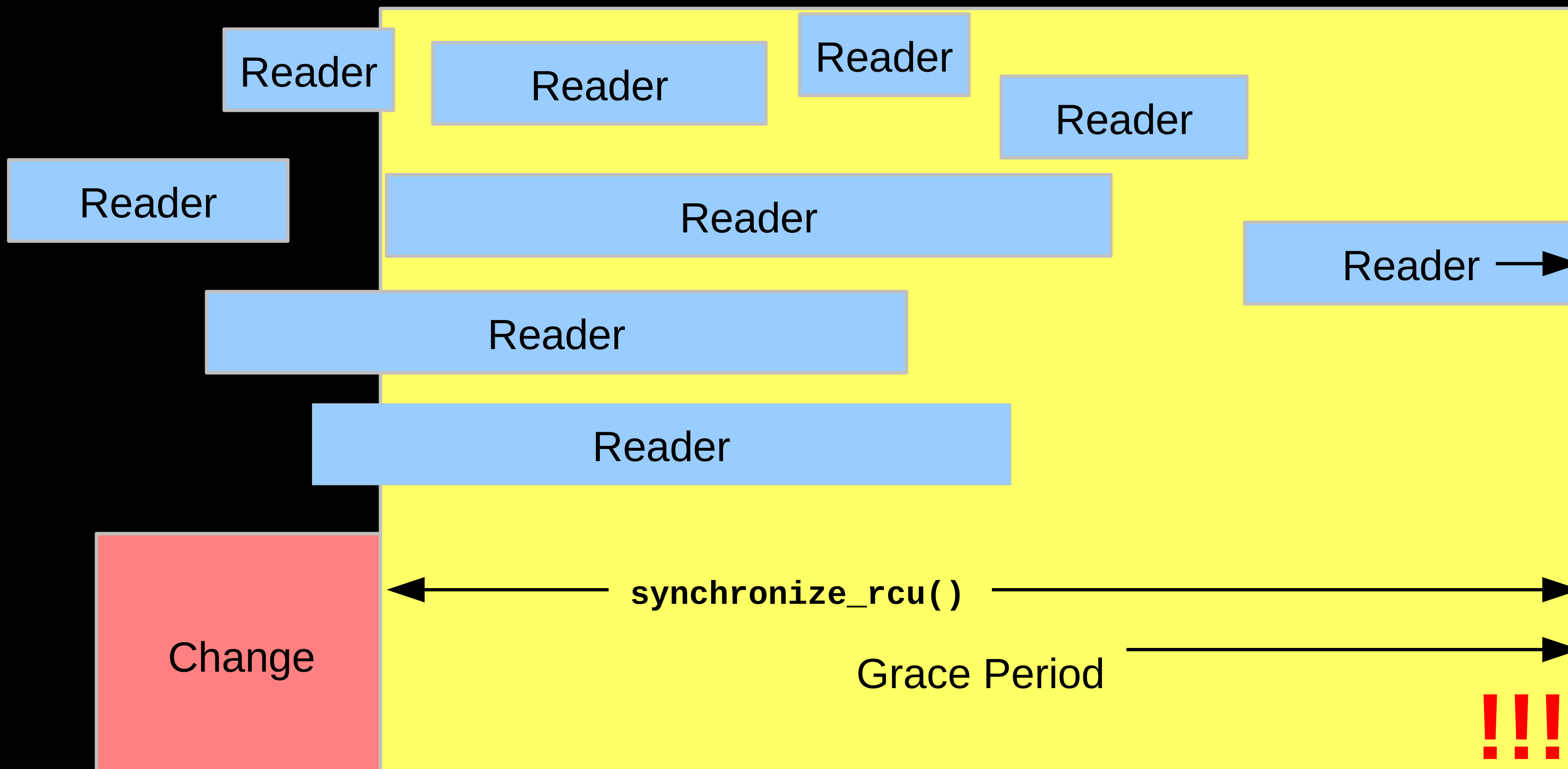



Starting a grace period late can allow it to serve multiple updates, decreasing the per-update RCU overhead. But...

# The Costs and Benefits of Laziness

- Starting the grace period later increases the number of updates per grace period, reducing the per-update overhead
- Delaying the end of the grace period increases grace-period latency
- Increasing the number of updates per grace period increases the memory usage
  - Therefore, starting grace periods late is a good tradeoff if memory is cheap and communication is expense, as is the case in modern multicore systems
    - And if real-time threads avoid waiting for grace periods to complete
  - However...

# RCU Grace Period: A Too-Lazy Graphical View




And it is OK for the system to complain (or even abort) if a grace period extends too long. Too-long of grace periods are likely to result in death by memory exhaustion anyway.

# RCU Asynchronous Grace-Period Detection

# RCU Asynchronous Grace-Period Detection

- The call_rcu() function registers an RCU callback, which is invoked after a subsequent grace period elapses
- API:

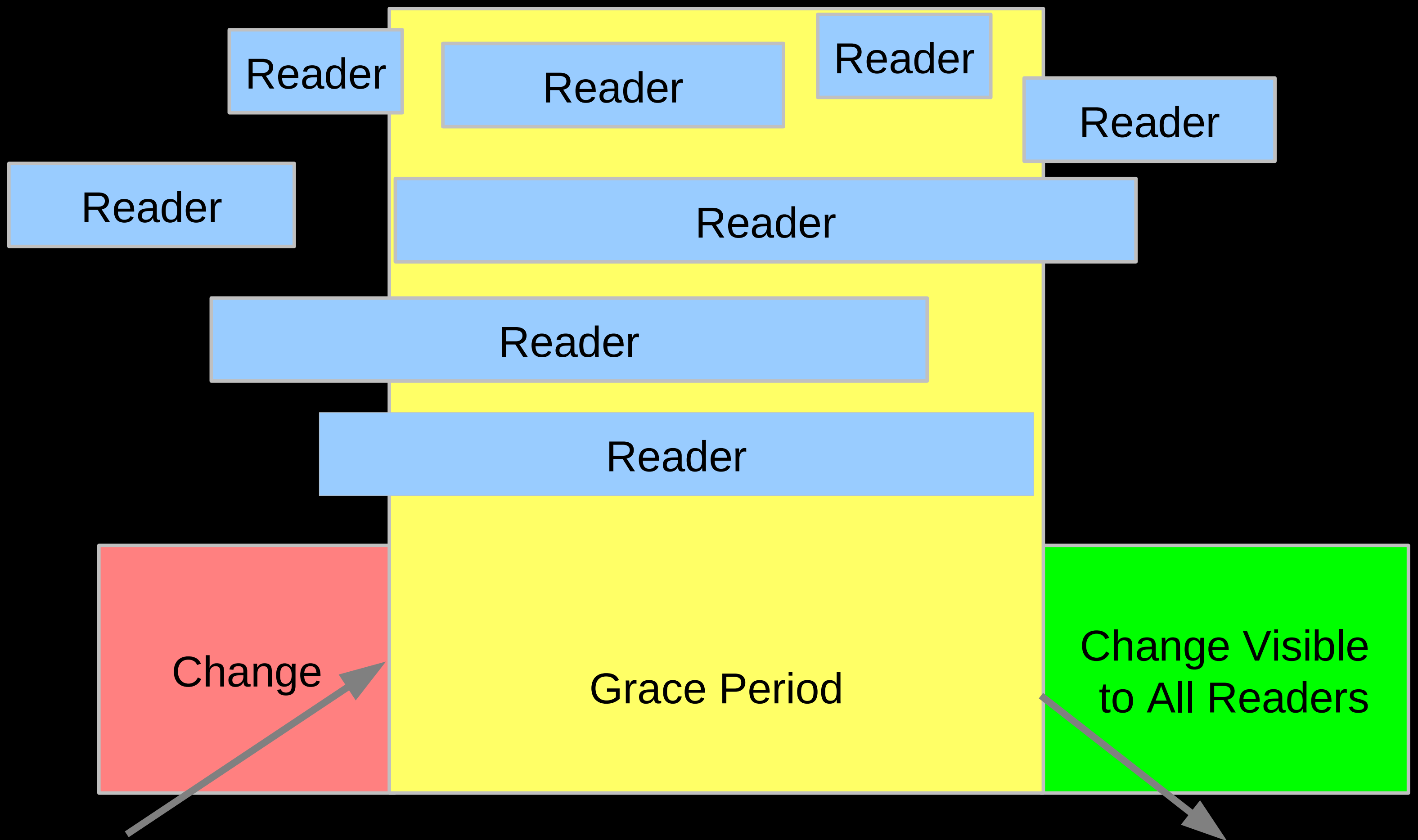
```
call_rcu(struct rcu_head head,
         void (*func)(struct rcu_head *rcu));
```

- The `rcu_head` structure:

```
struct rcu_head {
        struct rcu_head *next;
        void (*func)(struct rcu_head *rcu);
};
```

- The `rcu_head` structure is normally embedded within the RCU-protected data structure

# RCU Grace Period: An Asynchronous Graphical View

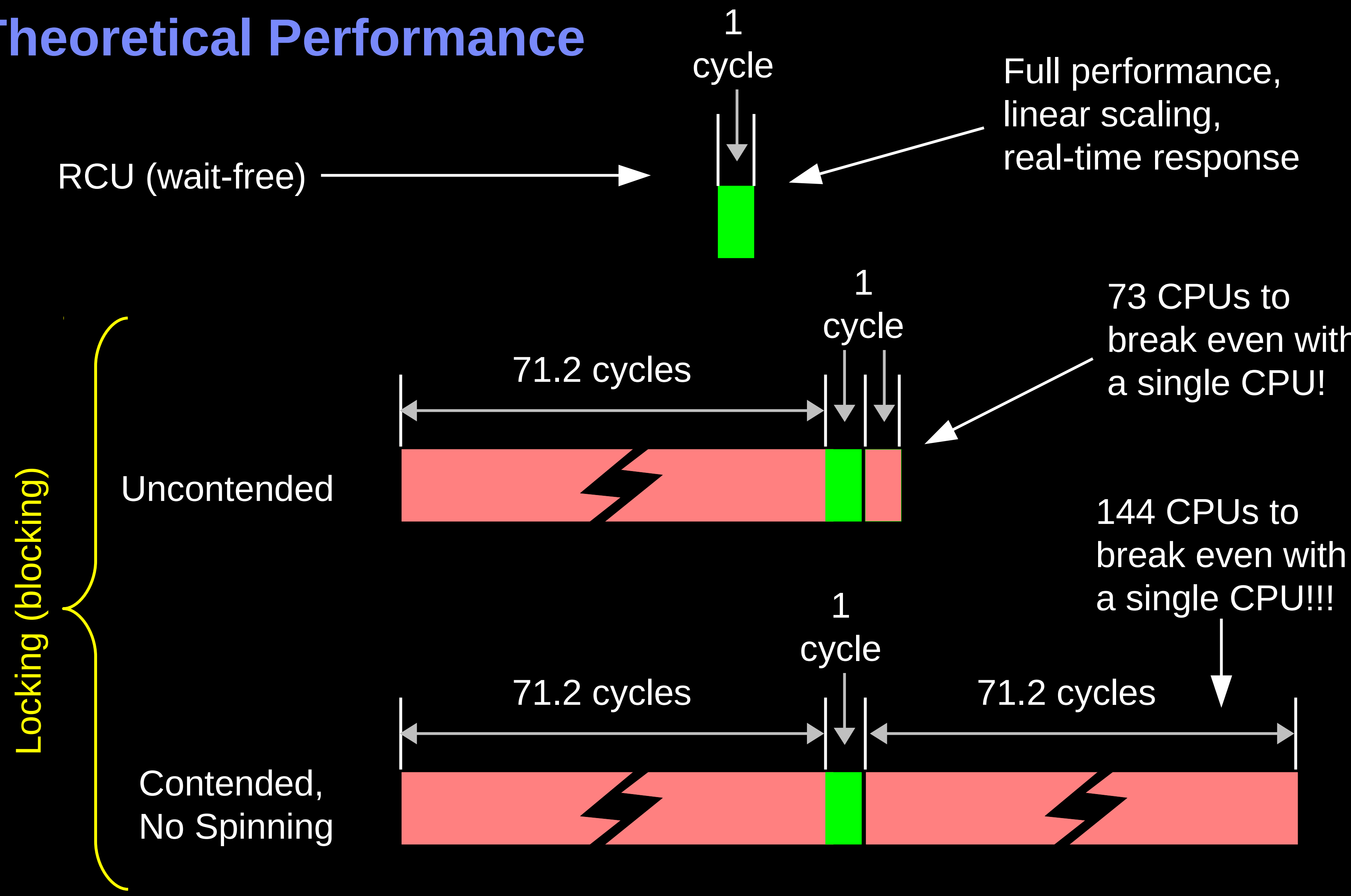



`call_rcu(&p->rcu, func);`

`func(&p->rcu);`

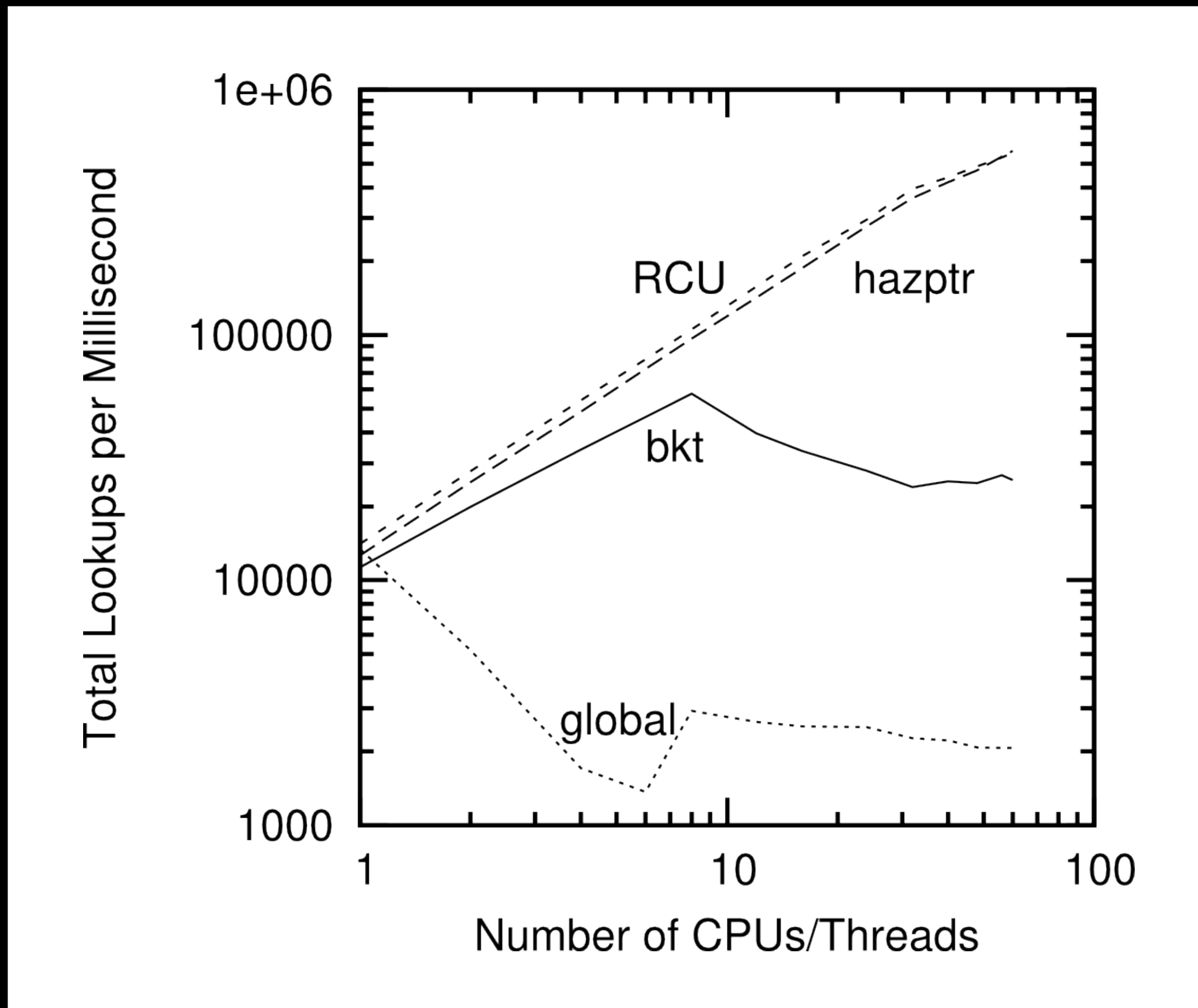
# Performance

# Theoretical Performance



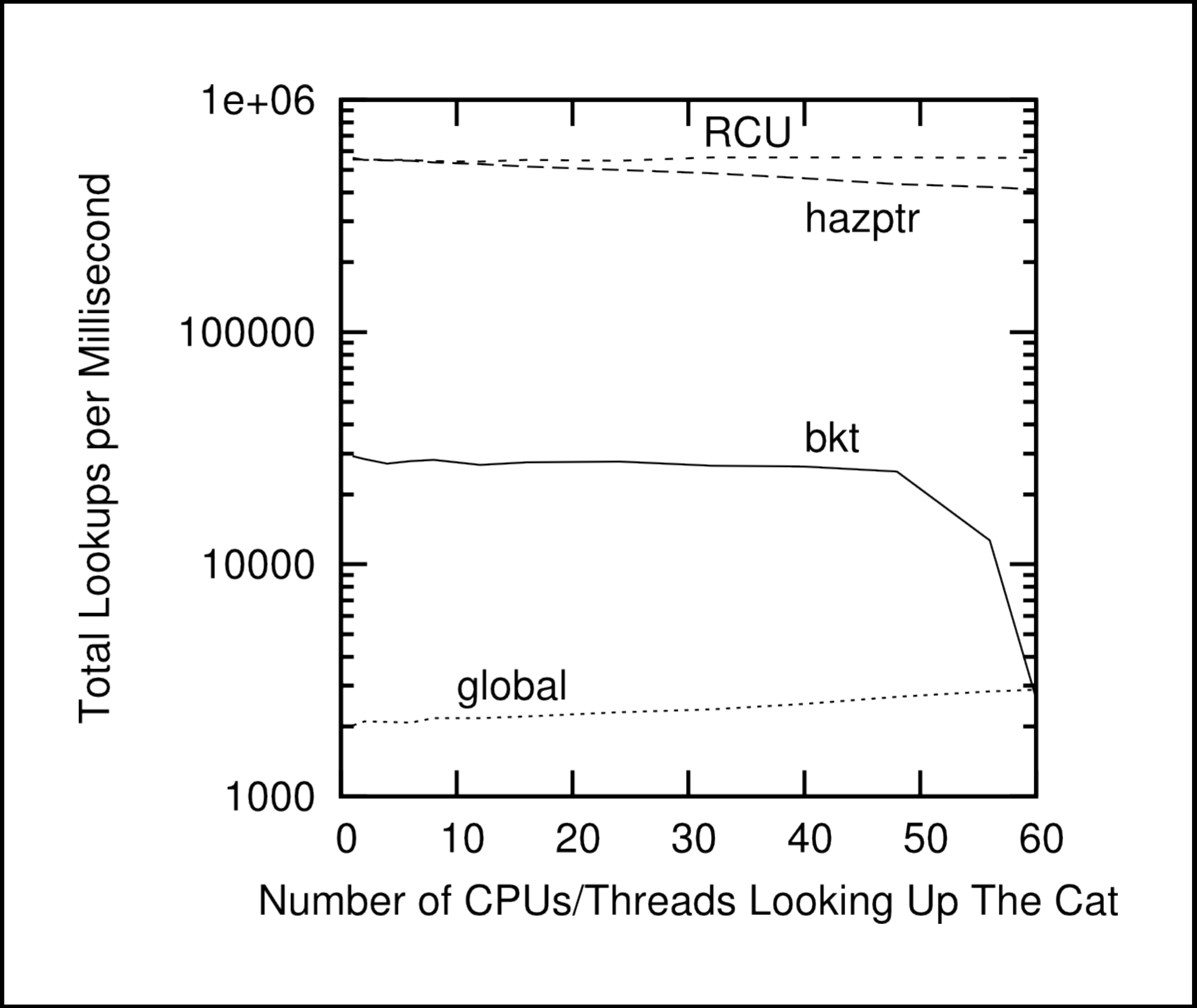
# Measured Performance

# Schrödinger's Zoo: Read-Only




RCU and hazard pointers scale quite well!!!

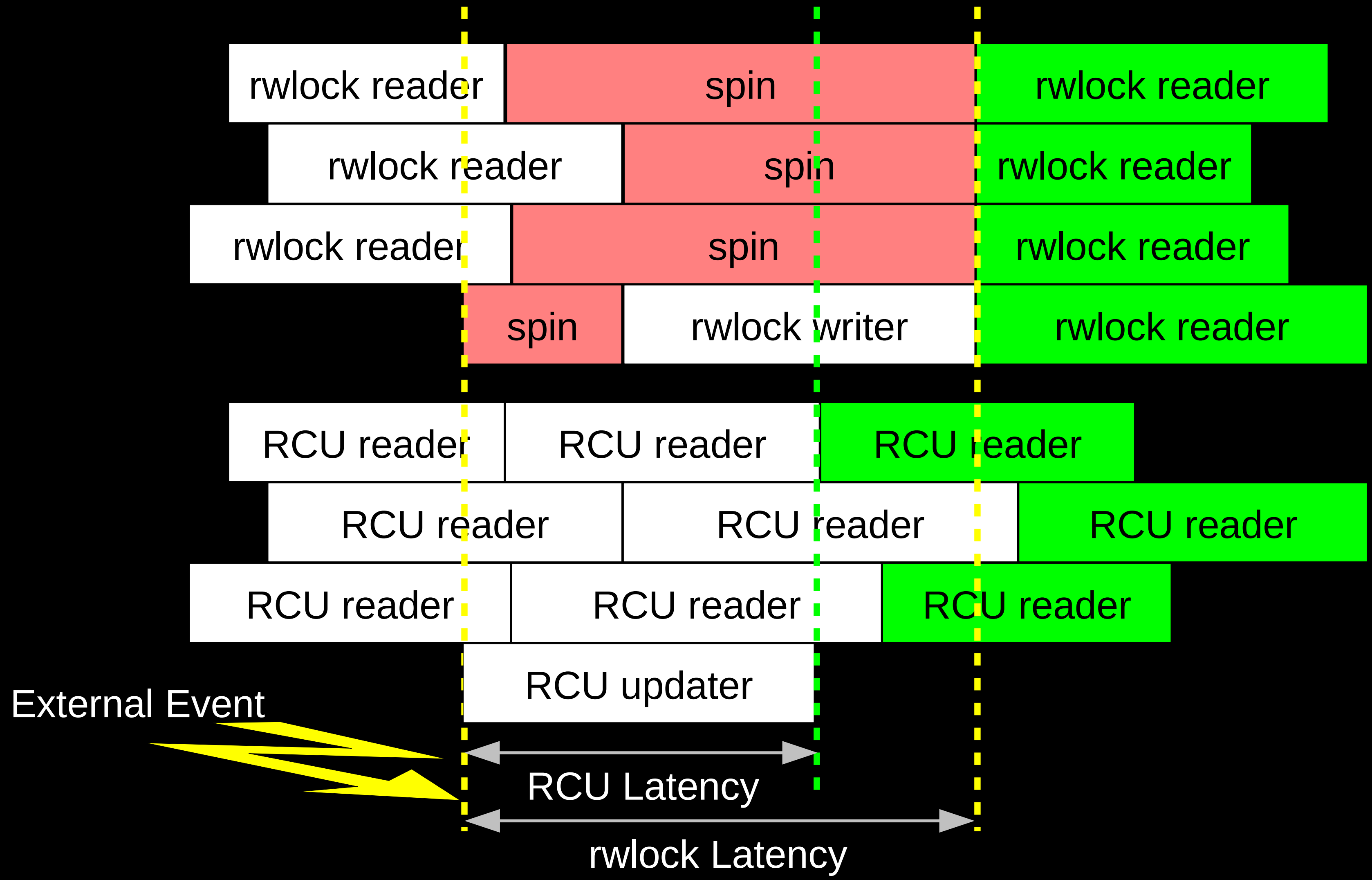
# Schrödinger's Zoo: Read-Only Cat-Heavy Workload




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

# Real-Time Response to Changes

# RCU vs. Reader-Writer-Lock Real-Time Latency



# RCU Performance: “Free is a *Very* Good Price!!!”

# 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!!!)

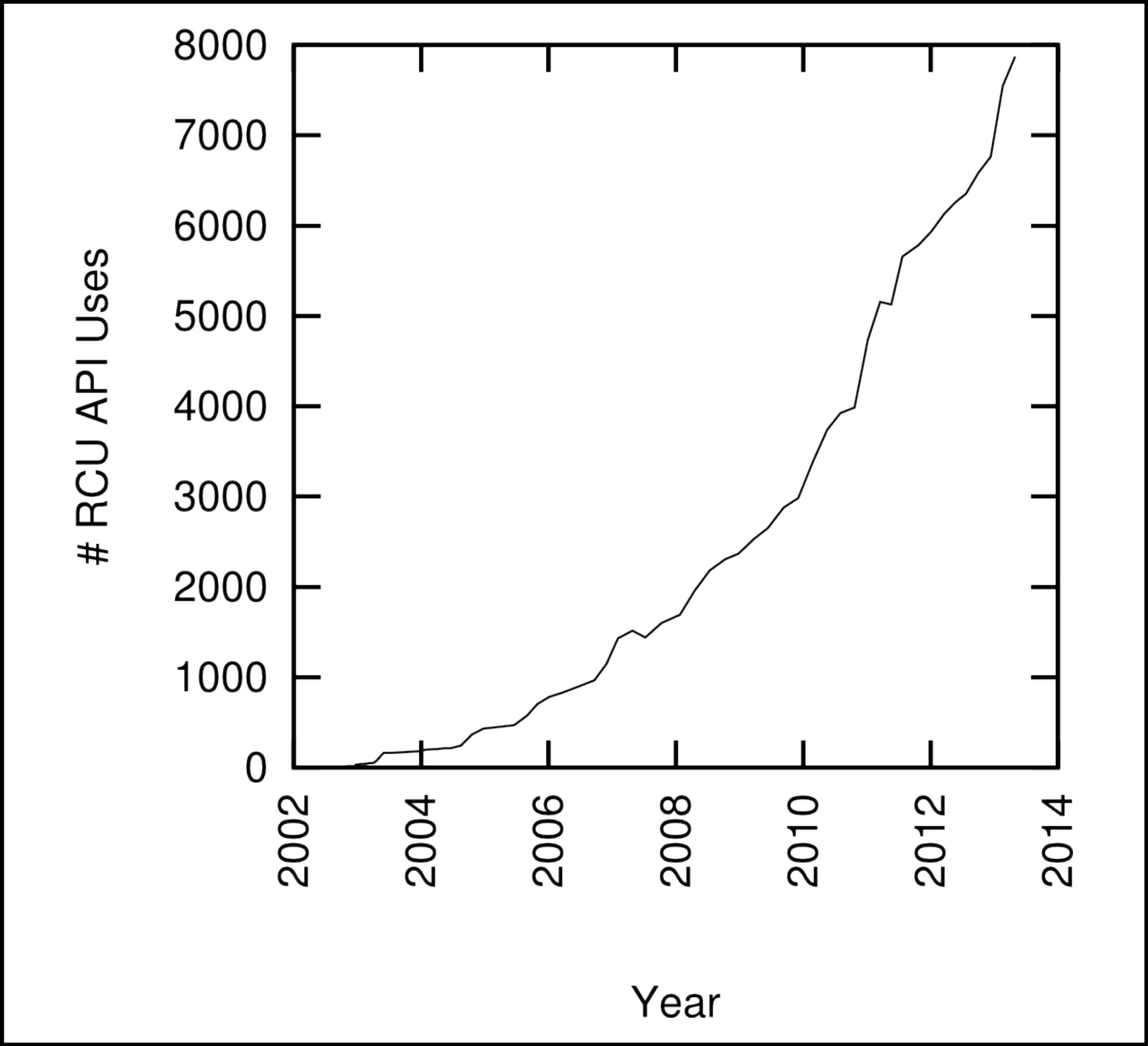
Read-Mostly, Need Consistent Data
(RCU Works OK)

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
  - 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
  - Used heavily in the Linux kernel
- Much more information on RCU is available...

# 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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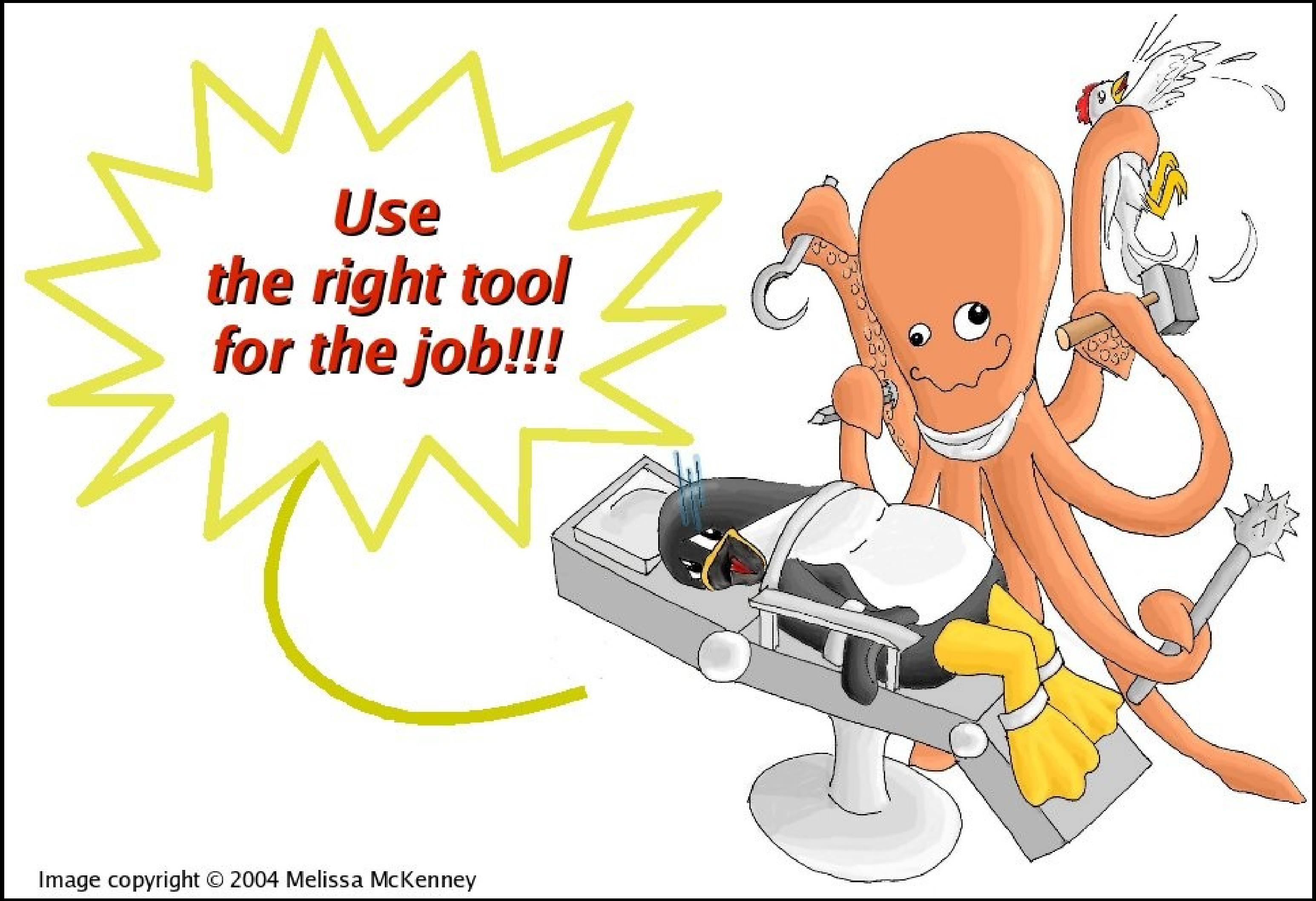
  - Additional reviewers: Carsten Weinhold and Mingming Cao.

# Questions?


Use
the right tool
for the job!!!
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