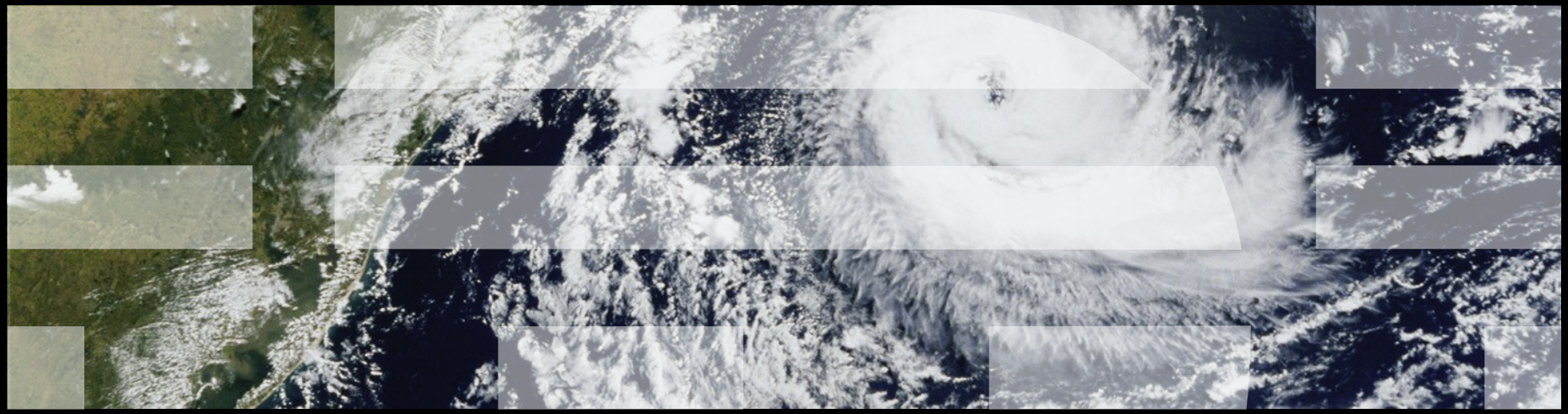
Paul E. McKenney, IBM Distinguished Engineer, Linux Technology Center

16 May 2012

What Is RCU?

Distributed OS Lecture, TU Dresden



Overview

- 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

Performance of Synchronization Mechanisms

Performance of Synchronization Mechanisms

4-CPU 1.8GHz AMD Opteron 844 system

Need to be here!
(Partitioning/RCU)

Operation	Cost (ns)	Ratio
Clock period	0.6	1
Best-case CAS	37.9	63.2
Best-case lock	65.6	109.3
Single cache miss	139.5	232.5
CAS cache miss	306.0	510.0

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Typical synchronization mechanisms do this a lot

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And why low-level details???

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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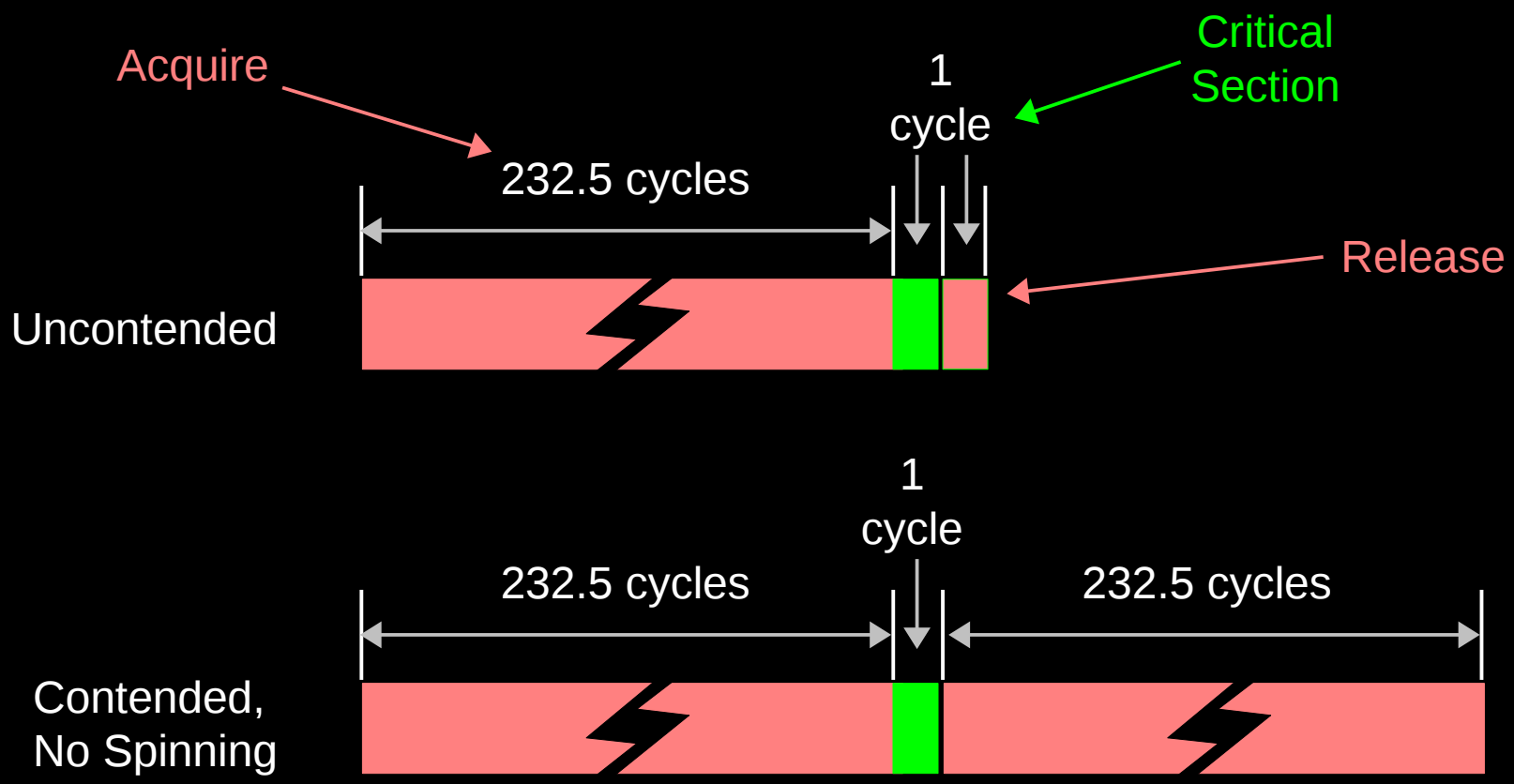
- Single-instruction critical sections protected by multiple locks



So, what *does* this mean?

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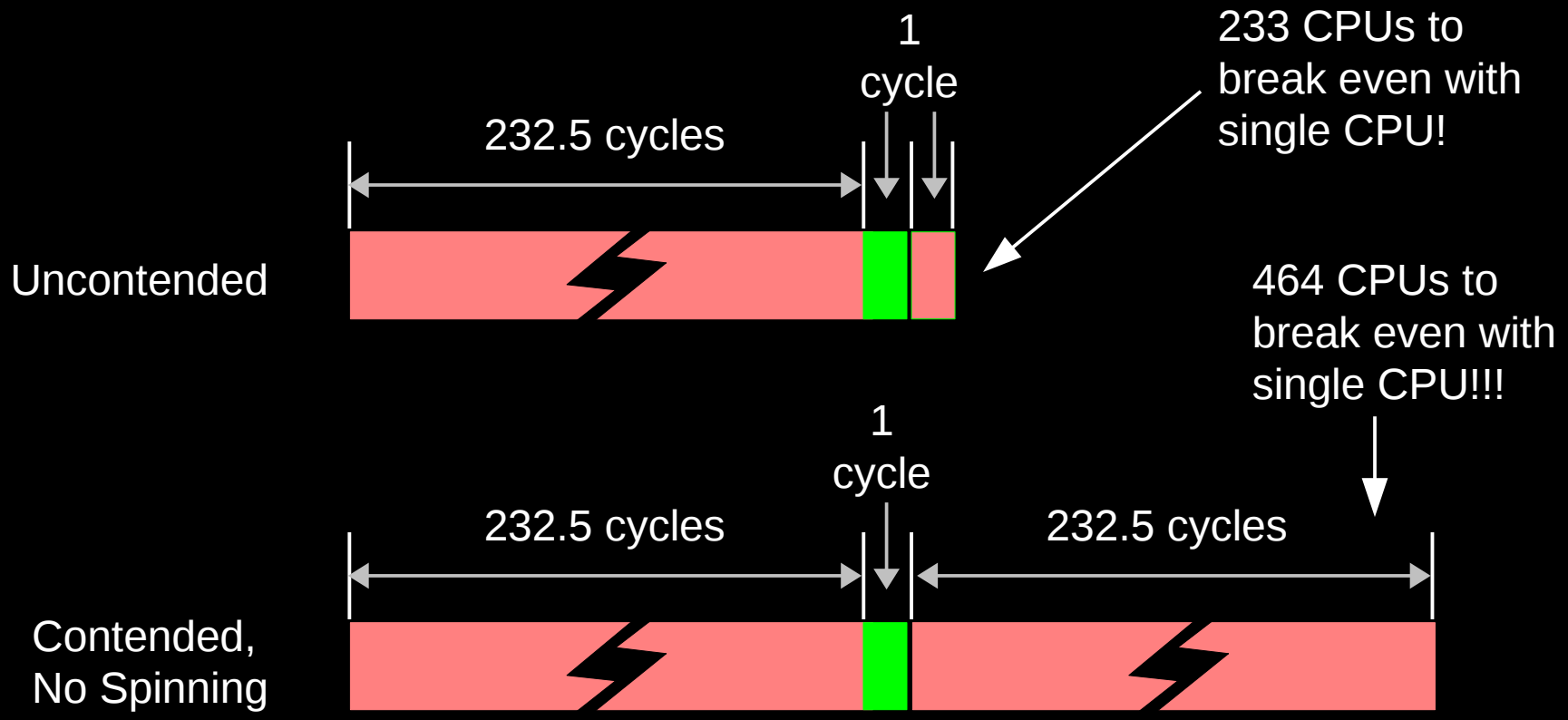

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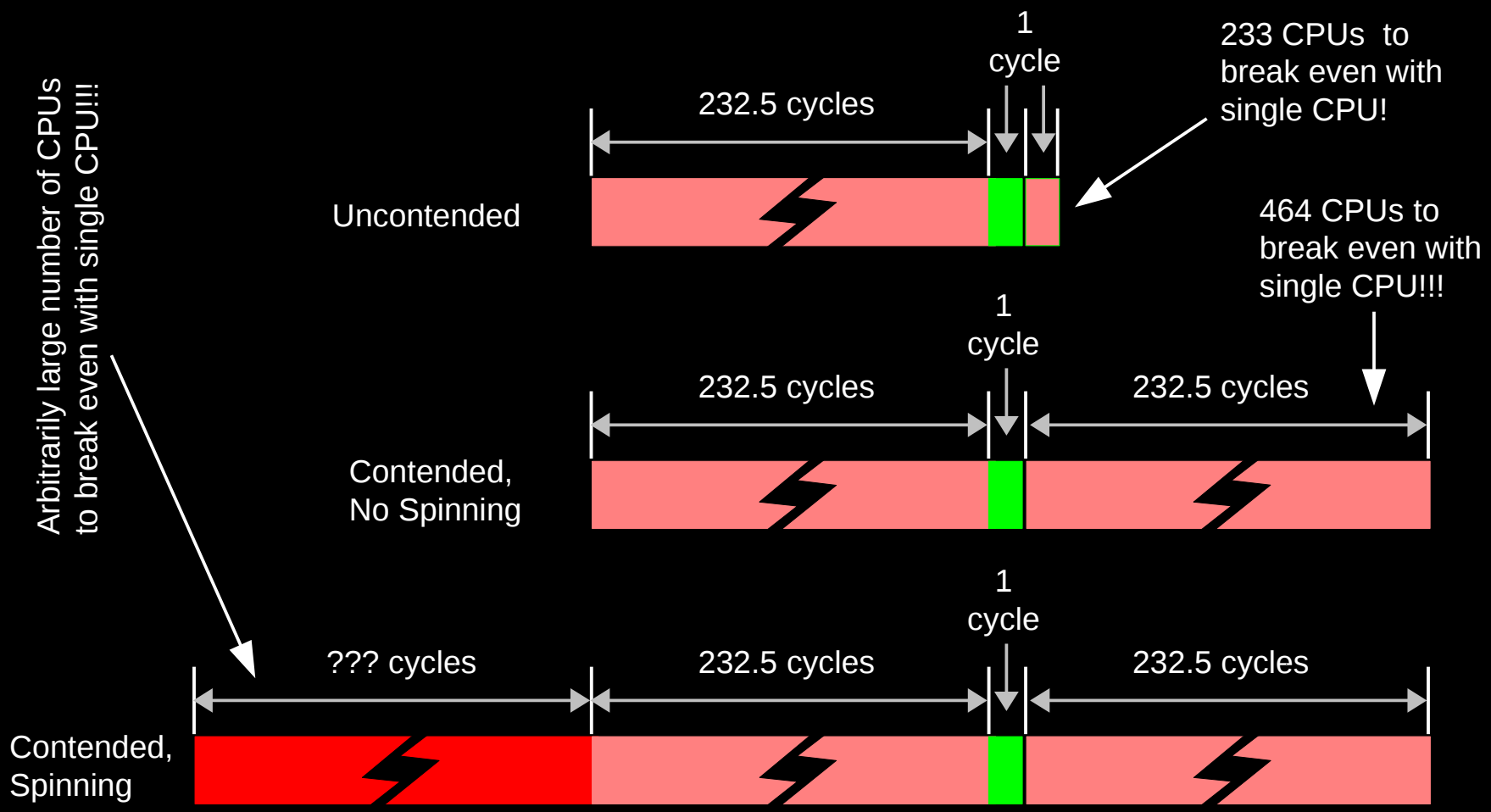

Reader-Writer Locks Are Even Worse!

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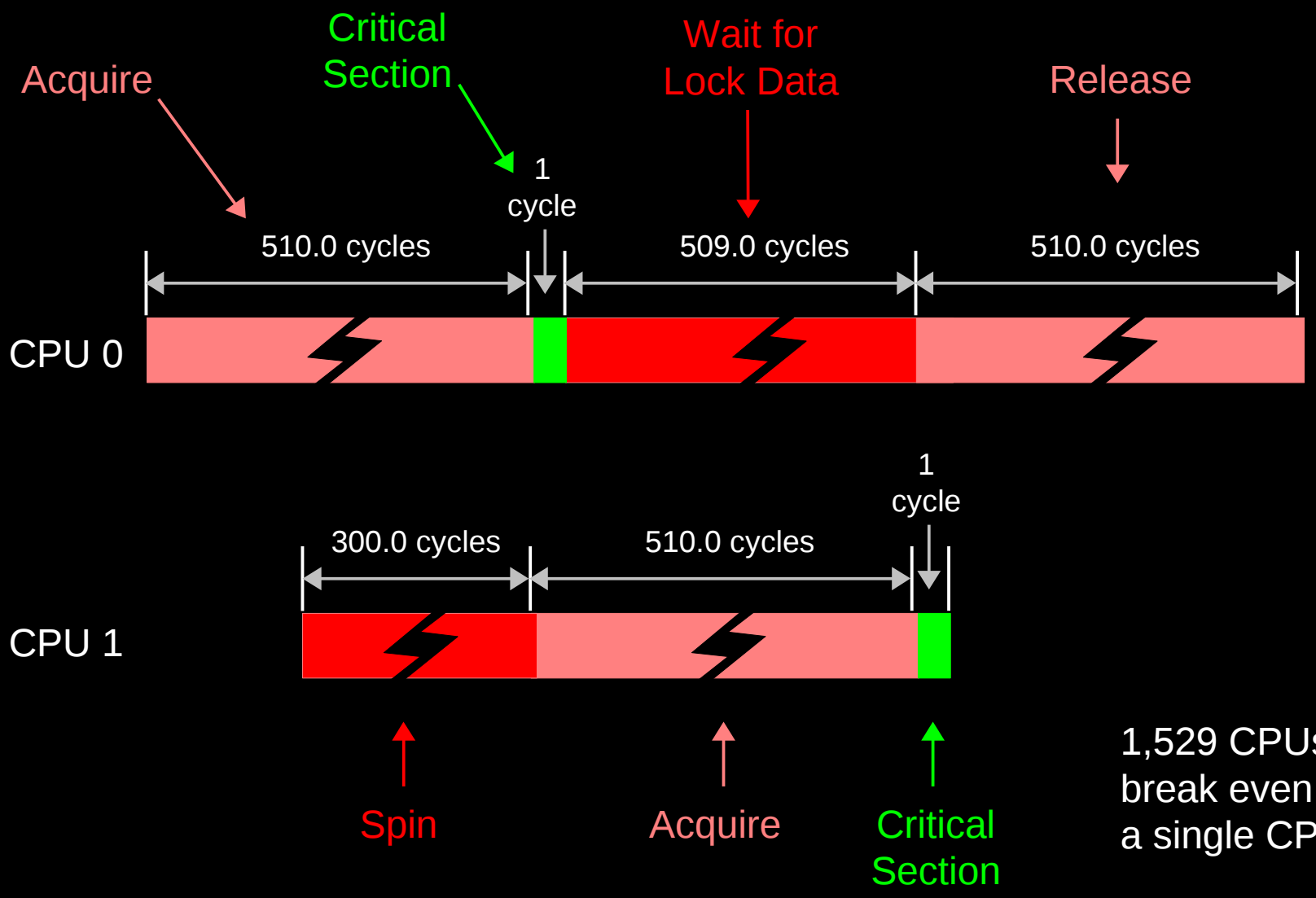

1,529 CPUs to break even with a single CPU!!!

But Isn't Hardware Just Getting Faster?

Performance of Synchronization Mechanisms

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

What a difference a few years can make!!!

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Single cache “miss”	12.9	35.8
CAS cache “miss”	7.0	19.4
Single cache miss **(off-core)**	31.2	86.6
CAS cache miss **(off-core)**	31.2	86.5

Not *quite* so good... But still a 6x improvement!!!

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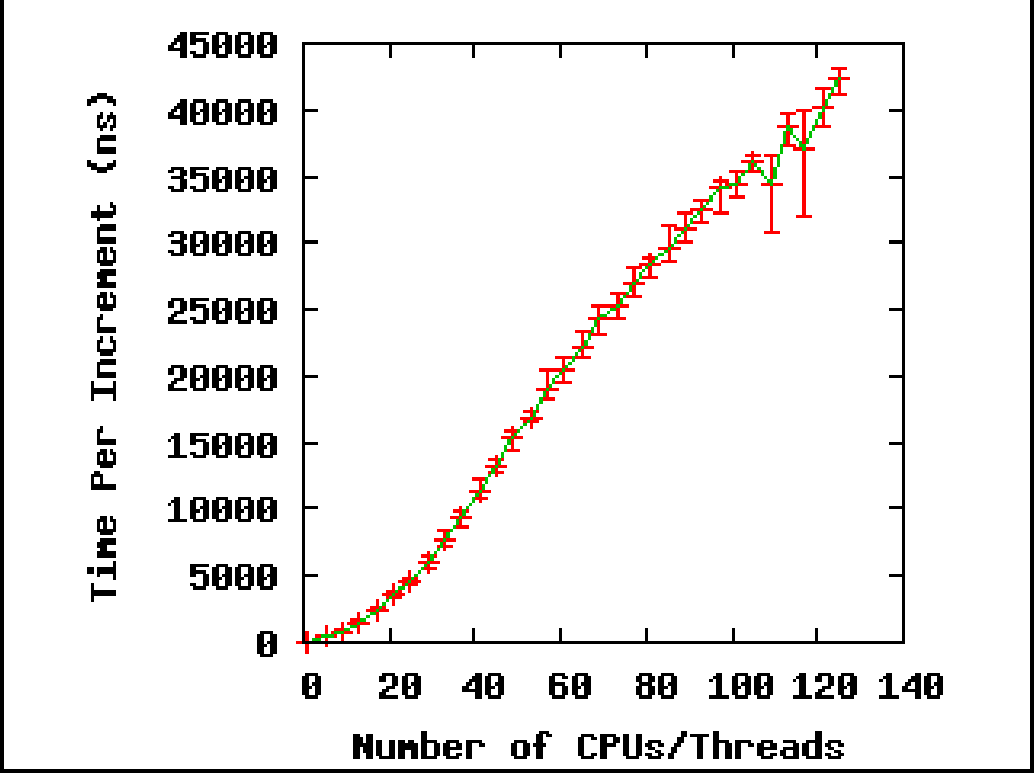
CAS cache miss	7.0	19.4
Single cache miss **(off-core)**	31.2	86.6
CAS cache miss **(off-core)**	31.2	86.5
Single cache miss **(off-socket)**	92.4	256.7
CAS cache miss **(off-socket)**	95.9	266.4

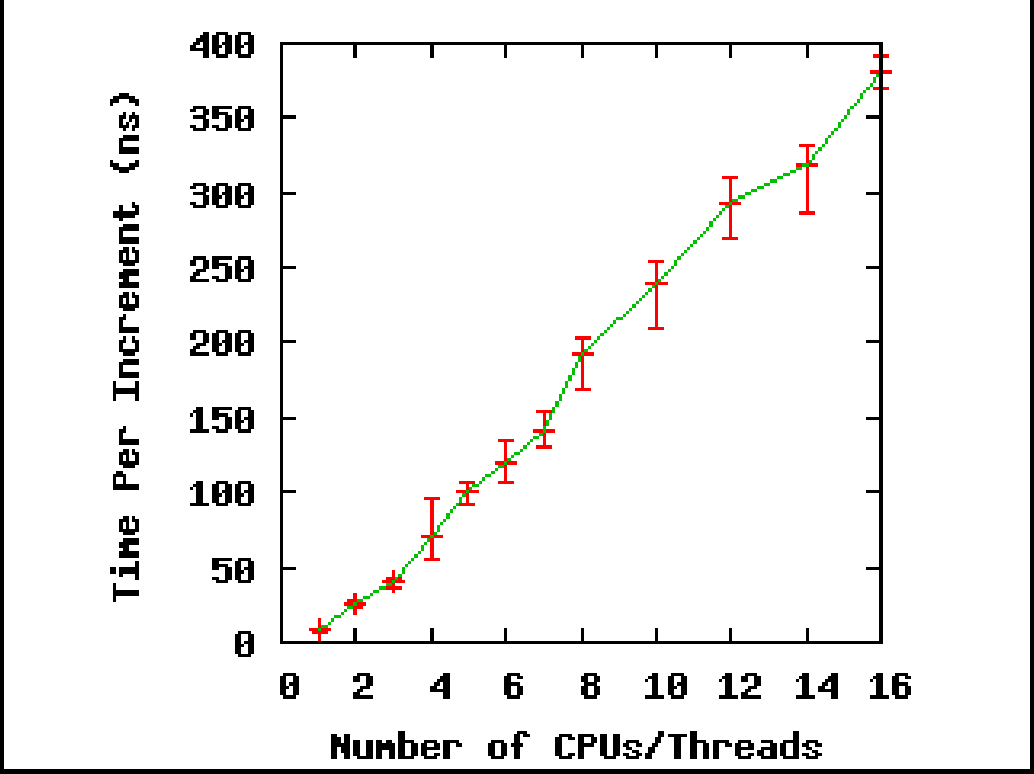
Maybe not such a big difference after all...
And these are best-case values!!! (Why?)

Performance of Synchronization Mechanisms



If you thought a *single* atomic operation was slow, try lots of them!!!
(Atomic increment of single variable on 1.9GHz Power 5 system)

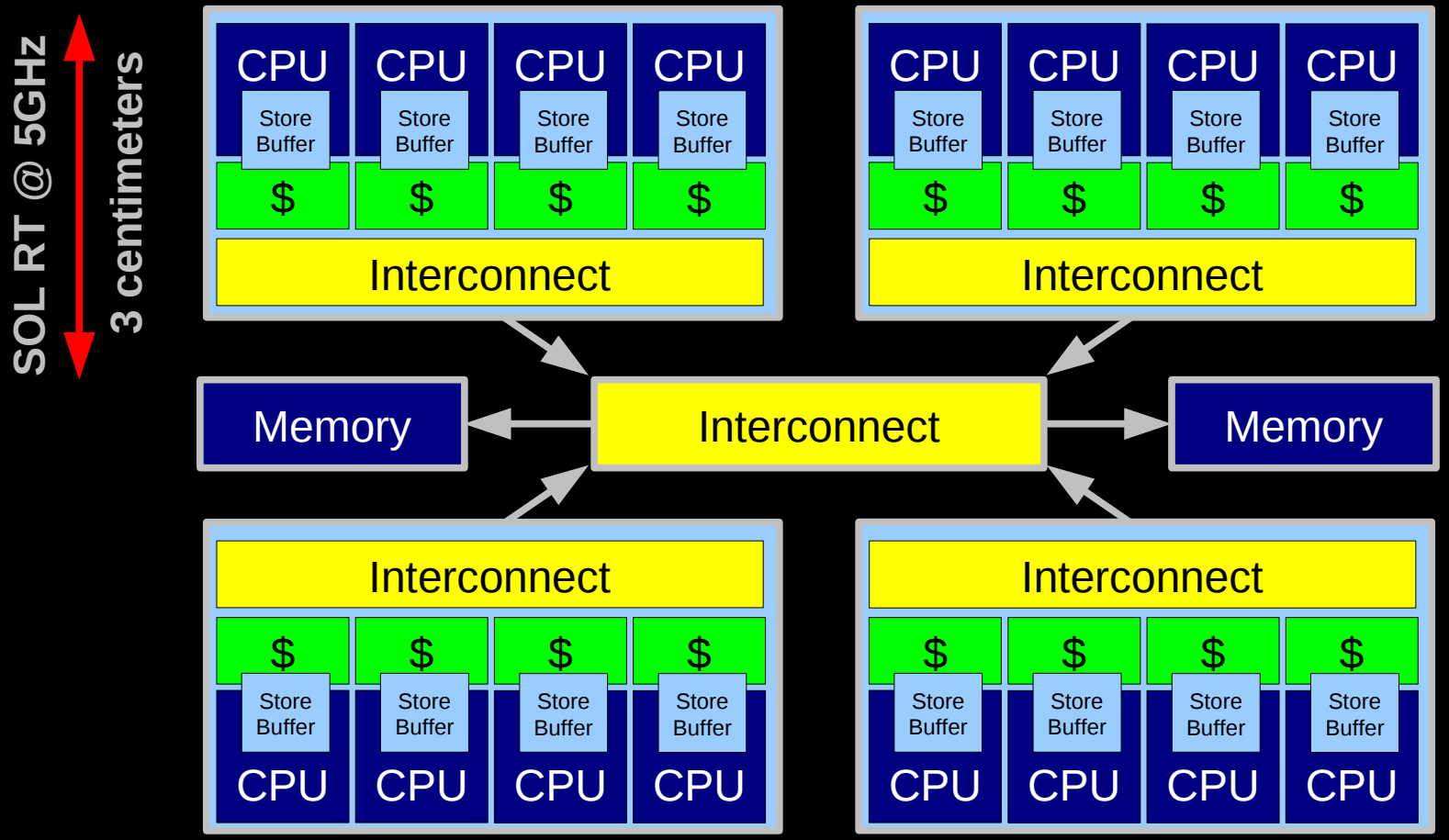
Performance of Synchronization Mechanisms



Same effect on a 16-CPU 2.8GHz Intel X5550 (Nehalem) system

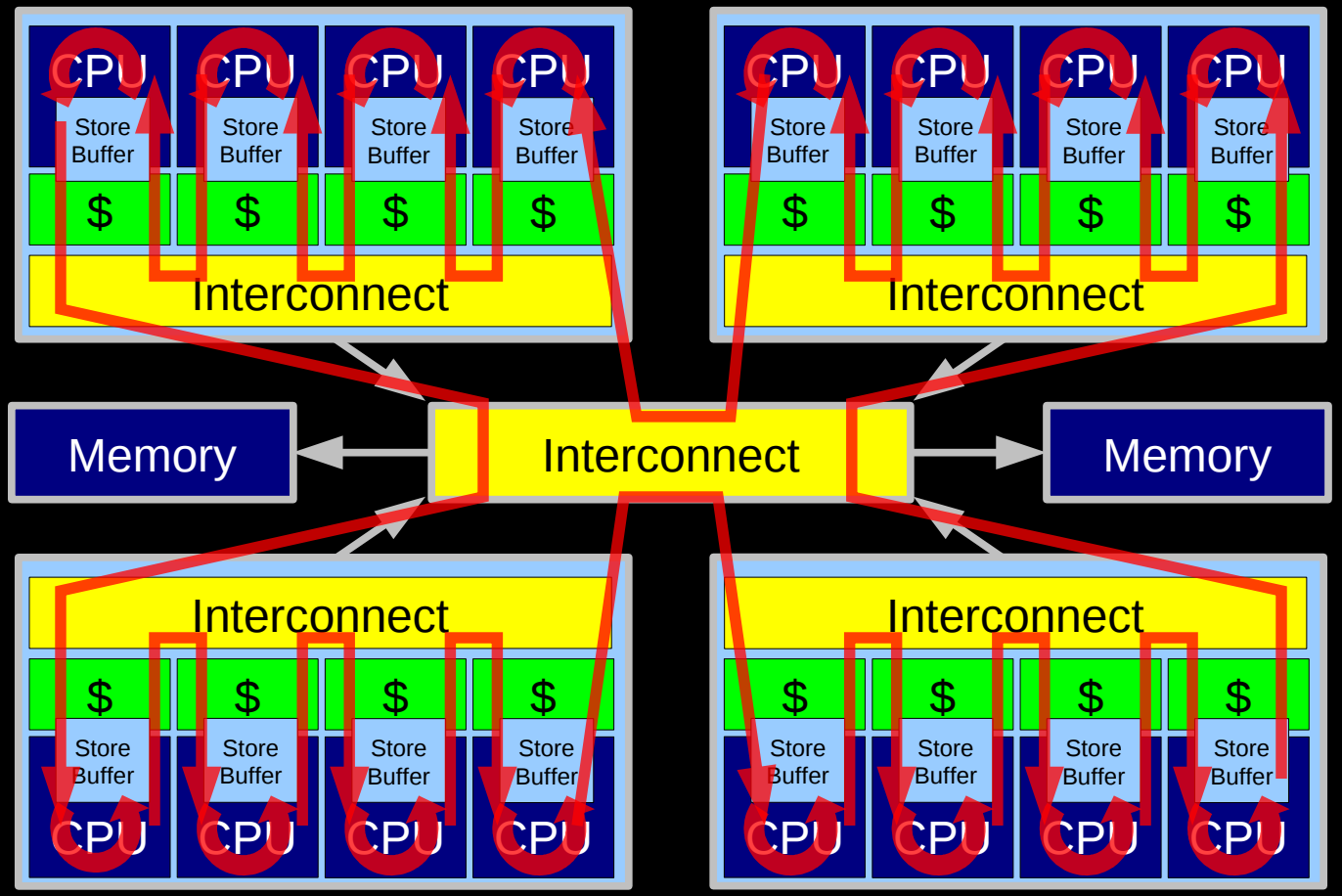
Why So Slow???

System Hardware Structure and Laws of Physics



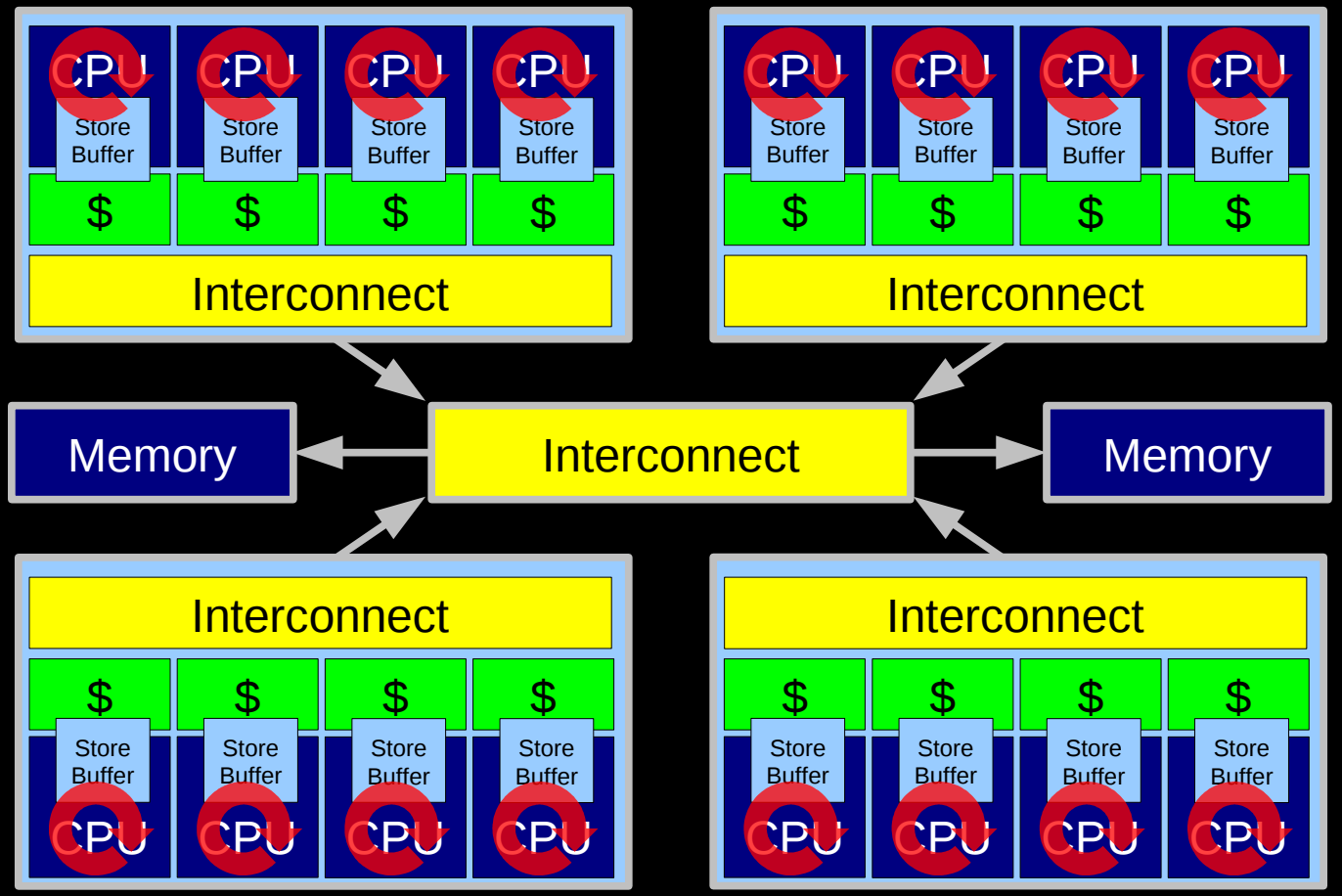
Electrons move at 0.03C to 0.3C in transistors and, so lots of waiting. 3D???

Atomic Increment of Global Variable



Lots and Lots of Latency!!!

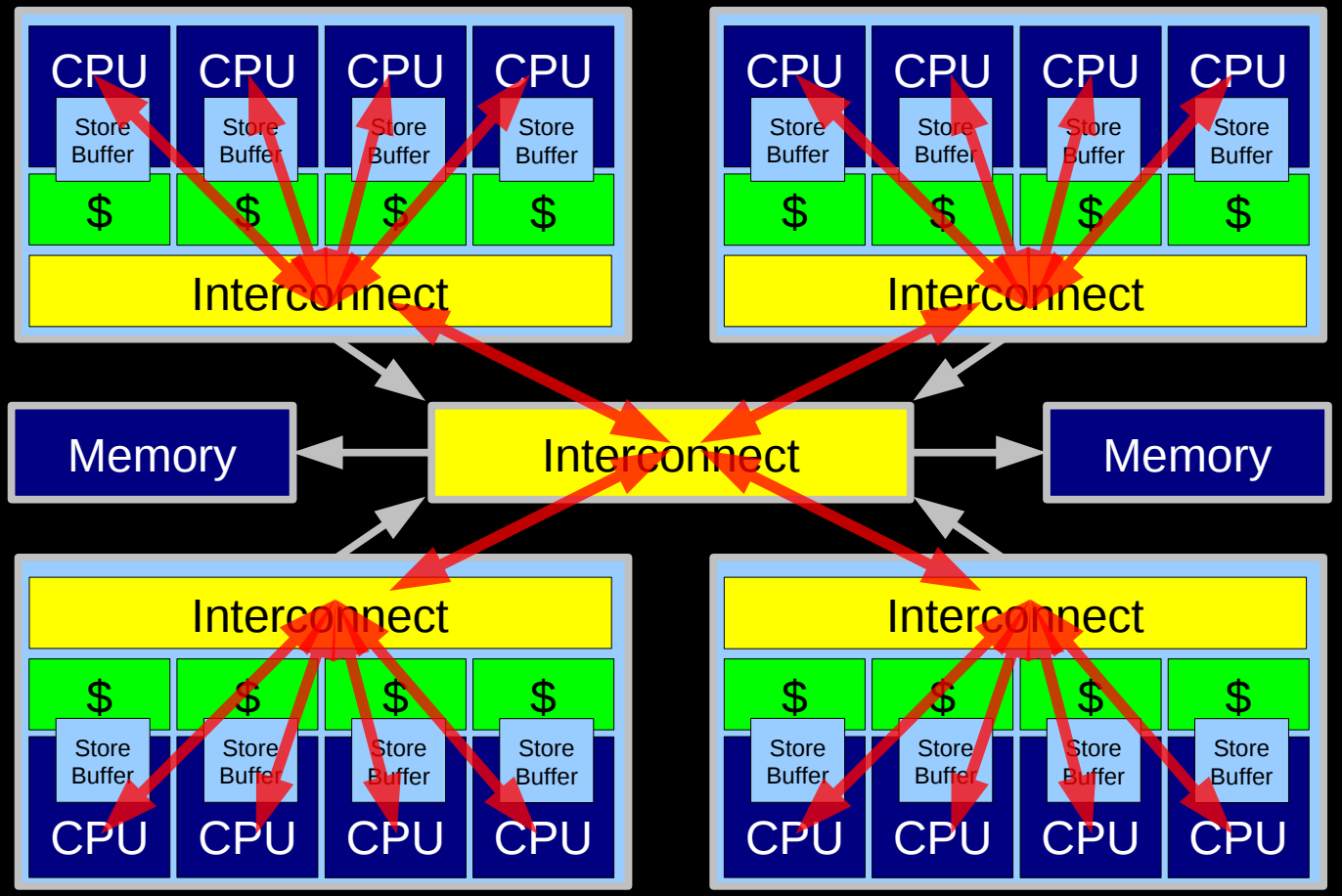
Atomic Increment of Per-CPU Counter



Little Latency, Lots of Increments at Core Clock Rate

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

HW-Assist Atomic Increment of Global Variable

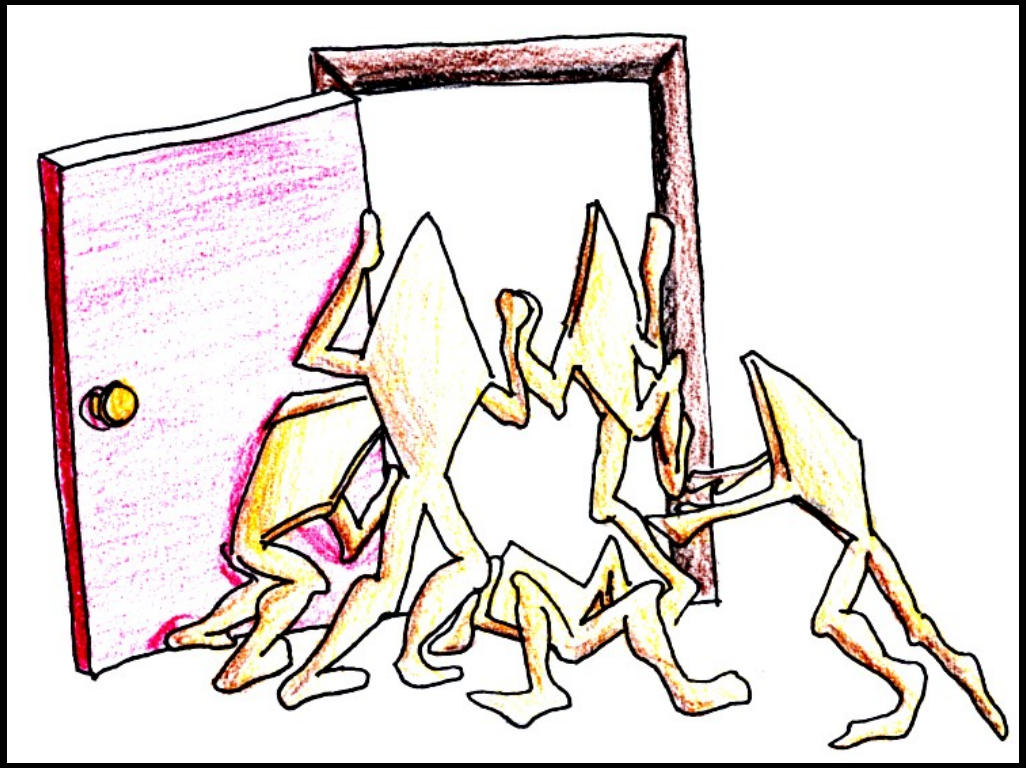


SGI systems used this approach in the 1990s, expect modern micros to pick it up.

Still not as good as per-CPU counters.

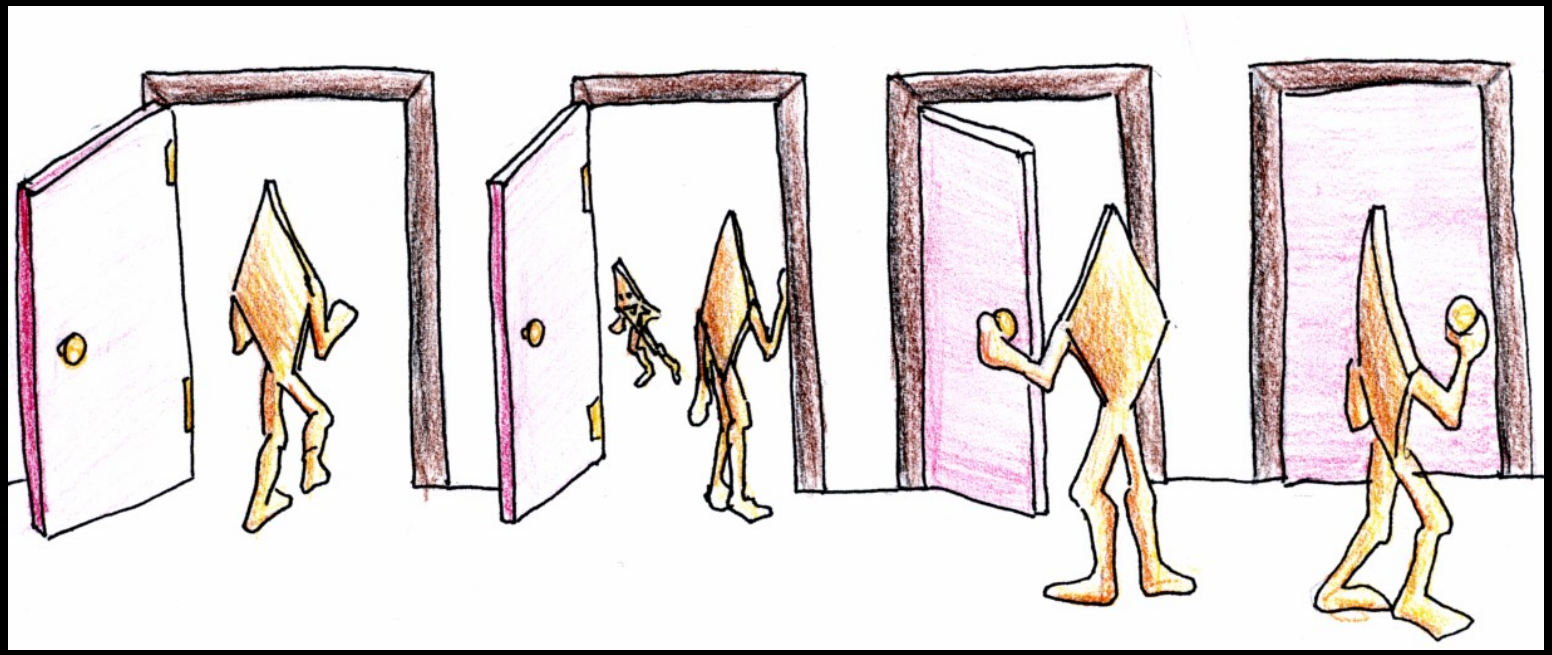
How Can Software Live With This Hardware???

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.

Design Principle: Avoid Expensive Operations

Need to be here! (Partitioning/RCU)

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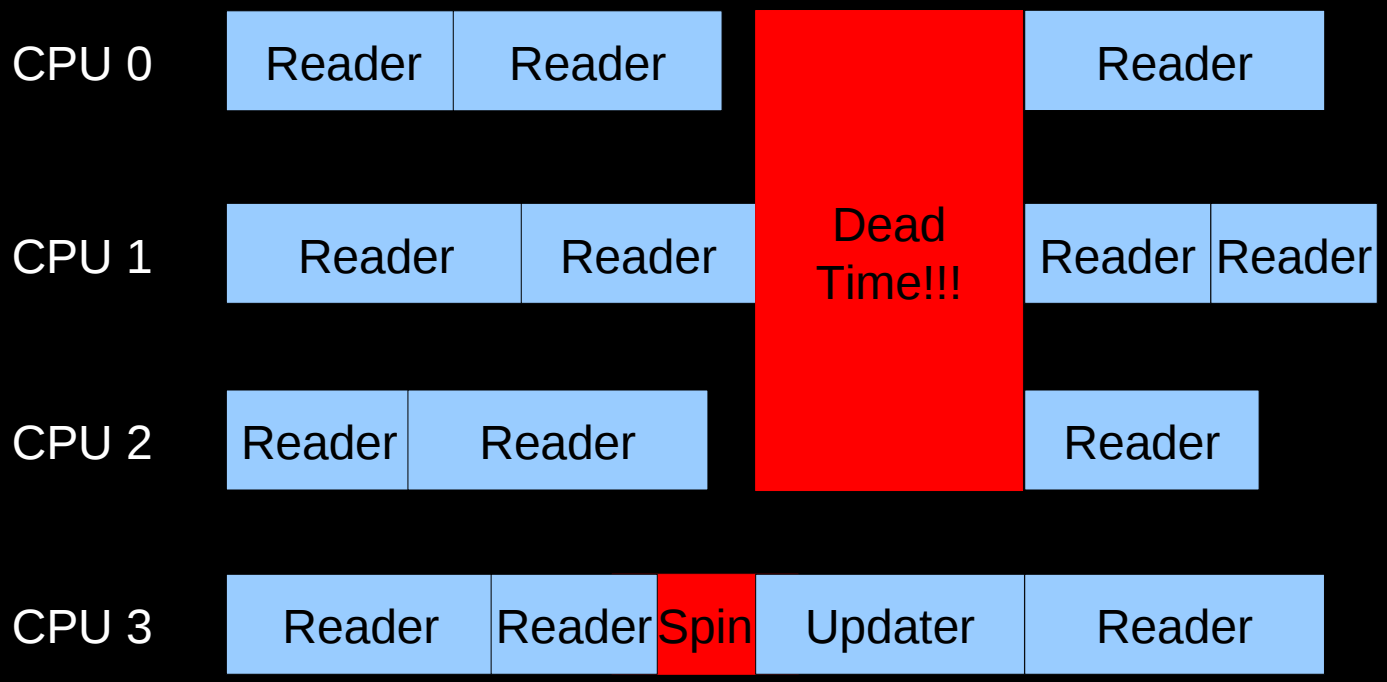
Heavily optimized reader-writer lock might get here for readers (but too bad about those poor writers...)

Typical synchronization mechanisms do this a lot

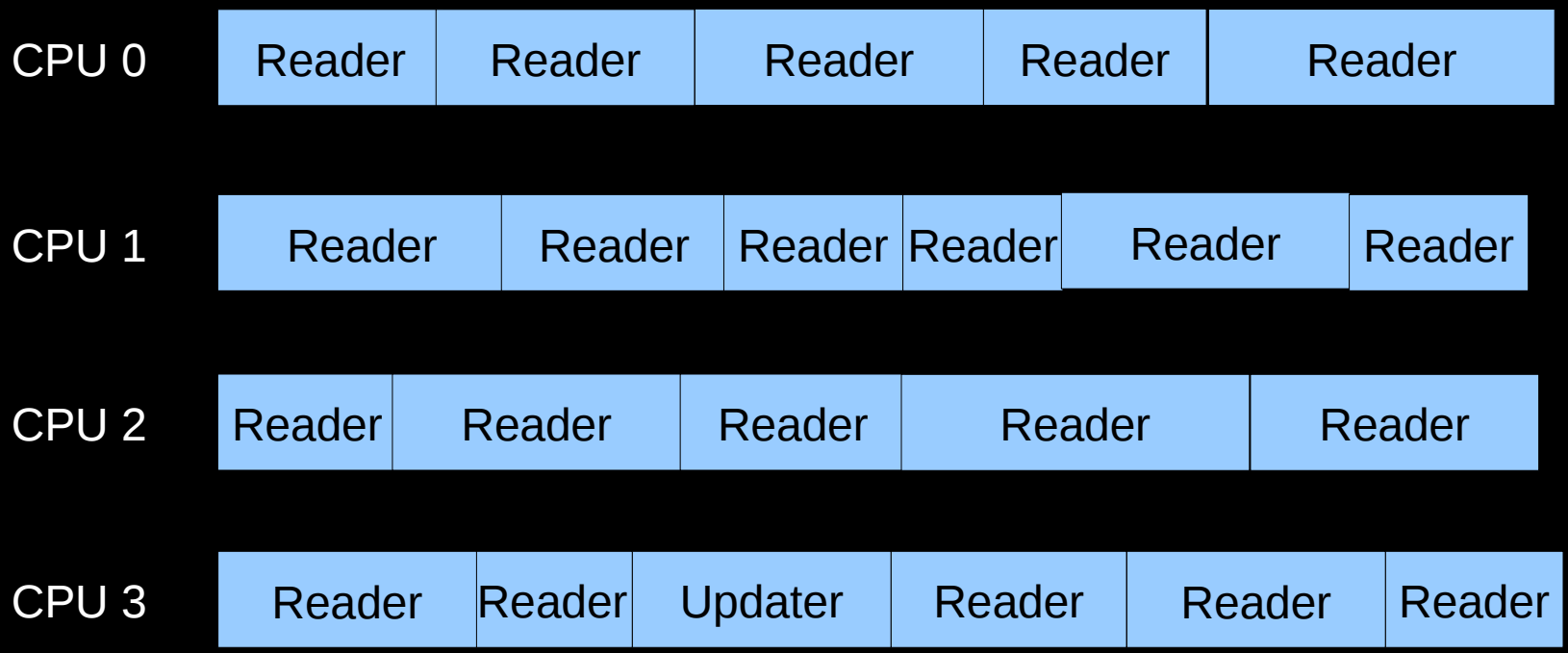
Design Principle: Get Your Money's Worth

- 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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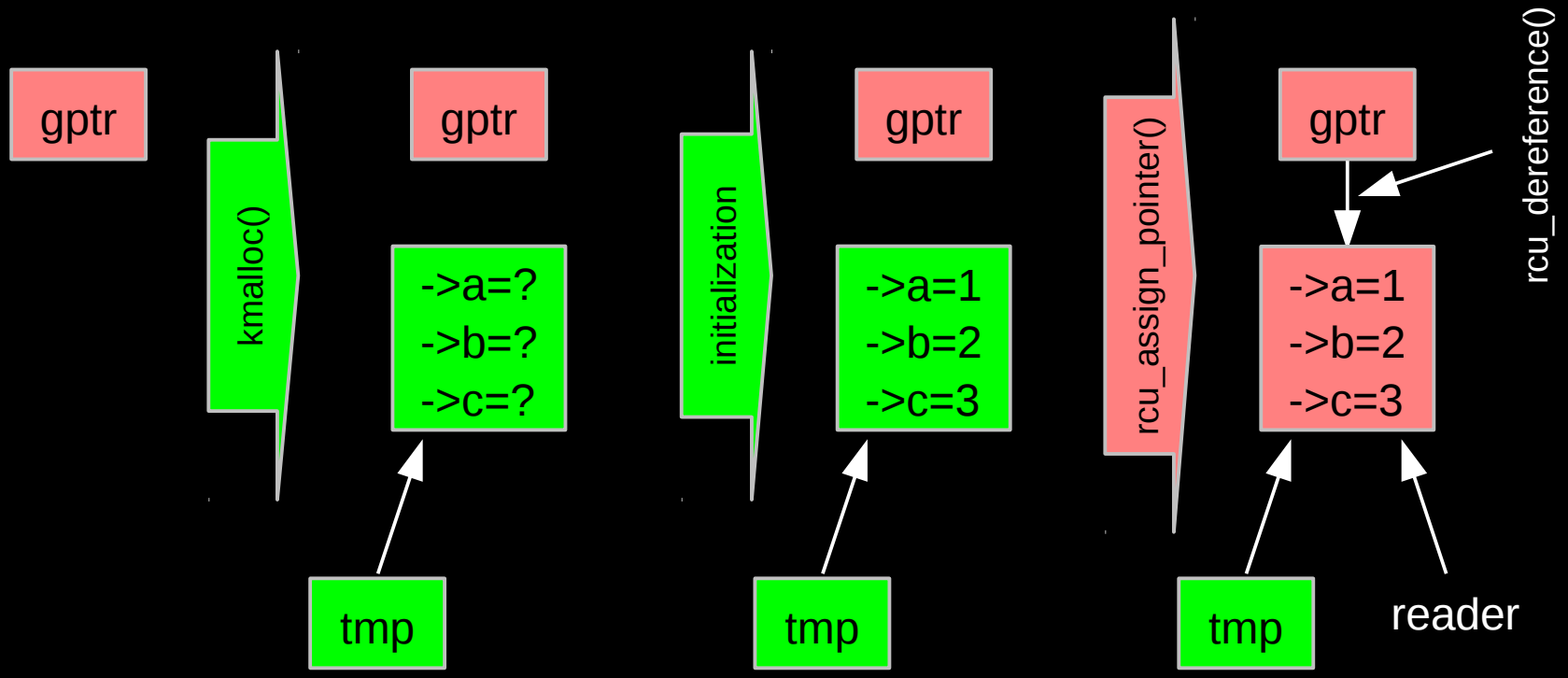
- But first, what is RCU???

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;
gptr = p;
```

- Original reader code:

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

- Mischievous updater code:

```
p = malloc(sizeof(*p));
gptr = p;
p->a = 1;
p->b = 2;
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- Mischievous reader code:

```
retry:
p = guess(gptr);
foo(p->a, p->b, p->c);
if (p != gptr)
    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(gptr, p);
```

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

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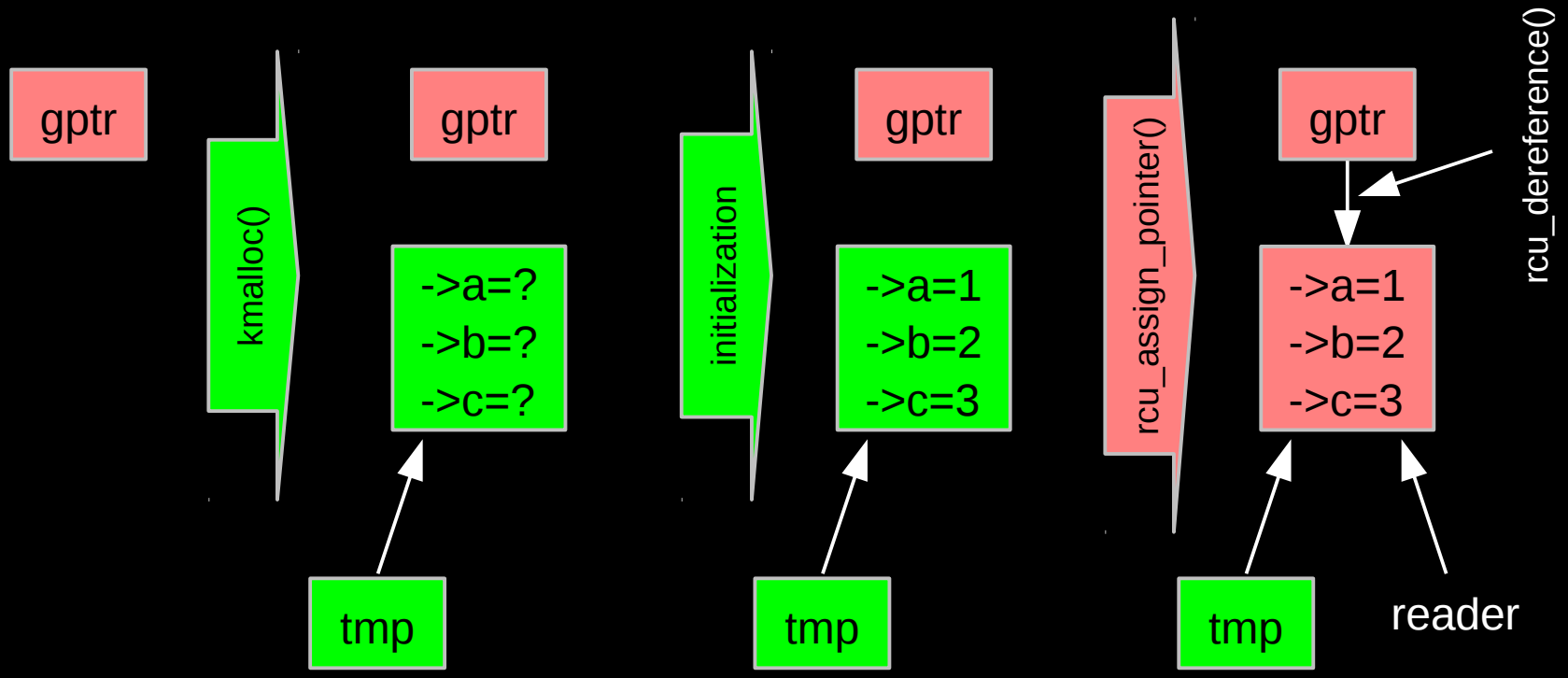
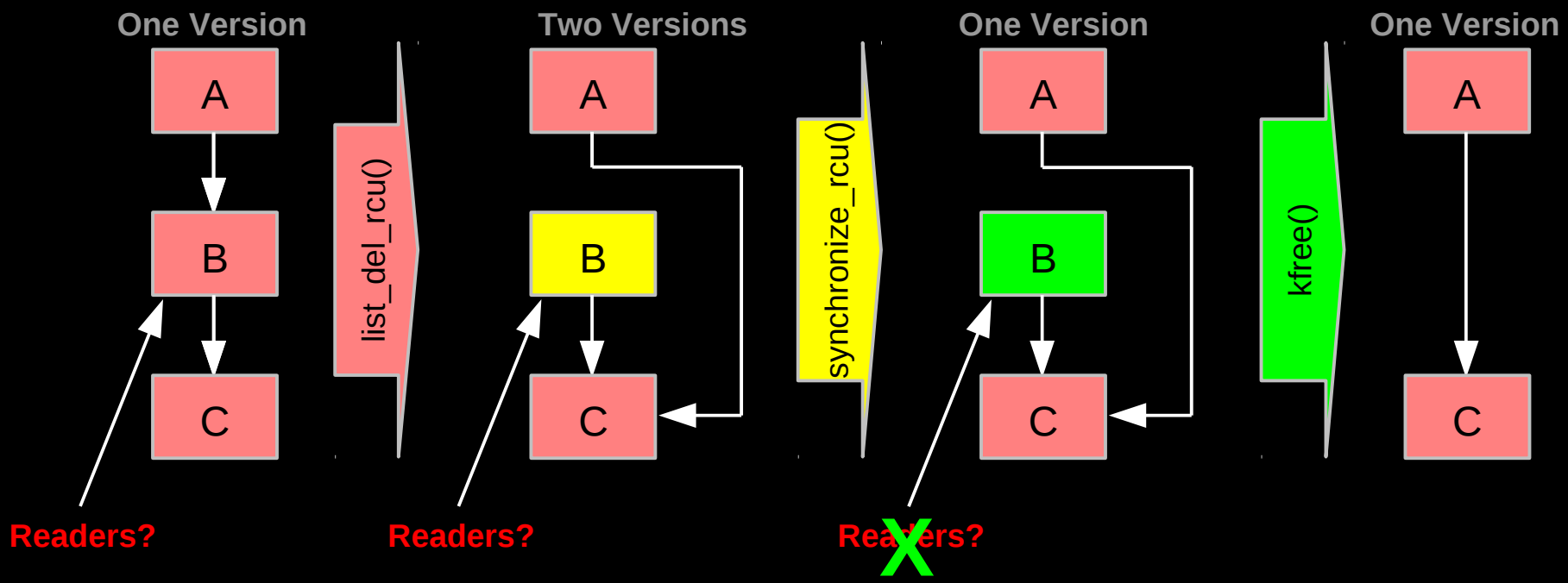


But if all we do is add, we have a big memory leak!!!

RCU Removal From Linked List

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



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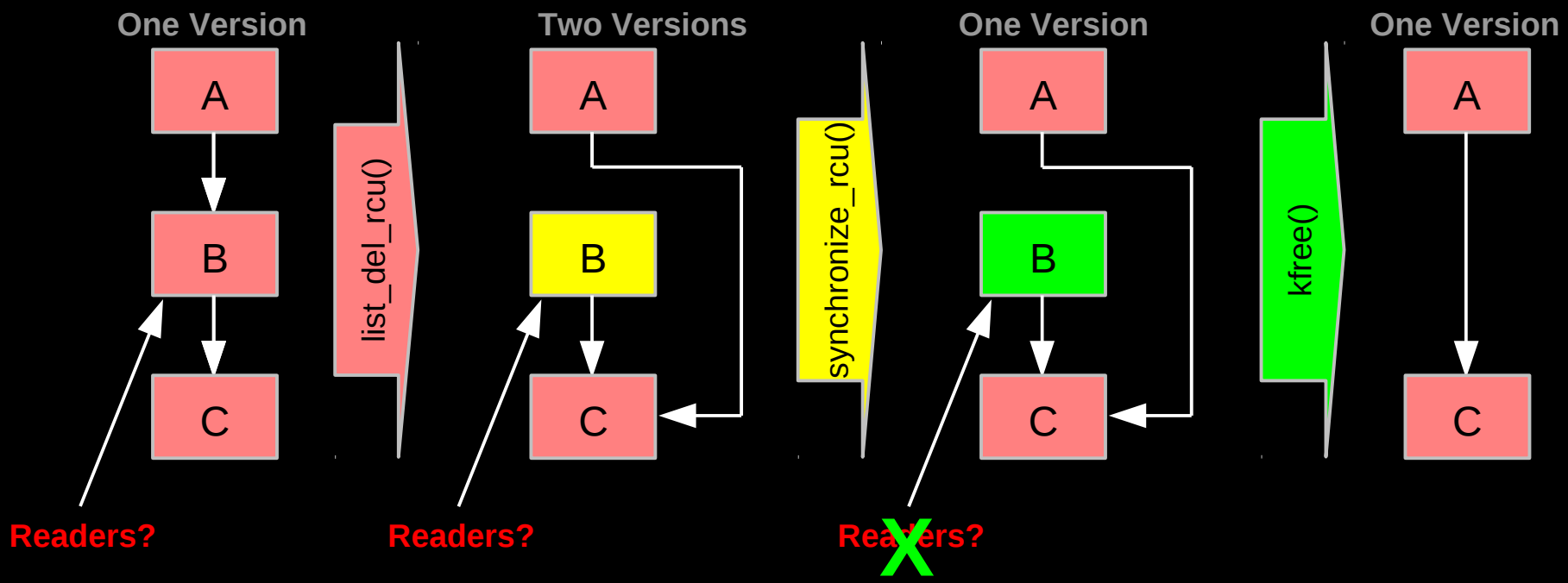

But if readers leave no trace in memory, how can we possibly tell when they are done???

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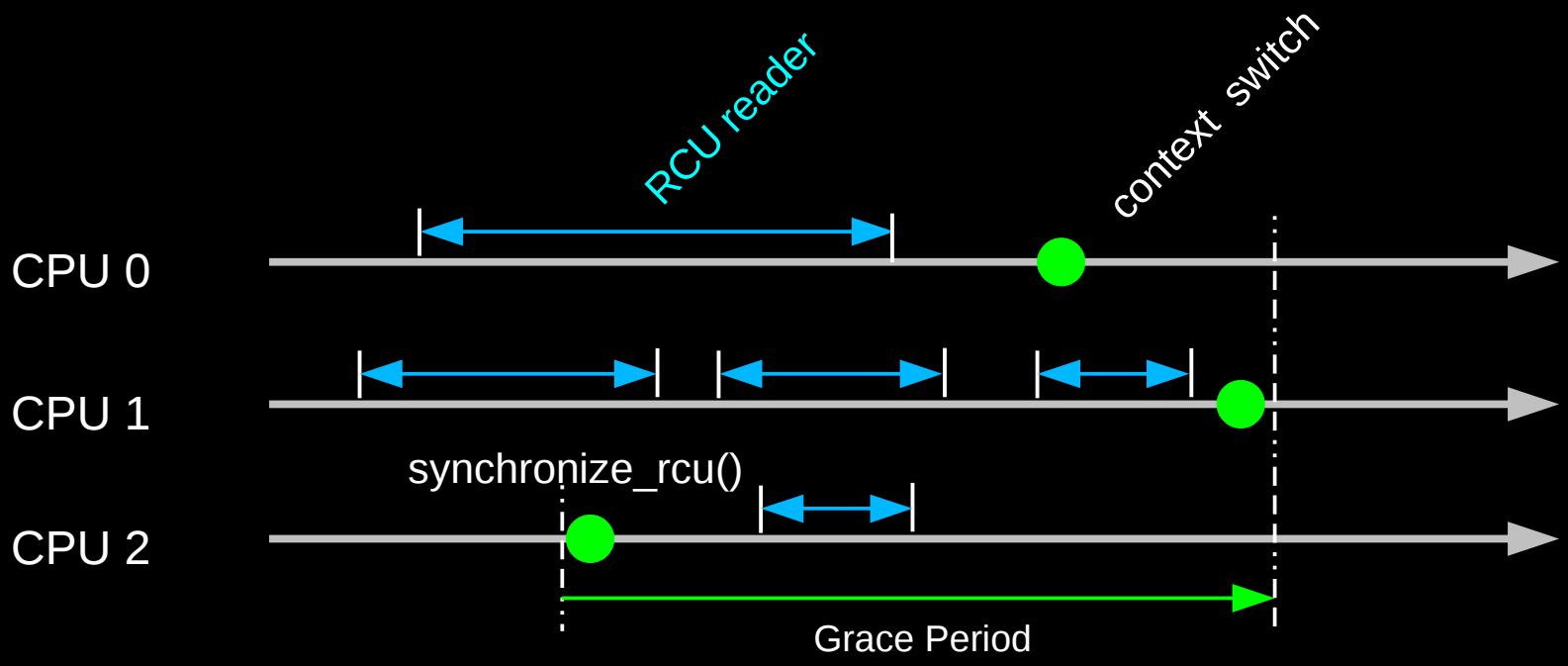
  - Time period when every thread was in at least one quiescent state
- OK, names are nice, but how can you possibly implement this???

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

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



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);
}
```

Toy Implementation of RCU: 20 Lines of Code

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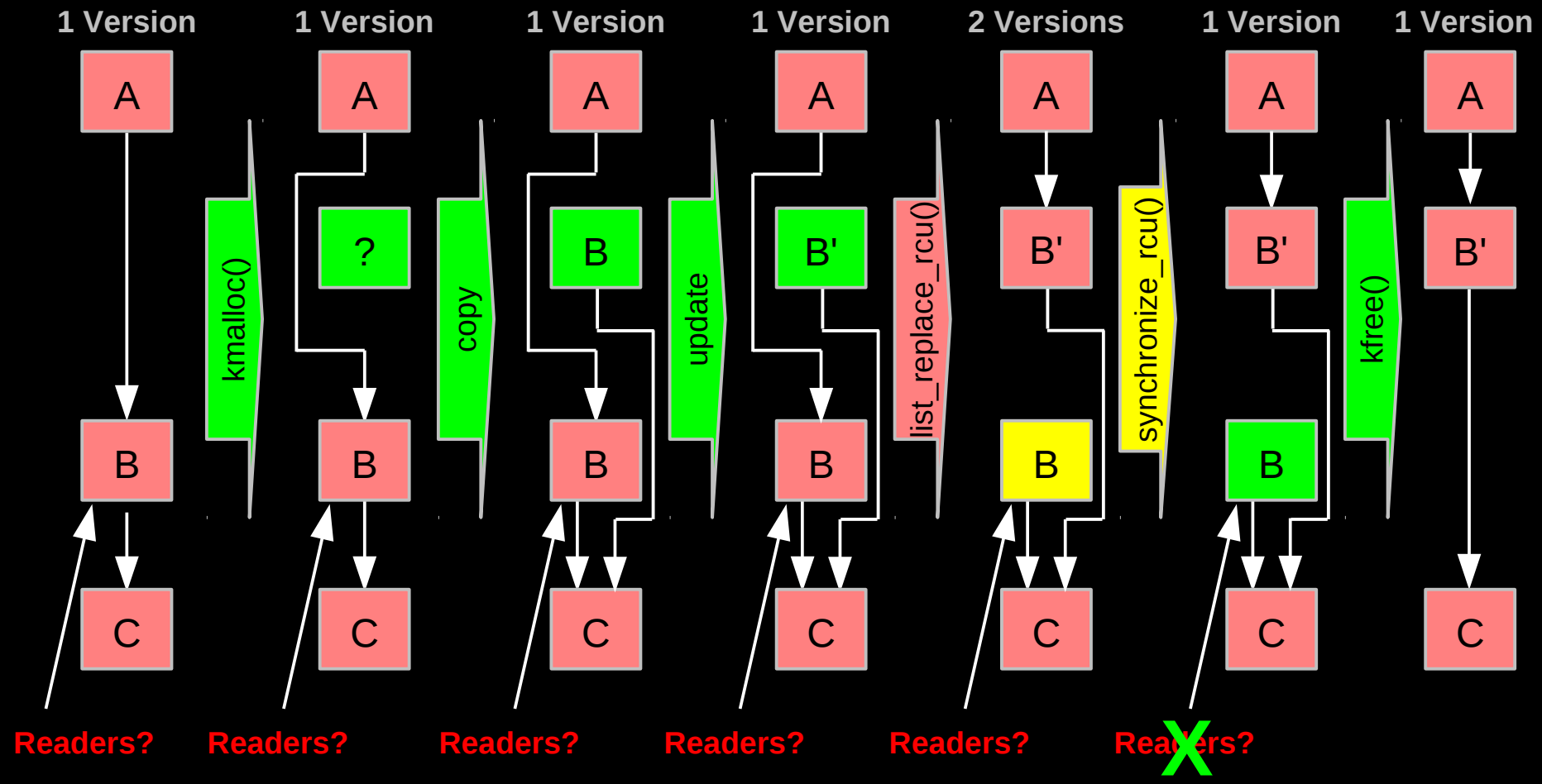
        for_each_online_cpu(cpu)
                run_on(cpu);
}
```

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

- *RCU read-side critical section*
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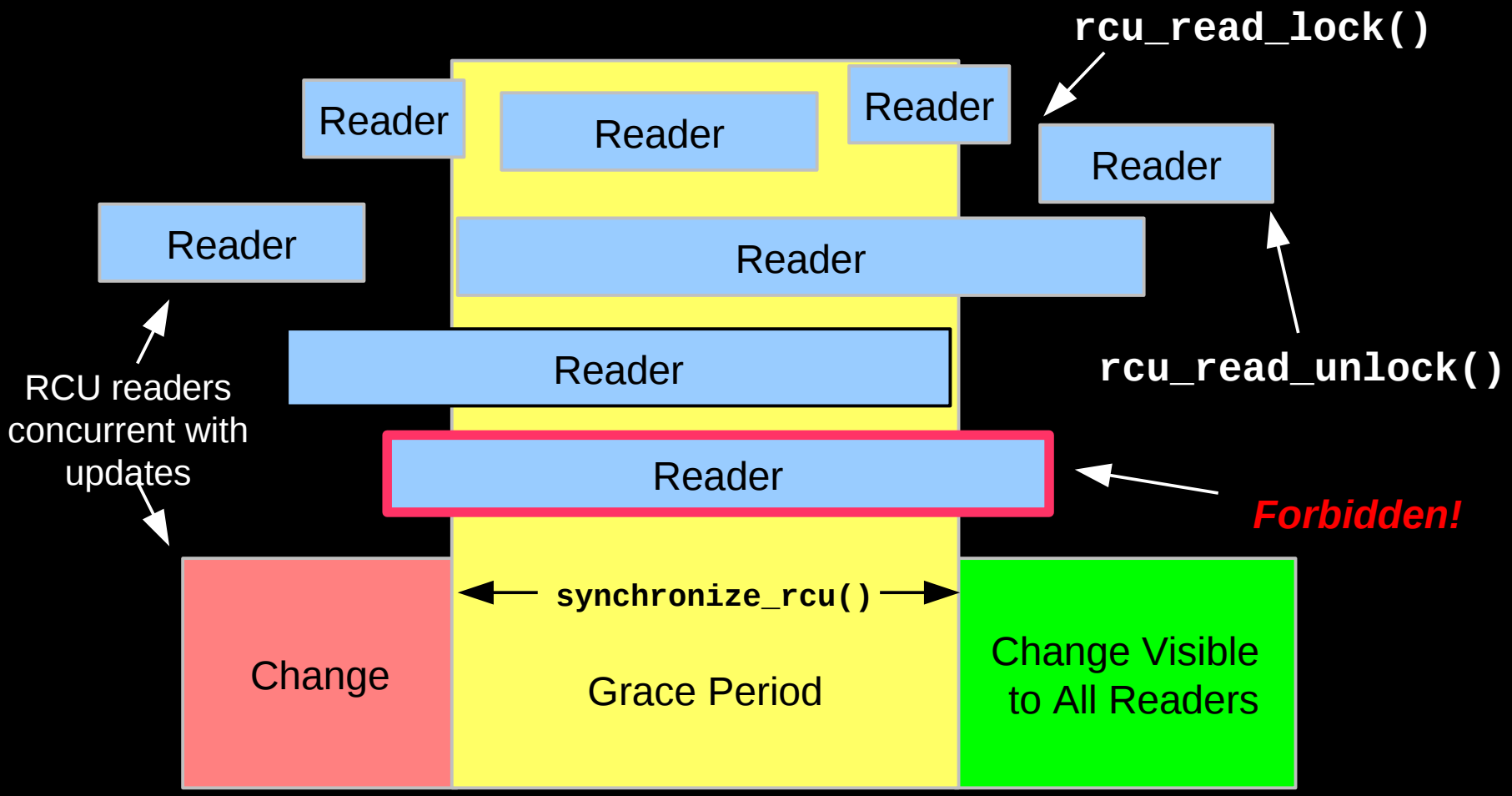
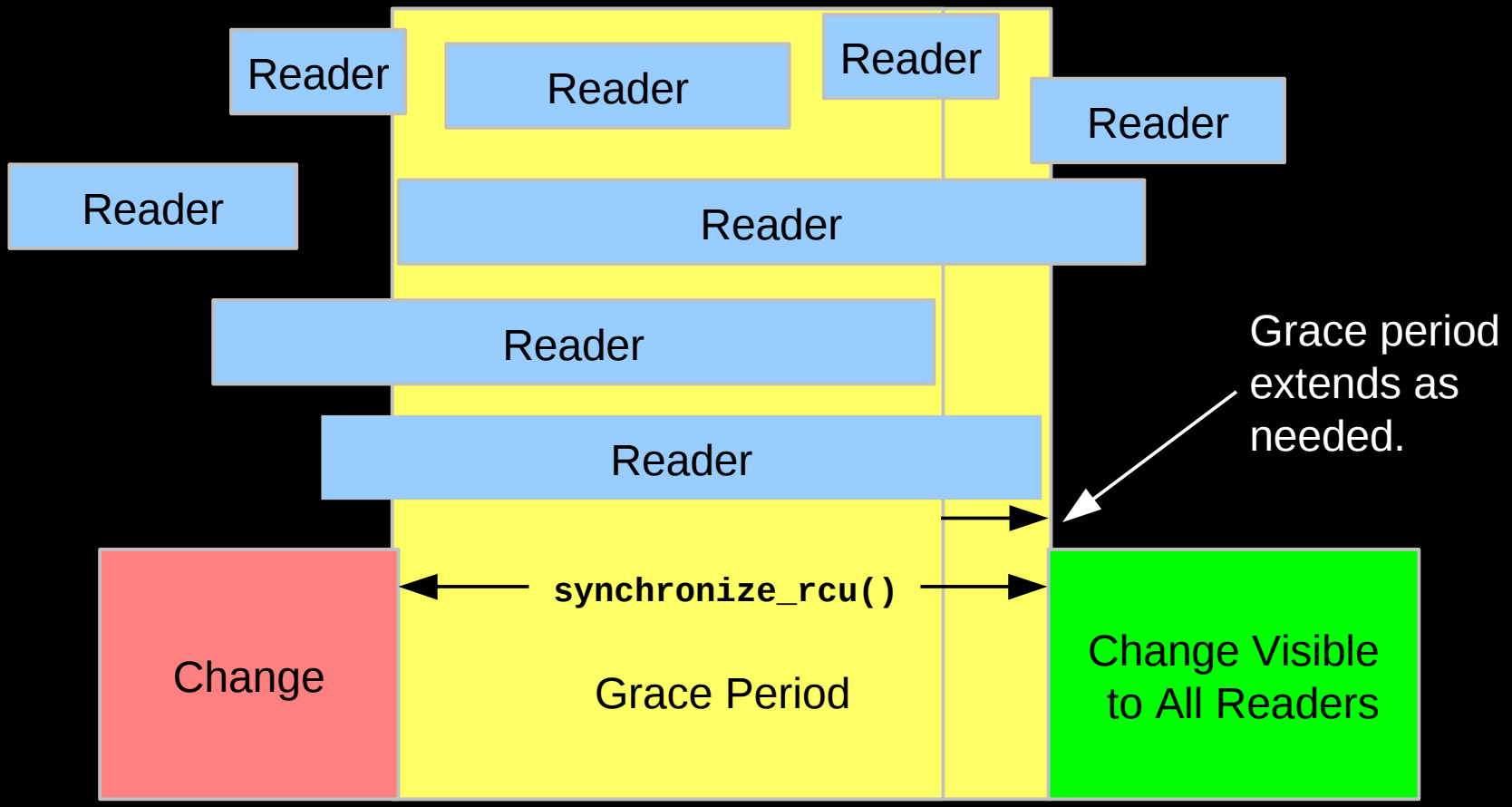
- *Quiescent state*
  - Any code that is not in an RCU read-side critical section
- *Extended quiescent state*
  - Quiescent state that persists for a significant time period
- *RCU grace period*
  - Time period when every thread is in at least one quiescent state
  - Ends when all pre-existing readers 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



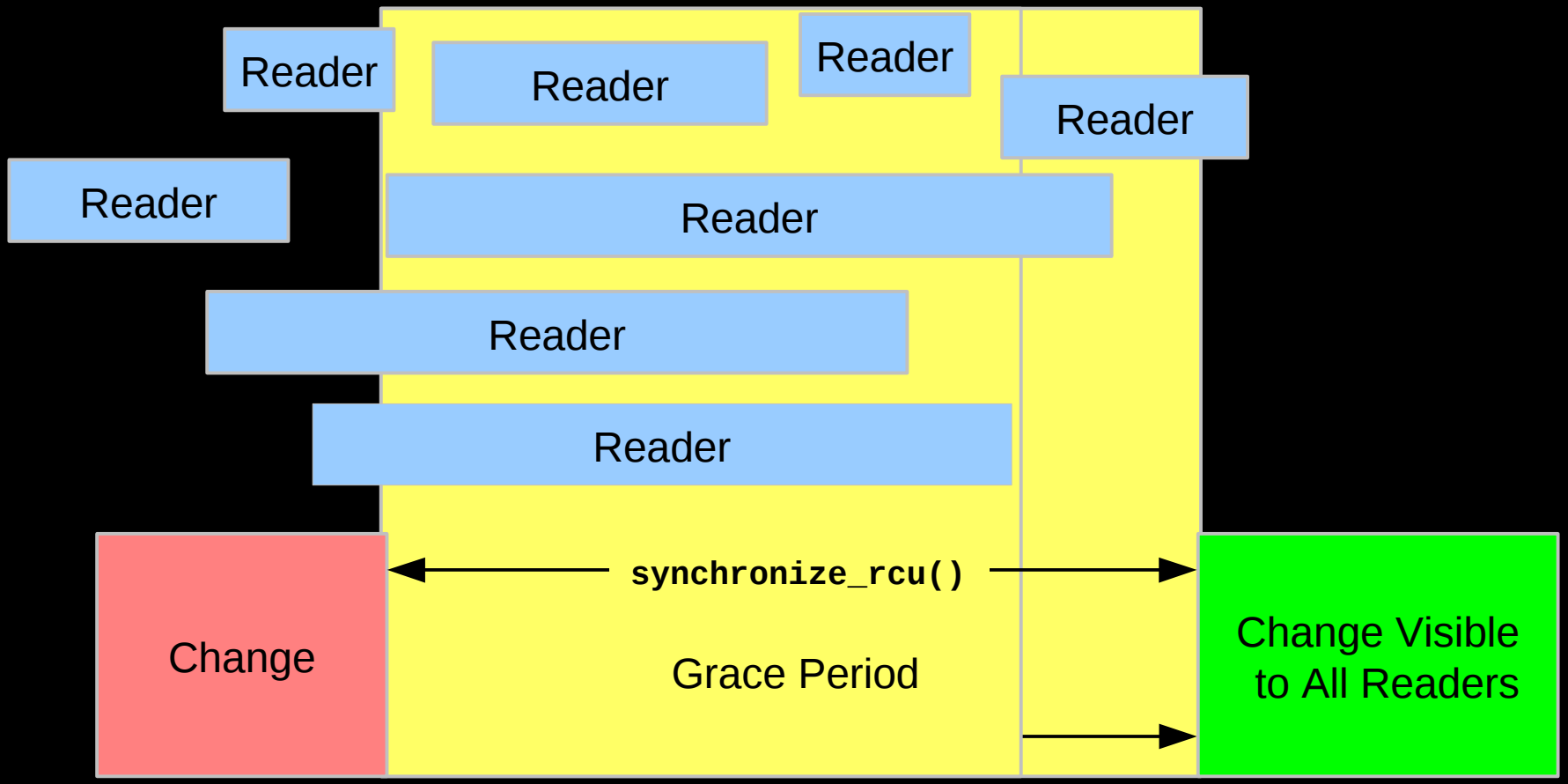
So what happens if you try to extend an RCU read-side critical section across a grace period?

RCU Grace Period: A Self-Repairing Graphical View



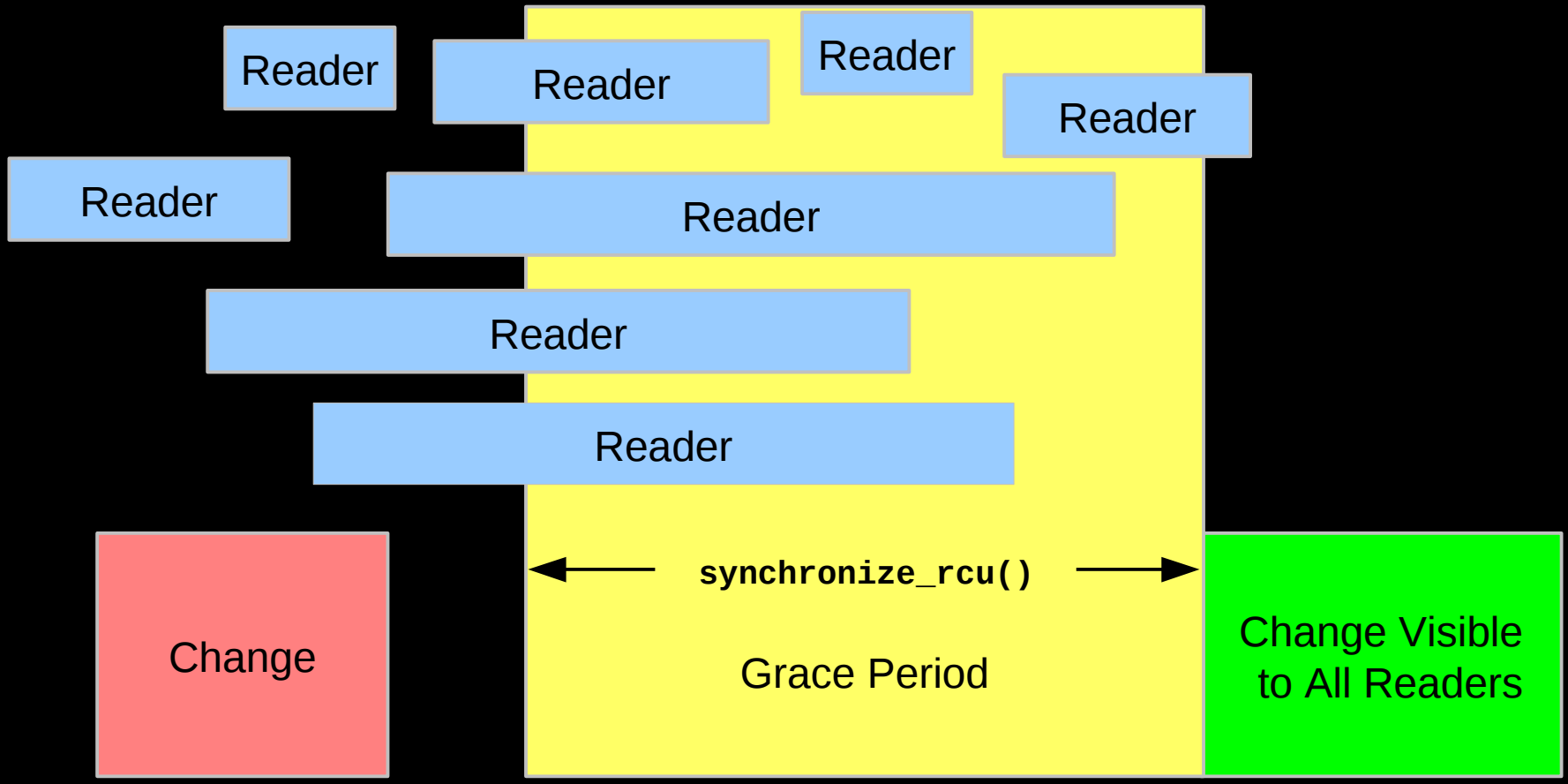
A grace period is not permitted to end until all pre-existing readers have completed.

RCU Grace Period: A Lazy Graphical View



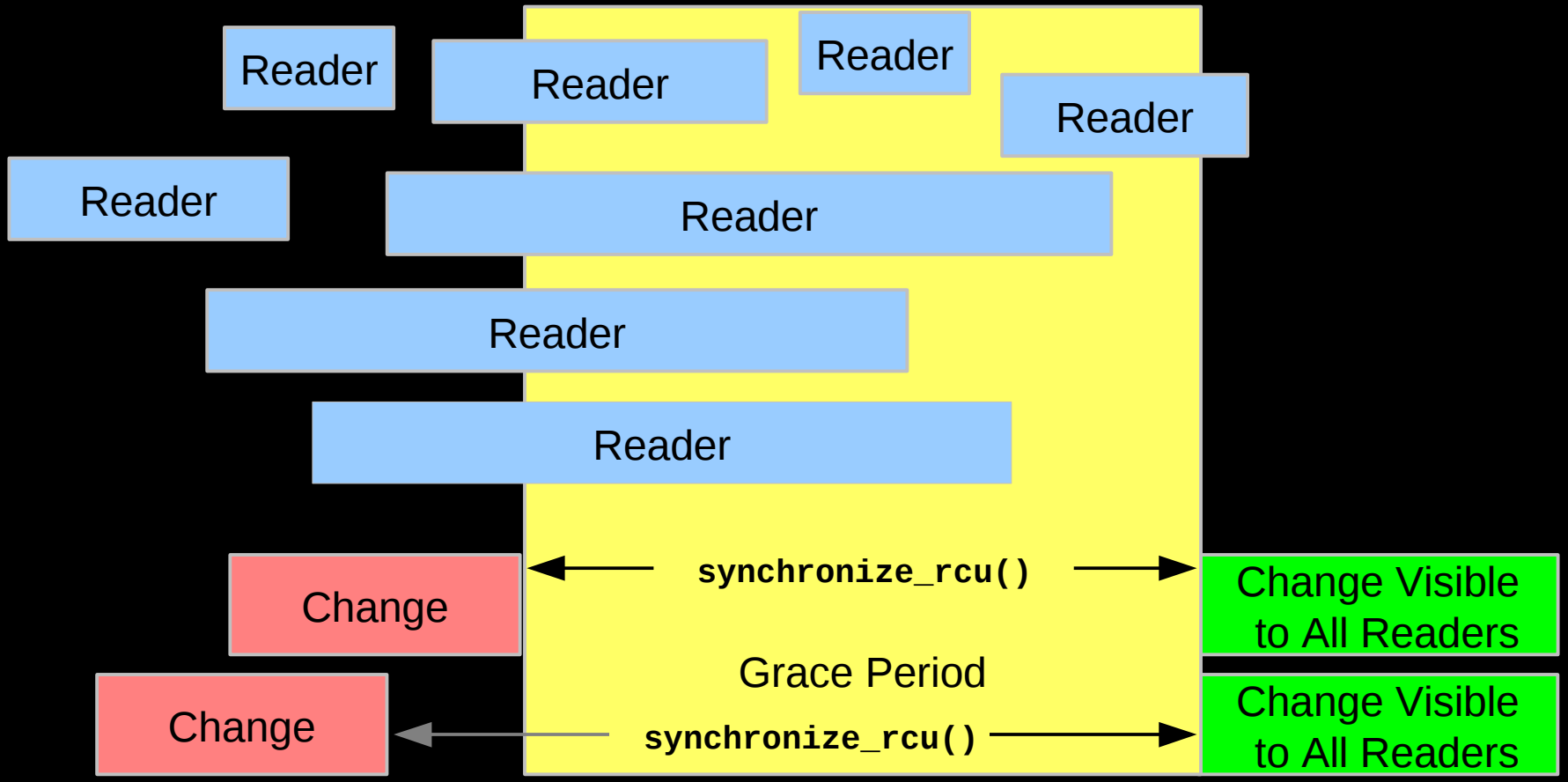
But it is OK for RCU to be lazy and allow a grace period to extend longer than necessary

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

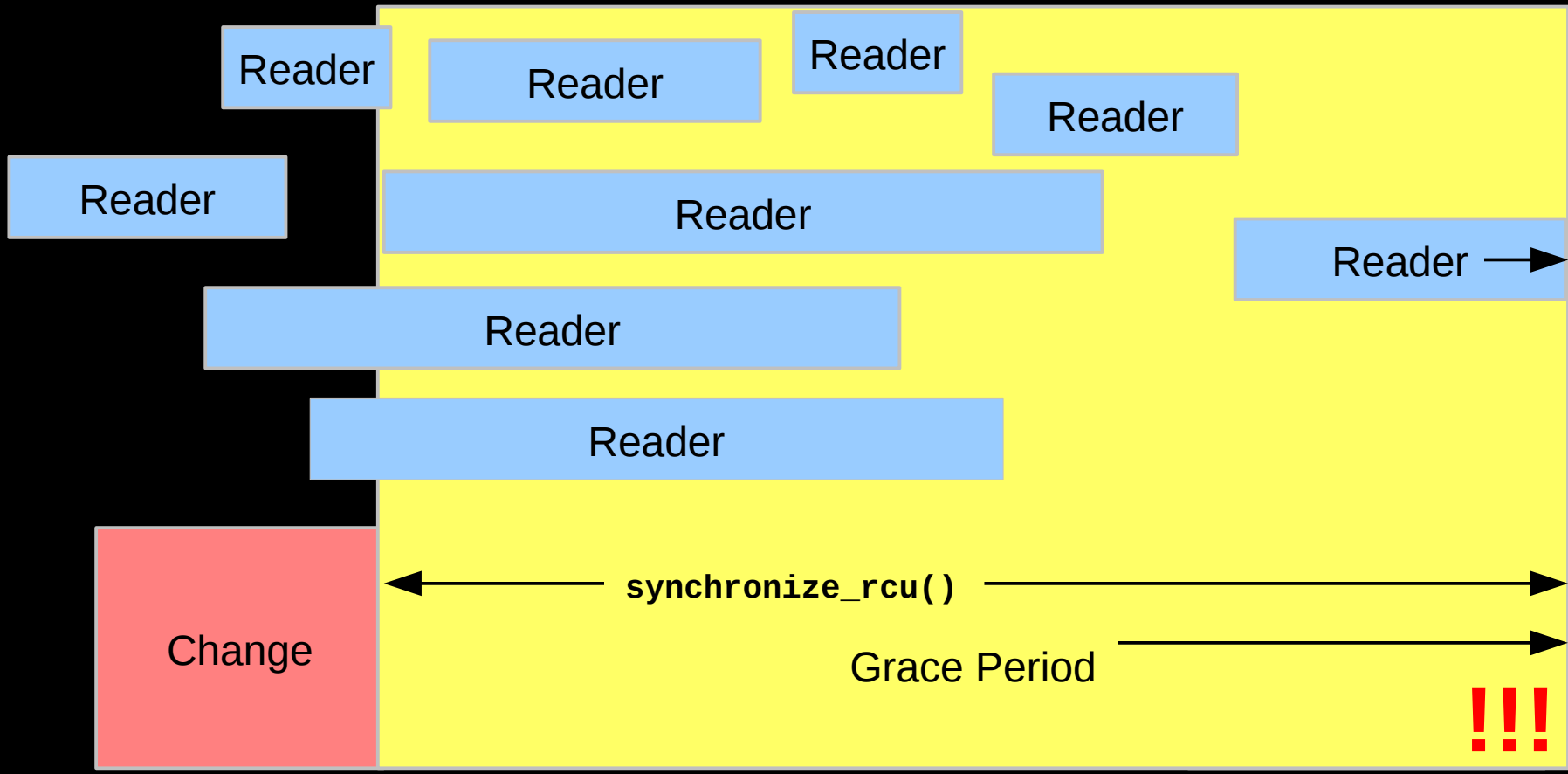


Starting a grace period late can allow it to serve multiple updates, decreasing the per-update RCU overhead. But...

The Costs and Benefits of Laziness

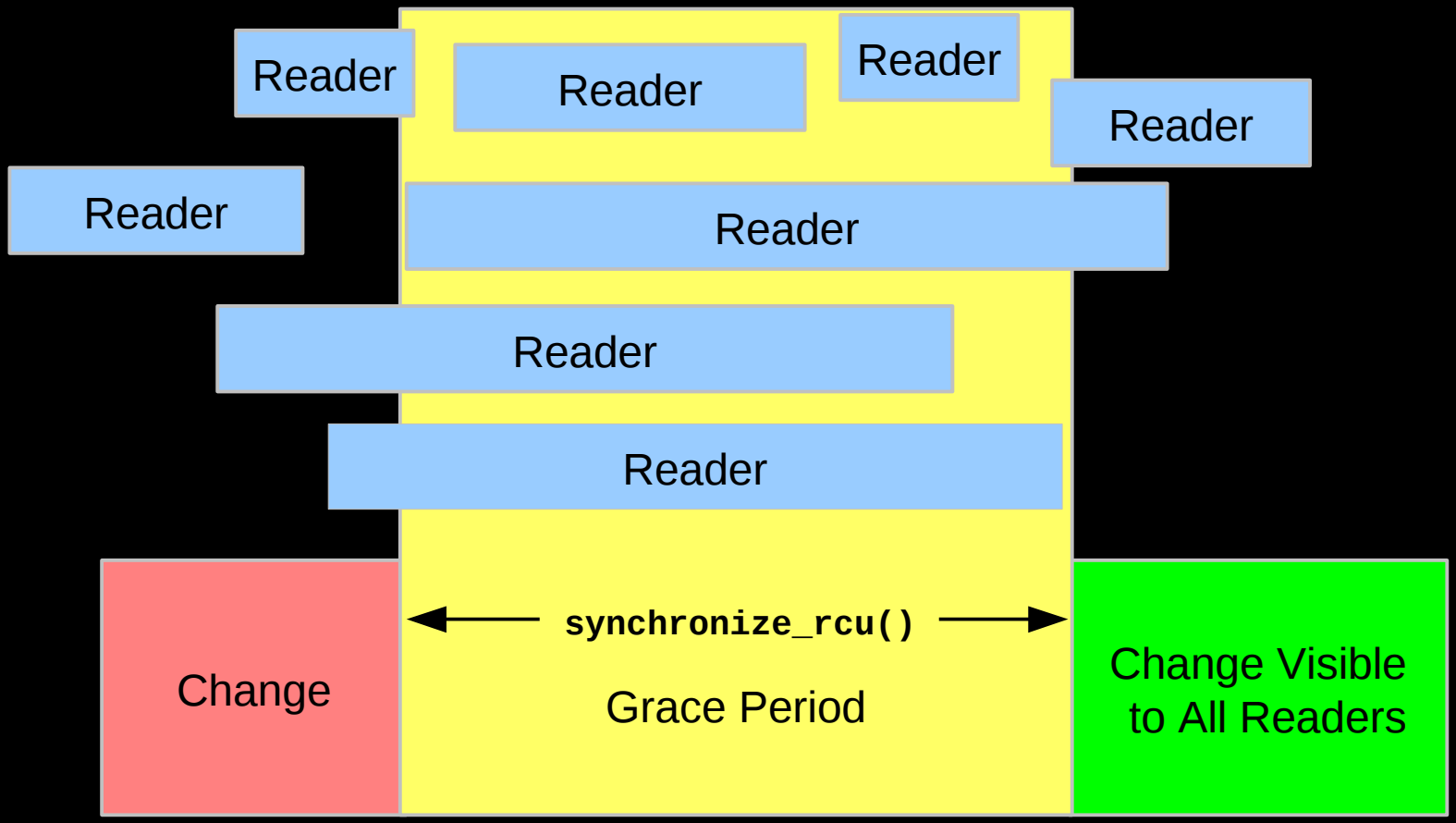
- Starting the grace period later increases the number of updates per grace period, reducing the per-update overhead
- Delaying the end of the grace period increases grace-period latency
- Increasing the number of updates per grace period increases the memory usage
  - Therefore, starting grace periods 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



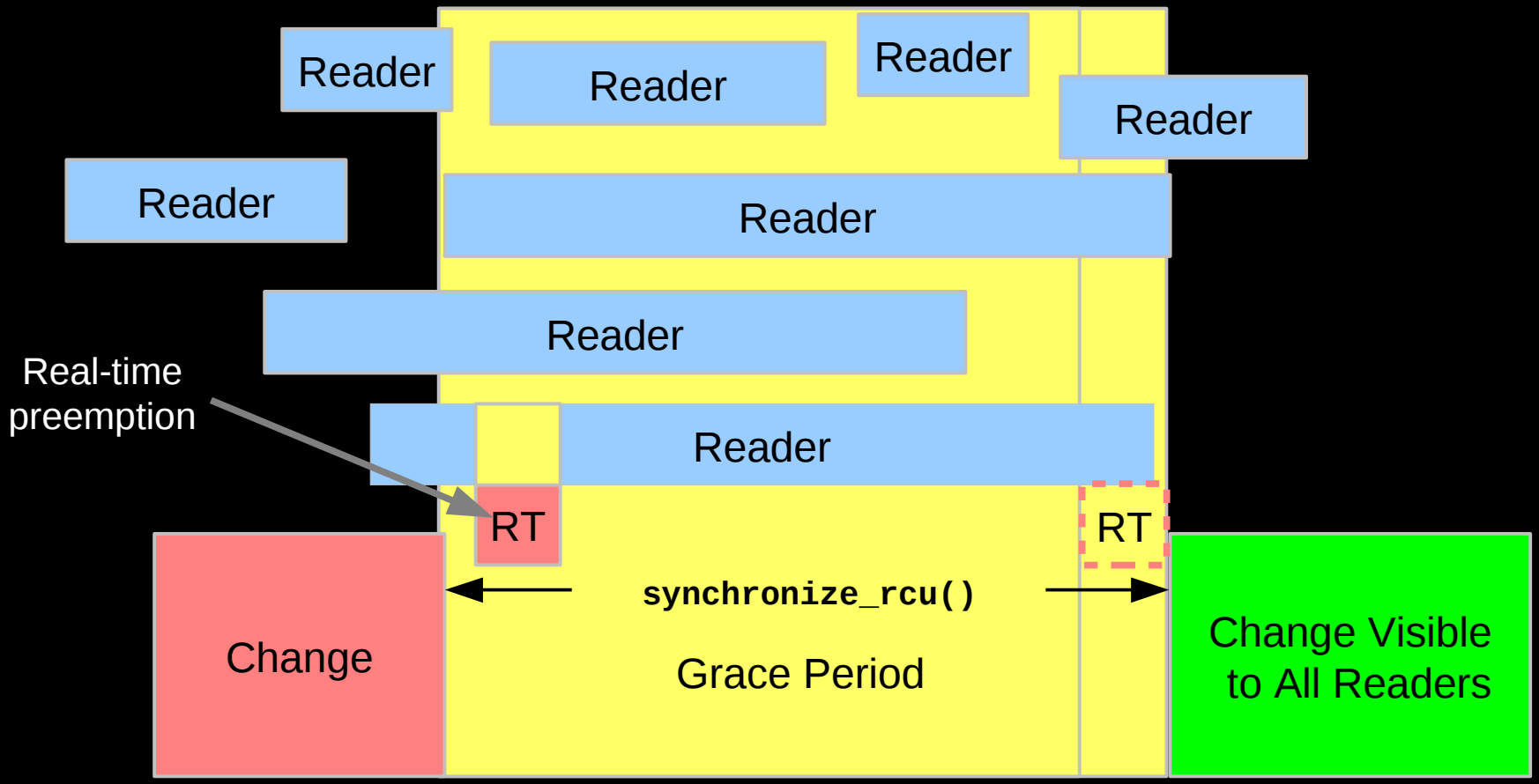
And it is OK for the system to complain (or even abort) if a grace period extends too long.
Too-long of grace periods are likely to result in death by memory exhaustion anyway.

RCU Grace Period: The Original Graphical View



Returning to the minimum-duration grace period.

RCU Grace Period: A Preempted Graphical View



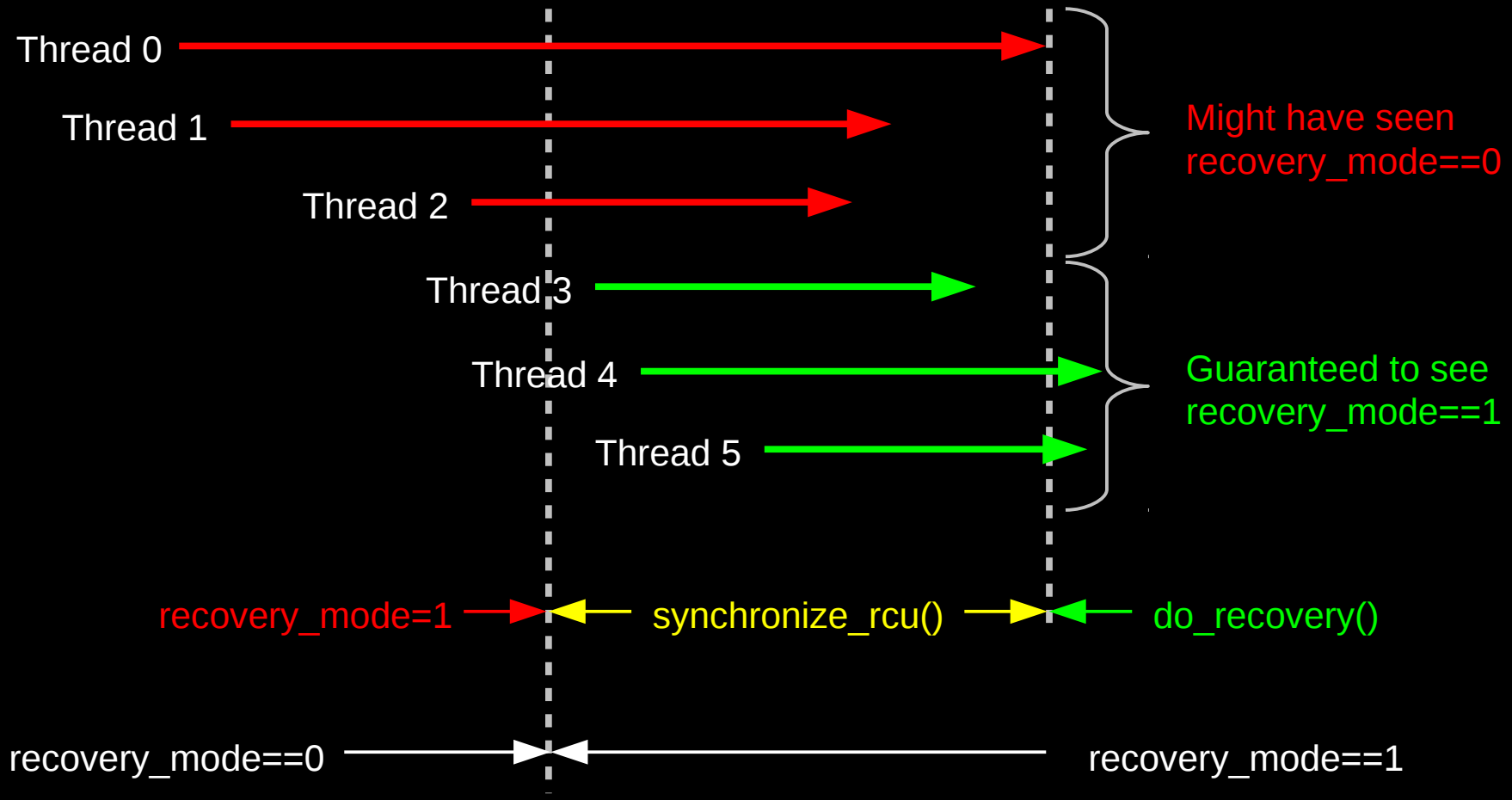
Real-time scheduling constraints can extend grace periods by preempting RCU readers.
It is sometimes necessary to priority-boost RCU readers.

RCU-Mediated Mode Change

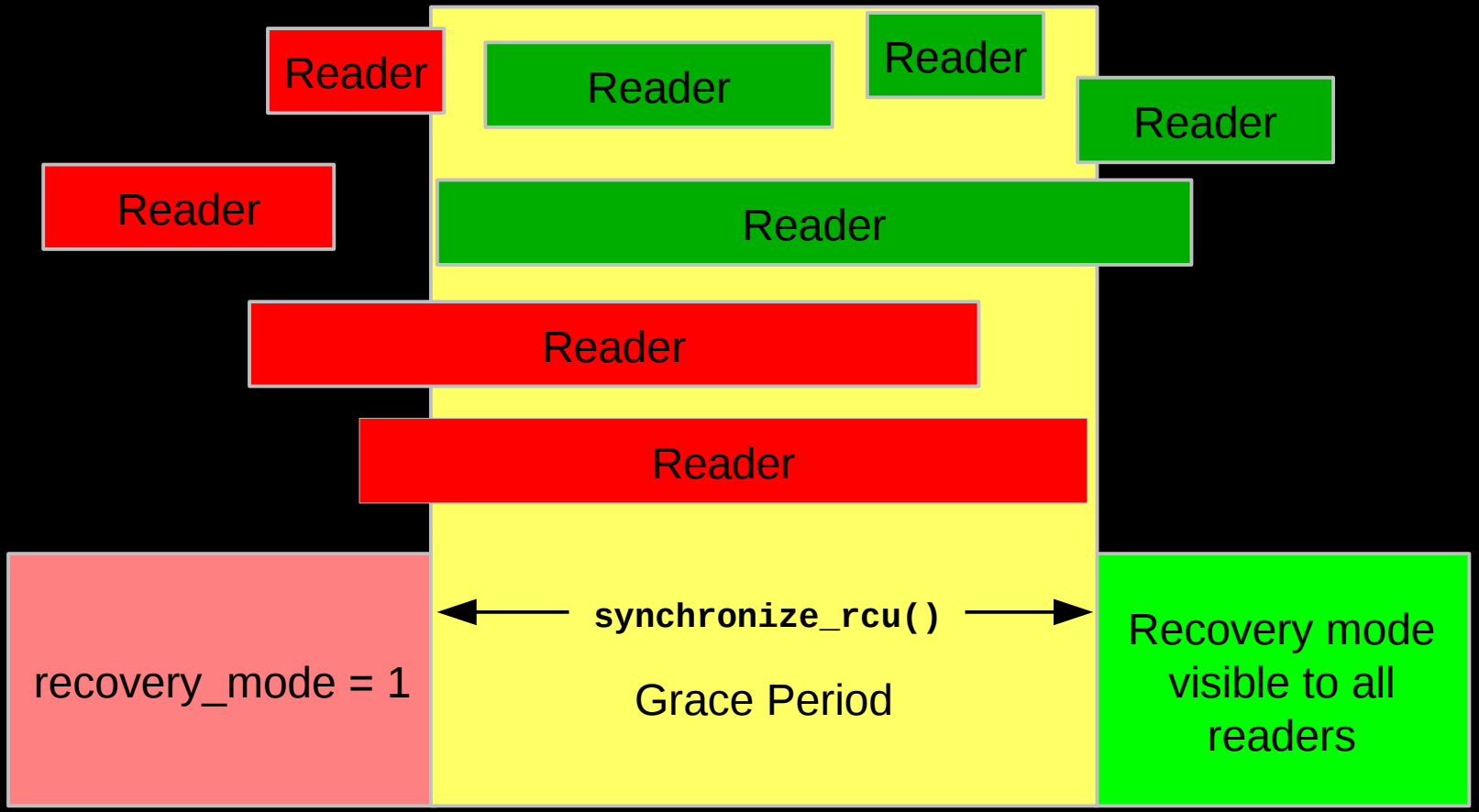
RCU-Mediated Mode Change

- One of the first uses for RCU
- Distributed lock manager for clustered computing
  - Nodes can fail
  - When node failure is detected, cluster enters recovery mode
  - Every distributed-lock operation checks for being in recovery mode
  - Having every operation acquire yet another lock would be slow
    - And prone to deadlock
  - Instead, RCU is used to protect the variable that indicates whether or not the system is in recovery mode

RCU-Mediated Mode Change Diagram



RCU Grace Period: A Mode-Change Graphical View



Red readers might be unaware of recovery_mode==1, green readers guaranteed to be aware.

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:

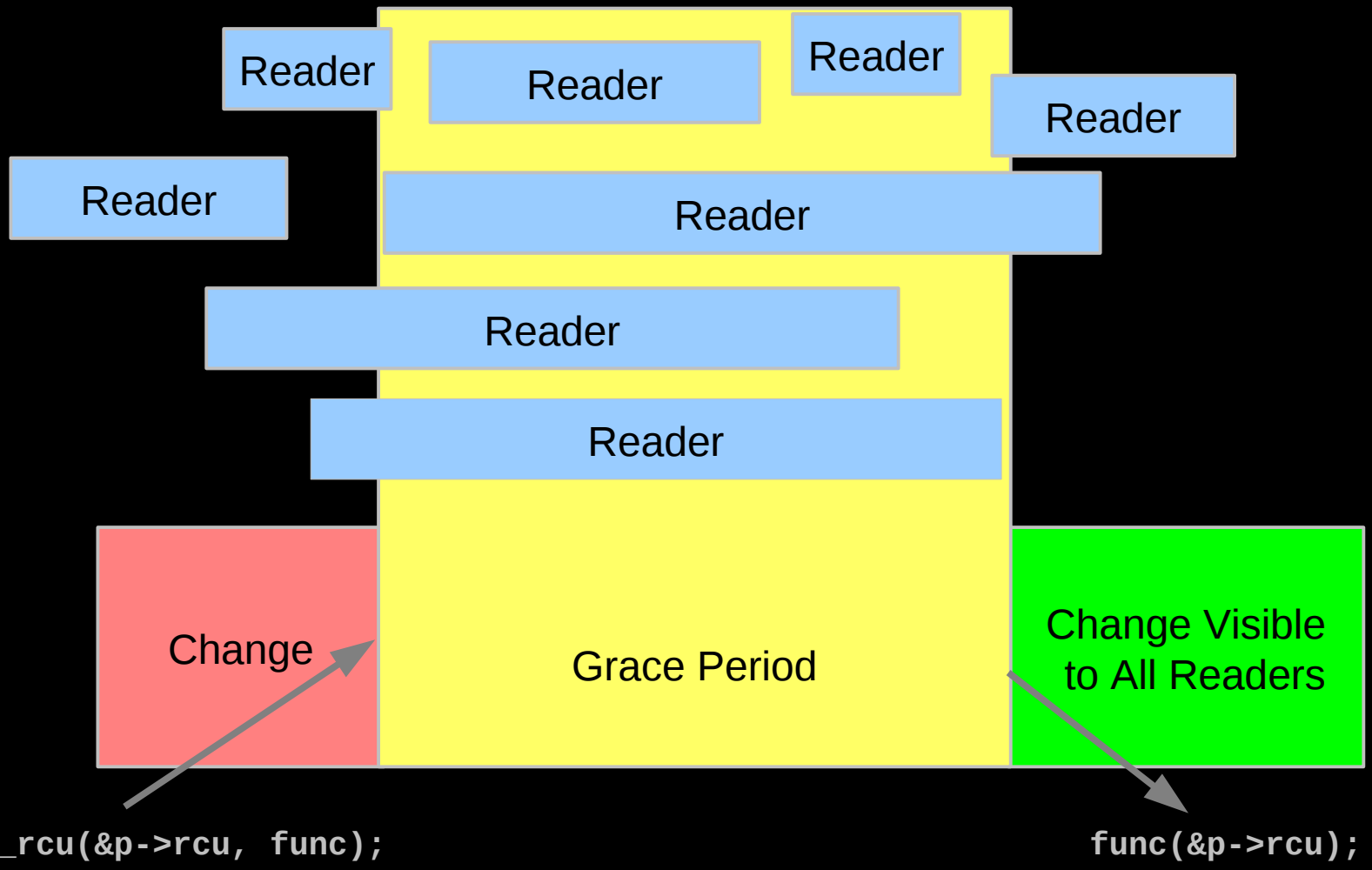
```
call_rcu(struct rcu_head head,
         void (*func)(struct rcu_head *rcu));
```

- 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

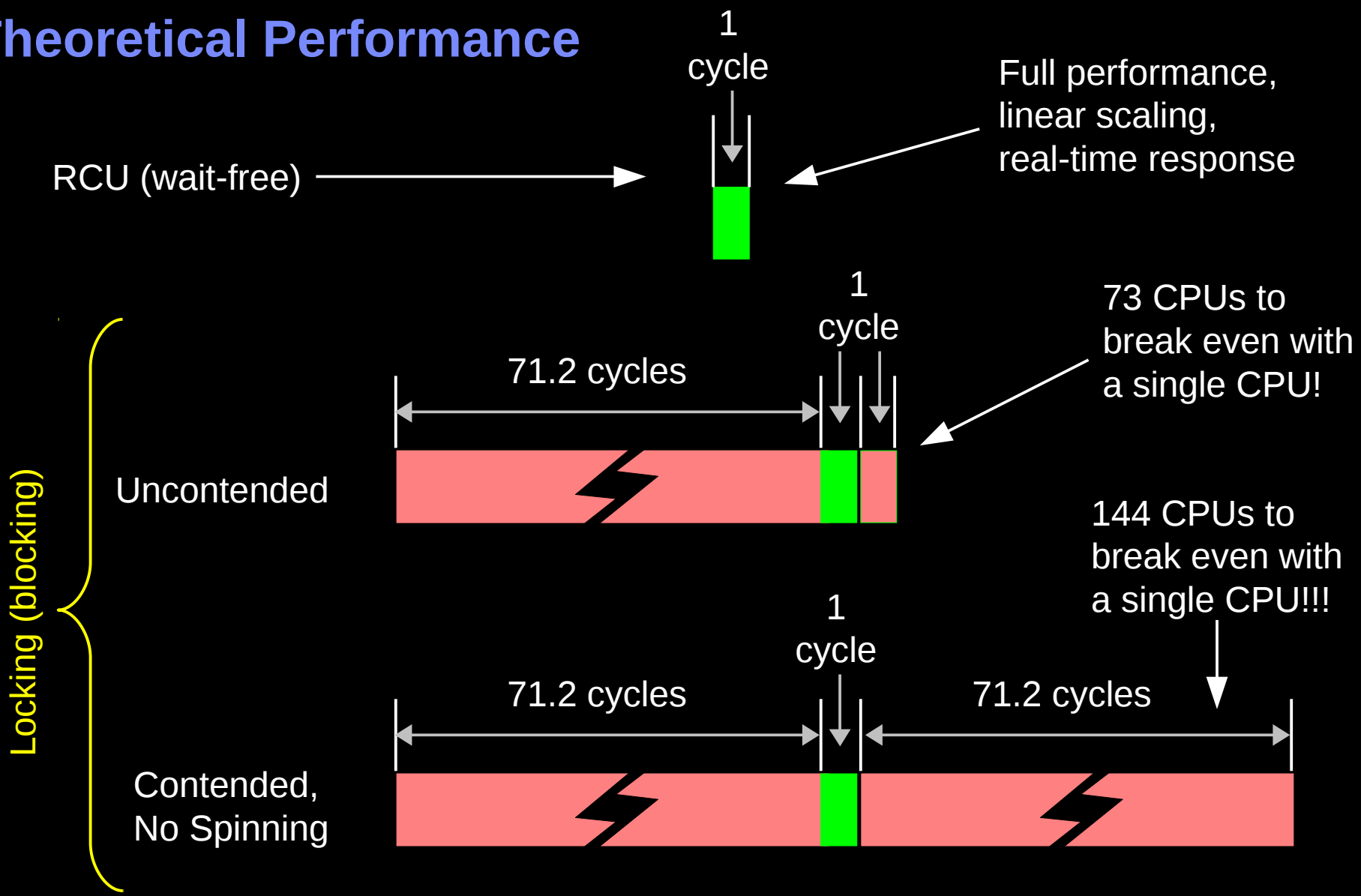


RCU Asynchronous Grace-Period Detection

- But suppose `call_rcu()` is invoked from a kernel module, which is later unloaded?
  - When is it safe to actually unload the module?
  - Only after all outstanding RCU callbacks registered by that module have been invoked!
  - Otherwise, later RCU callbacks will try to reference that module's code and data, which have now been unloaded!!!
- Use `rcu_barrier()`: waits until all currently registered RCU callbacks have been invoked
  - After `rcu_barrier()` returns, safe to unload module

Performance

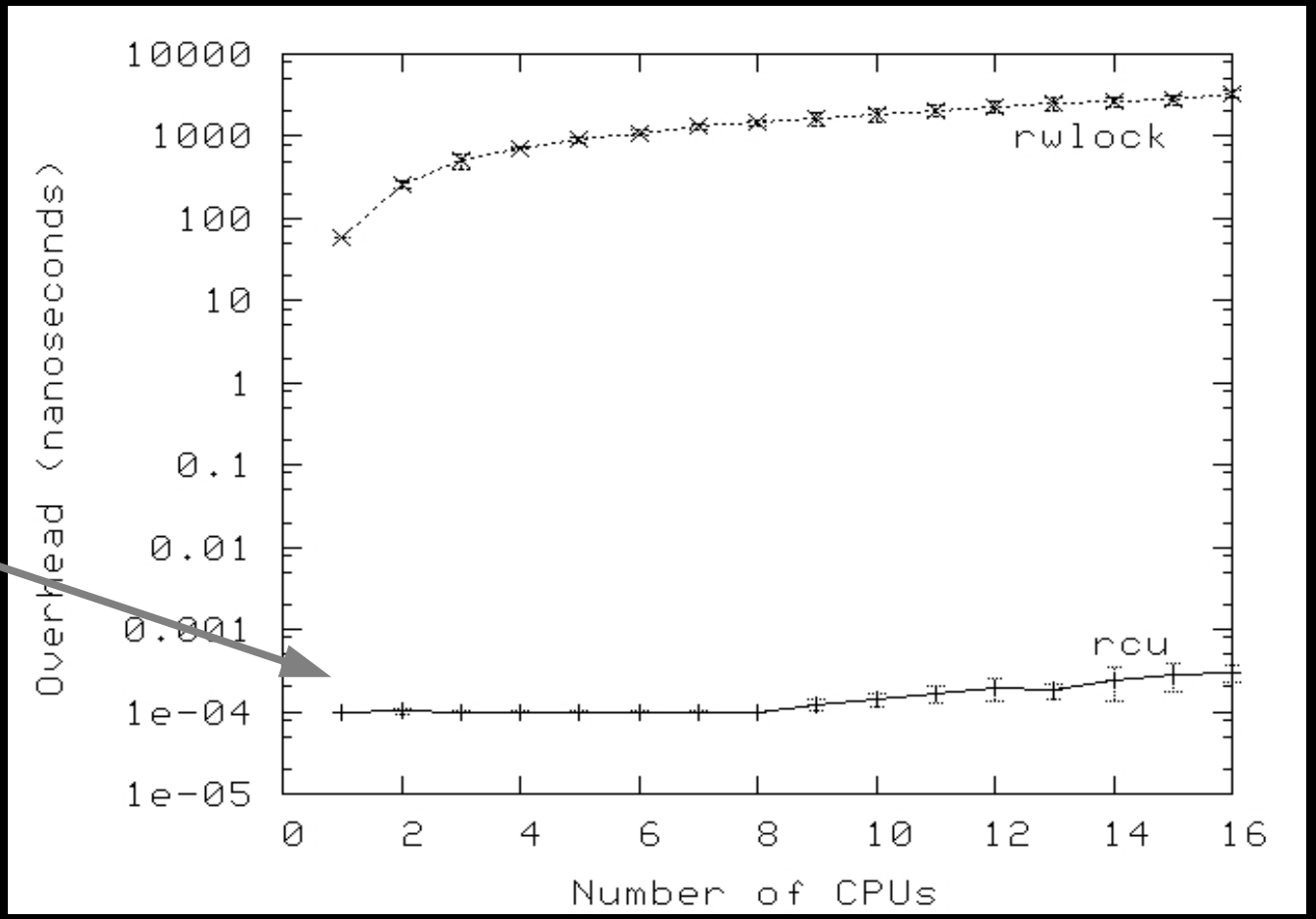
Theoretical Performance



Measured Performance

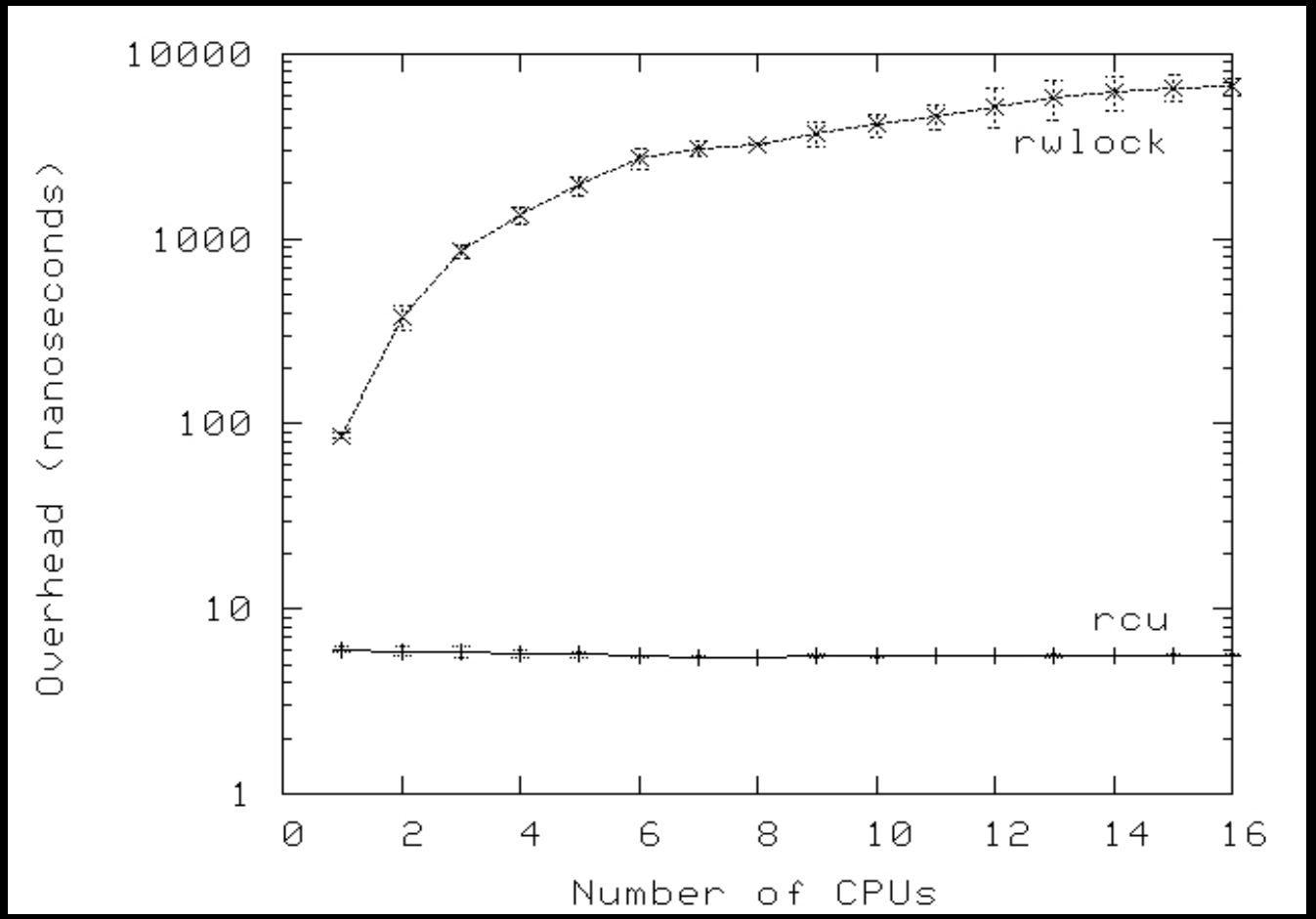
RCU vs. Reader-Writer Locking Read-Side Overhead

How is this possible?



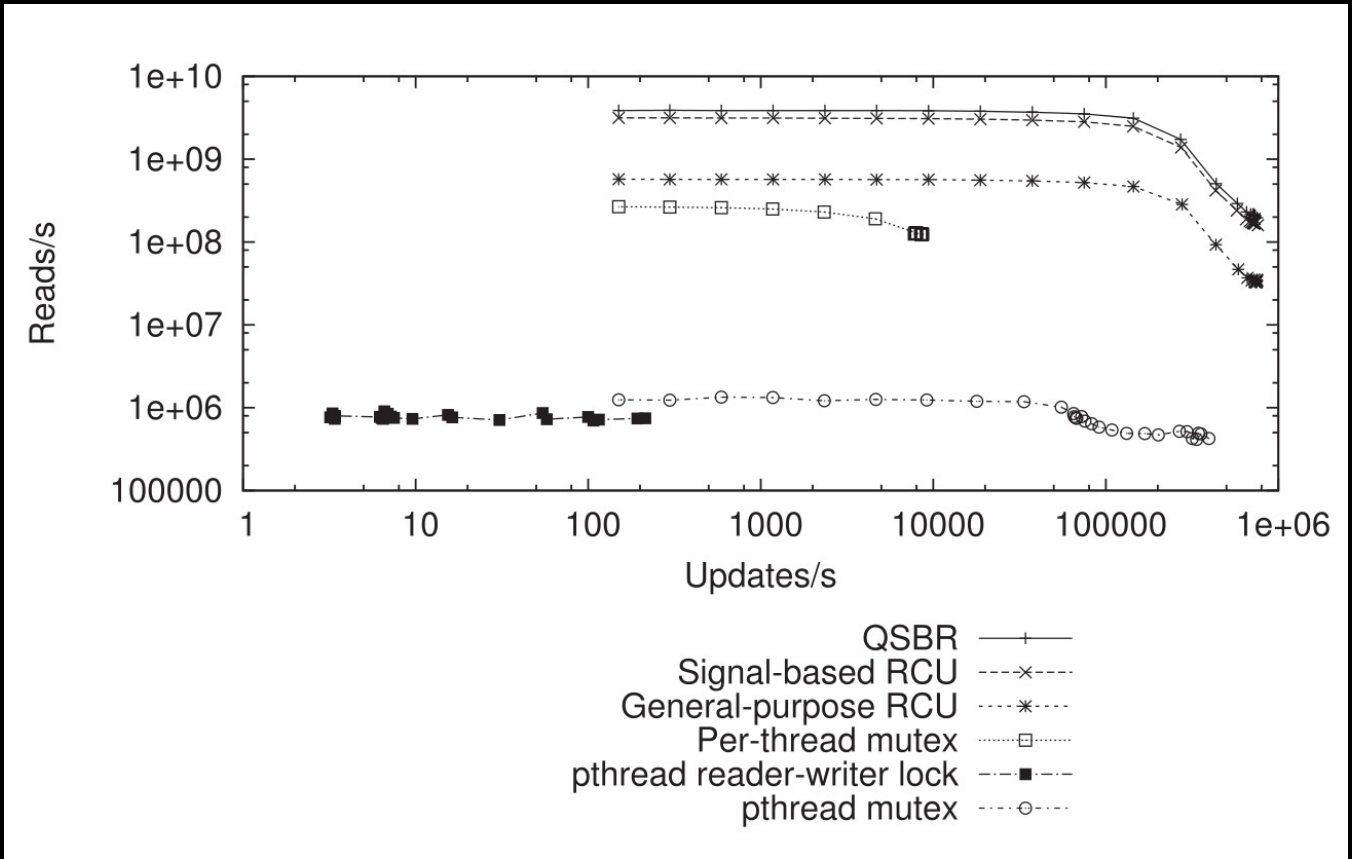
Non-CONFIG_PREEMPT kernel build (QSBR)

RCU vs. Reader-Writer Locking Read-Side Overhead



CONFIG_PREEMPT kernel build (counter-based RCU implementation)

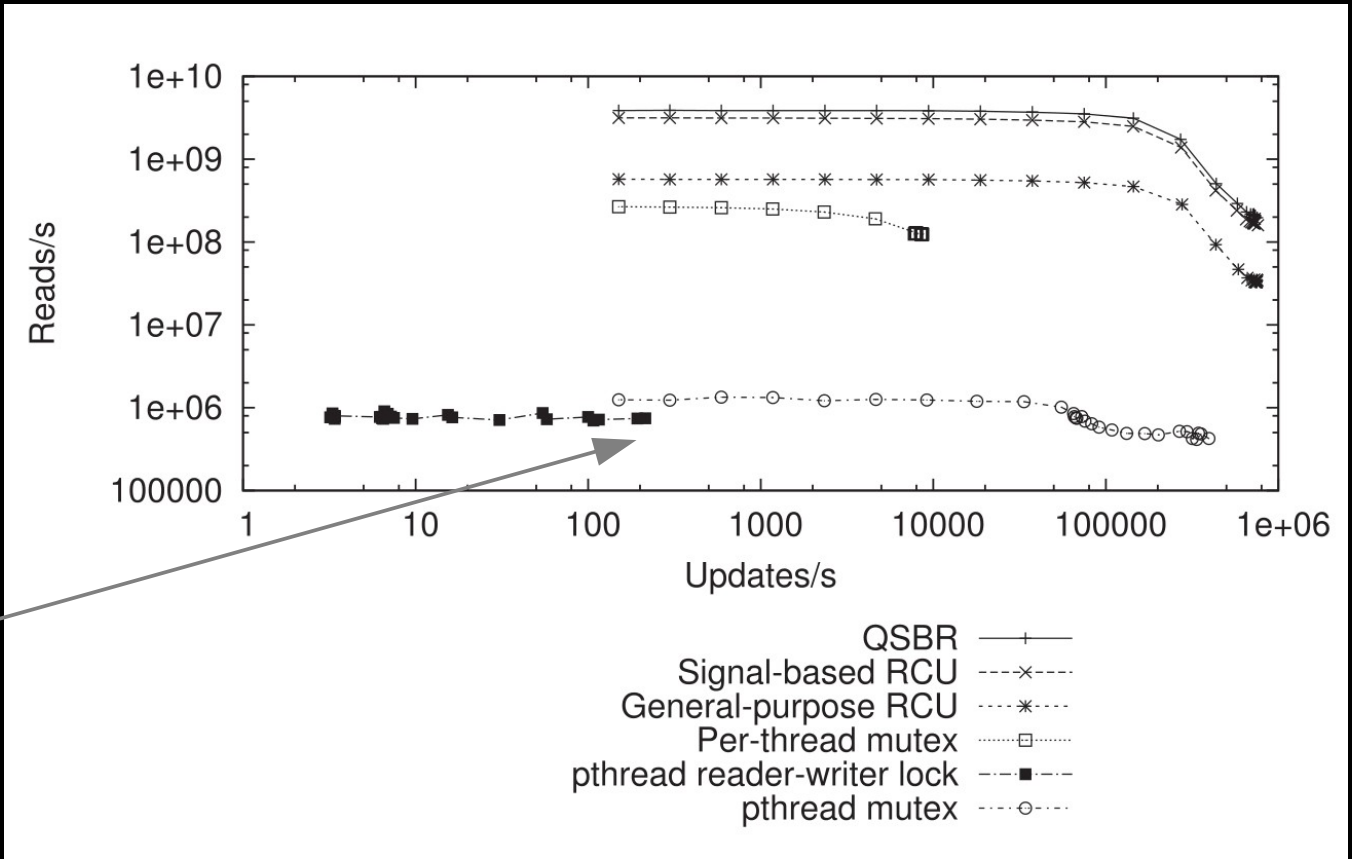
Read Performance vs. Update Frequency



64-core Power 5 system, 32 readers and 32 updaters. Update allocates, stores, frees.
Source: "User-Level Implementations of Read-Copy Update", Desnoyers et al., Feb. 2012 IEEE TPDS. Code at http://lttng.org/urcu or from Linux distros.

Read Performance vs. Update Frequency

Reader-Writer Lock
Reader Starvation



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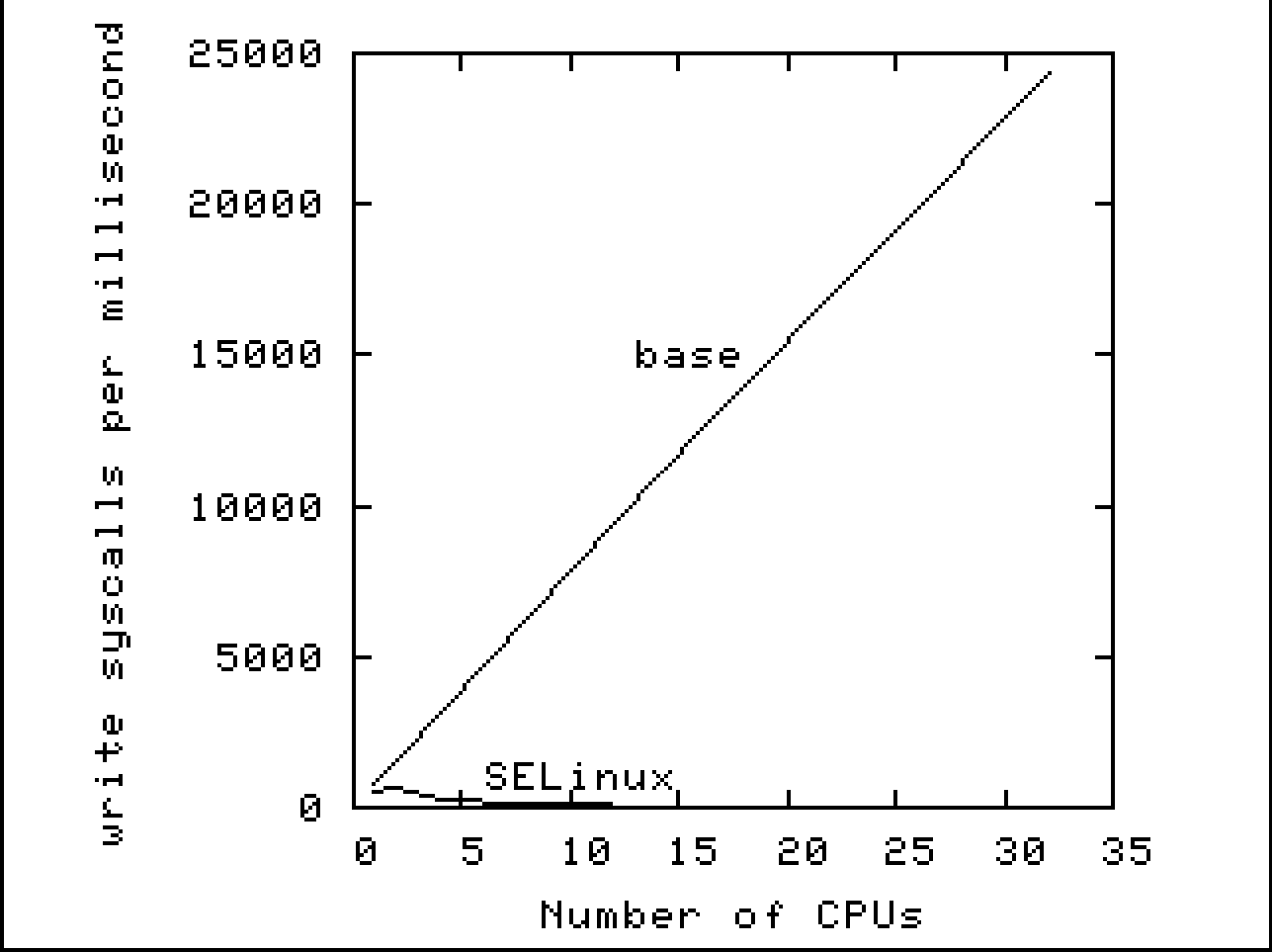
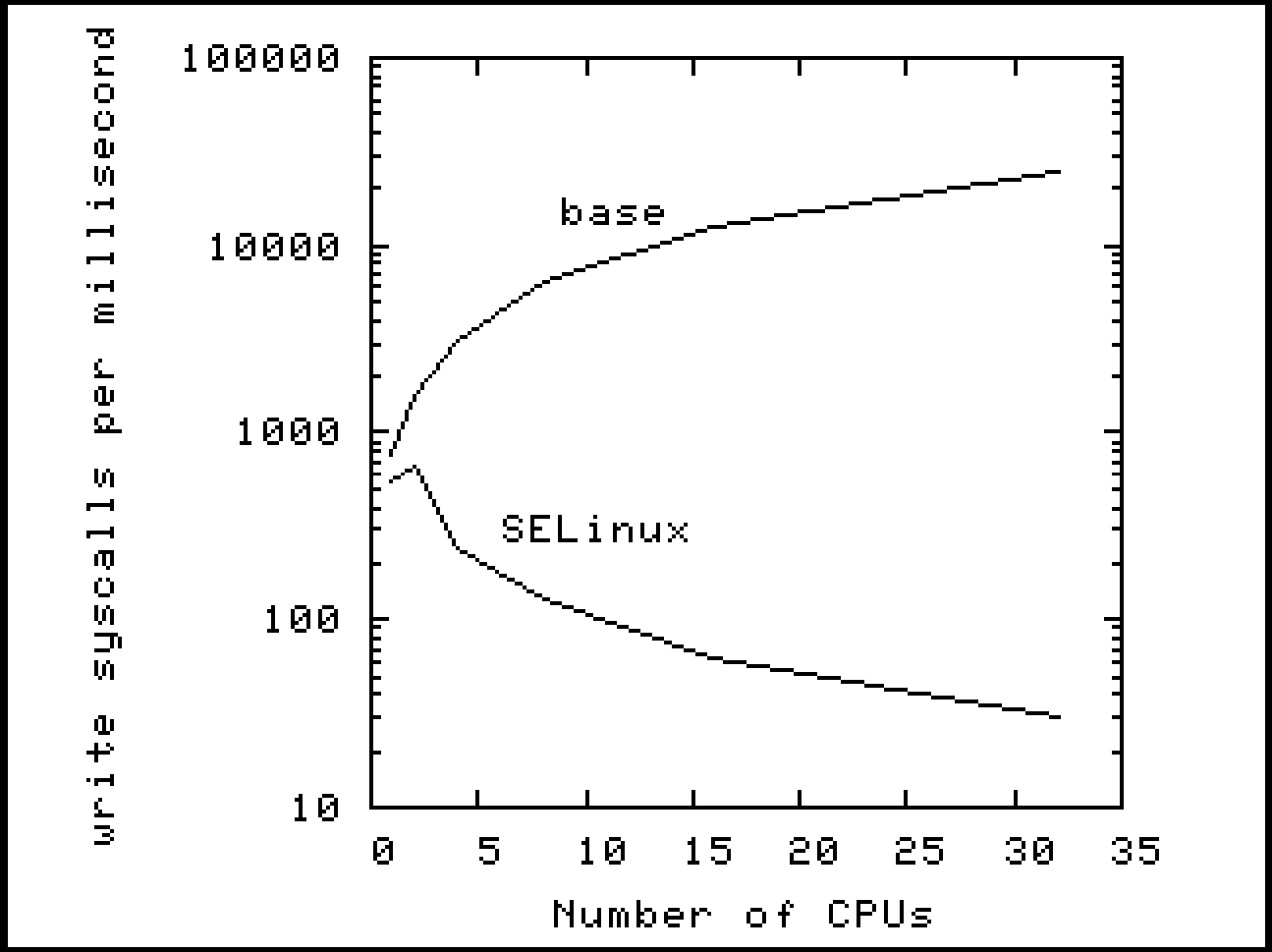
But These Only Measure Synchronization Primitives...

Linux Kernel write() System Call: SELinux

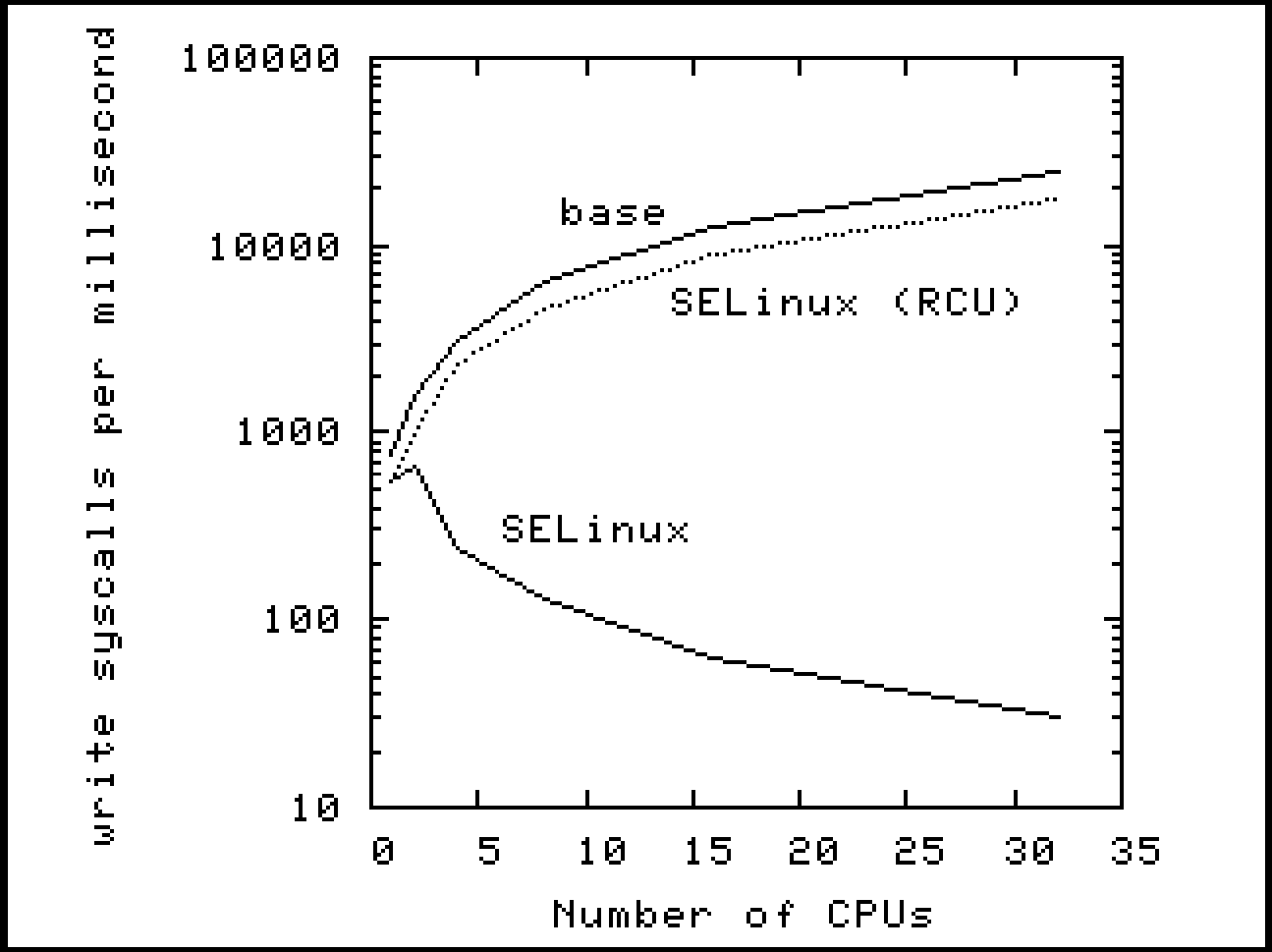


Linux Kernel write() System Call: SELinux (Logscale)



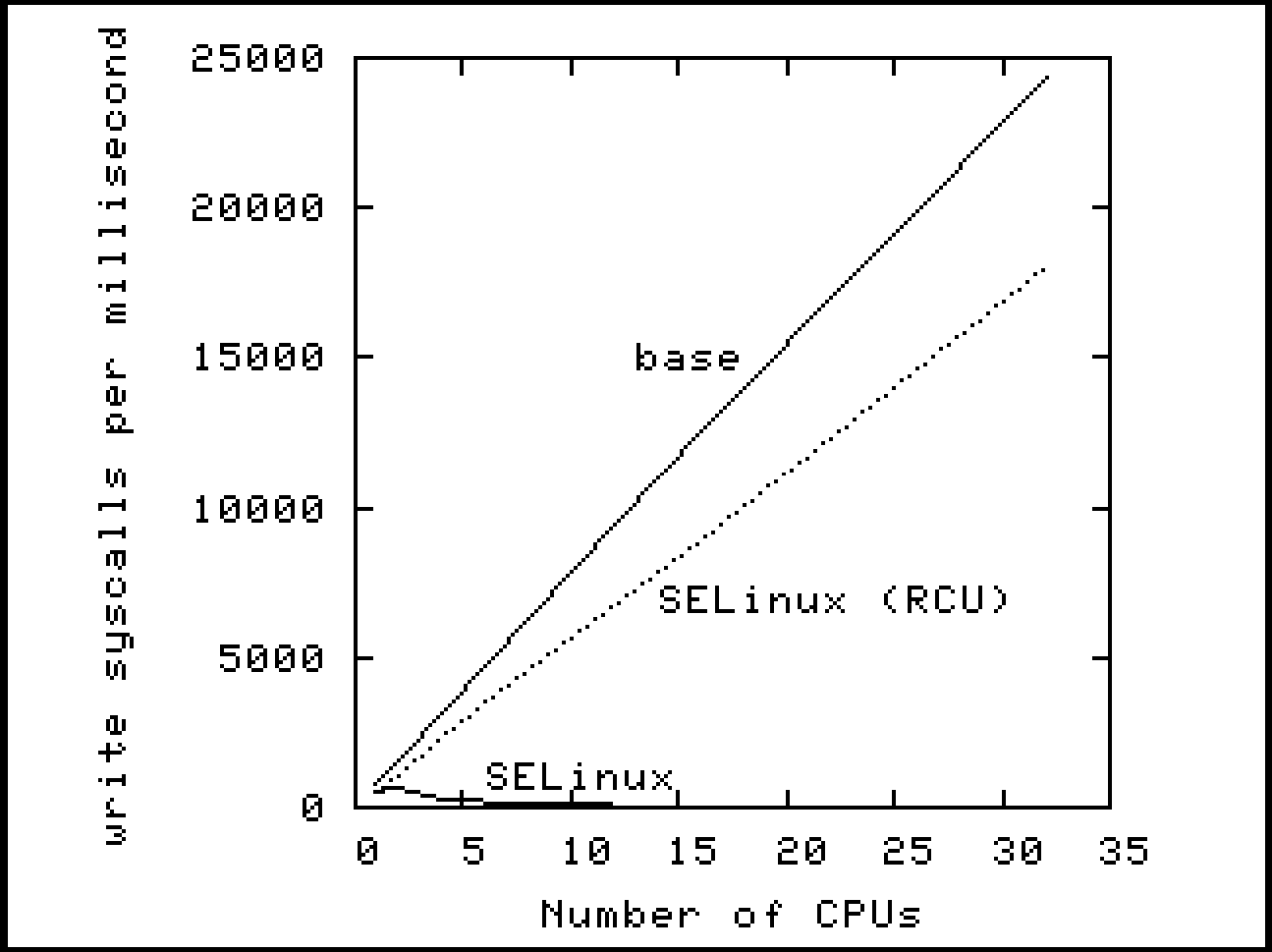
Get SELinux off the x-axis...

Linux Kernel write() System Call: SELinux (RCU)



Keep SELinux off the x-axis...

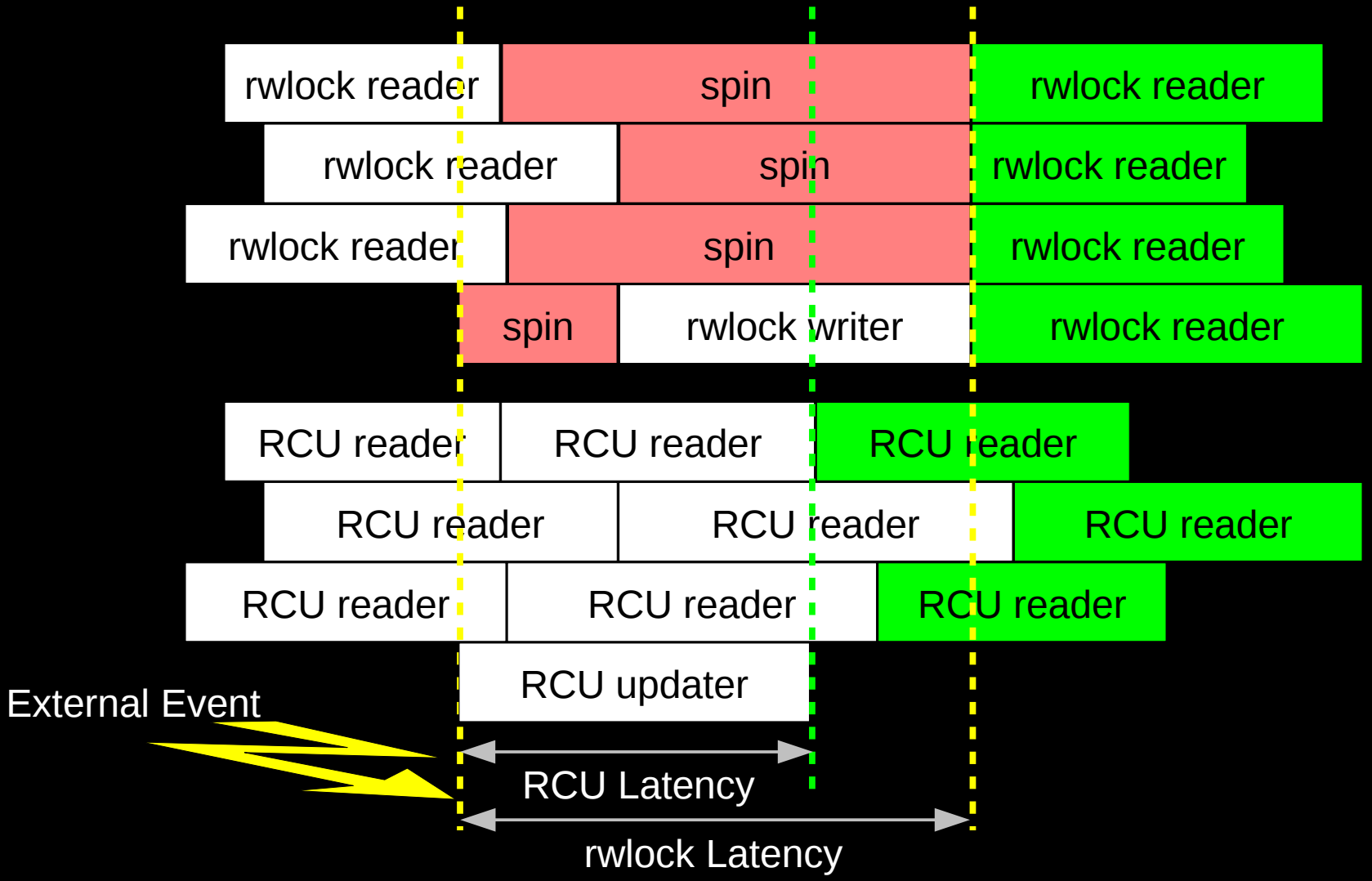
Linux Kernel write() System Call: SELinux (RCU)



SELinux scales linearly with RCU

Real-Time Response to Changes

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

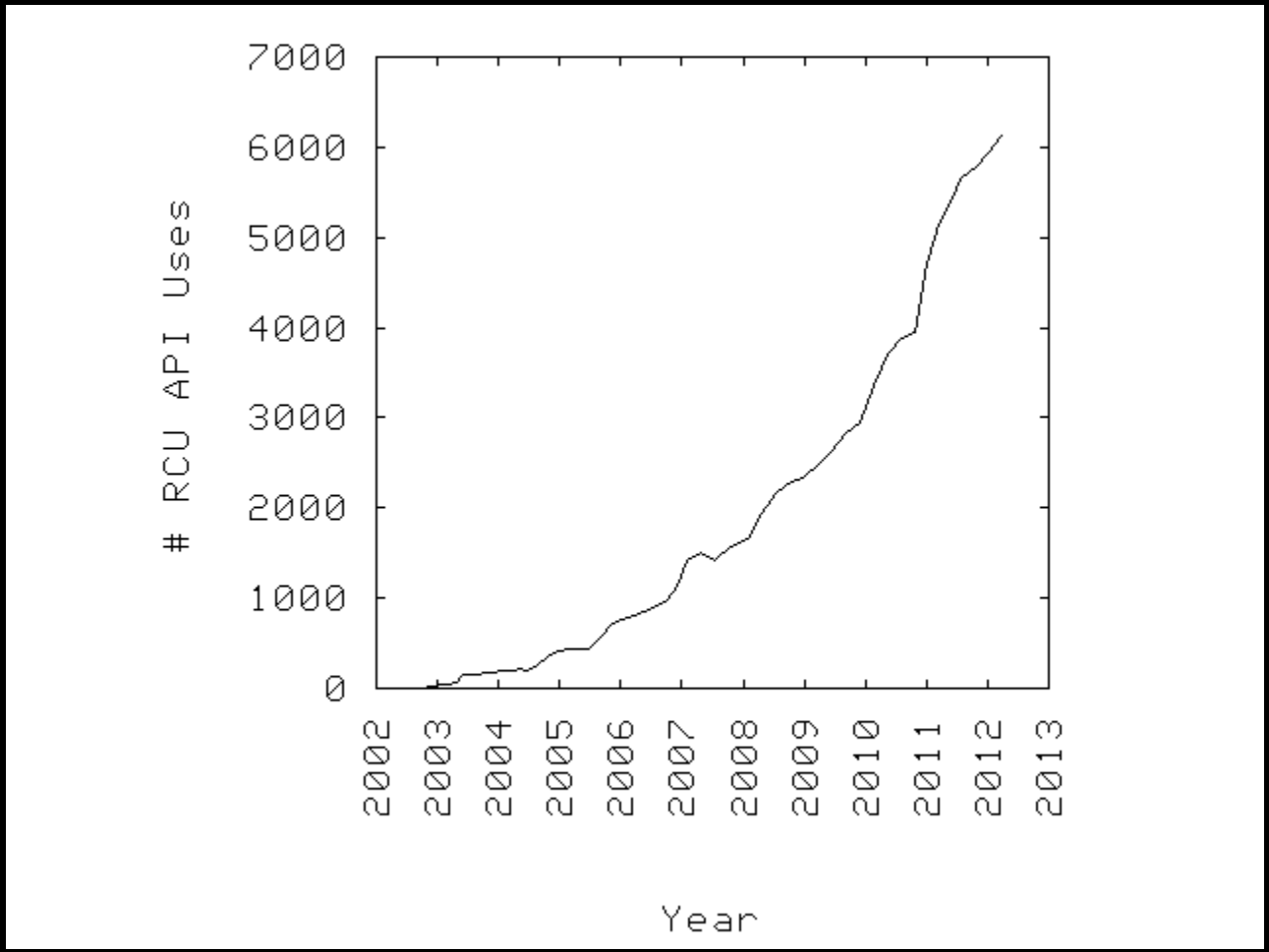


RCU Performance: “Free is a *Very* Good Price!!!”

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

RCU Area of Applicability

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:

- 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/lockperf.2004.01.17a.pdf
  - linux.conf.au paper comparing RCU vs. locking performance
- 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?