Paul E. McKenney, Meta Platforms Kernel Team

LSF/MM/BPF Summit (FS & MM), May 2 2022

Recent Linux-Kernel RCU Changes

RCU Changes

Yes, RCU is still under active development!

RCU Review

RCU Review (At Speed)

- Purpose
- Core API
- Semantics and Restrictions
- Spatio-Temporal Synchronization

https://linuxfoundation.org/webinars/unraveling-rcu-usage-mysteries/
https://linuxfoundation.org/webinars/unraveling-rcu-usage-mysteries-additional-use-cases/

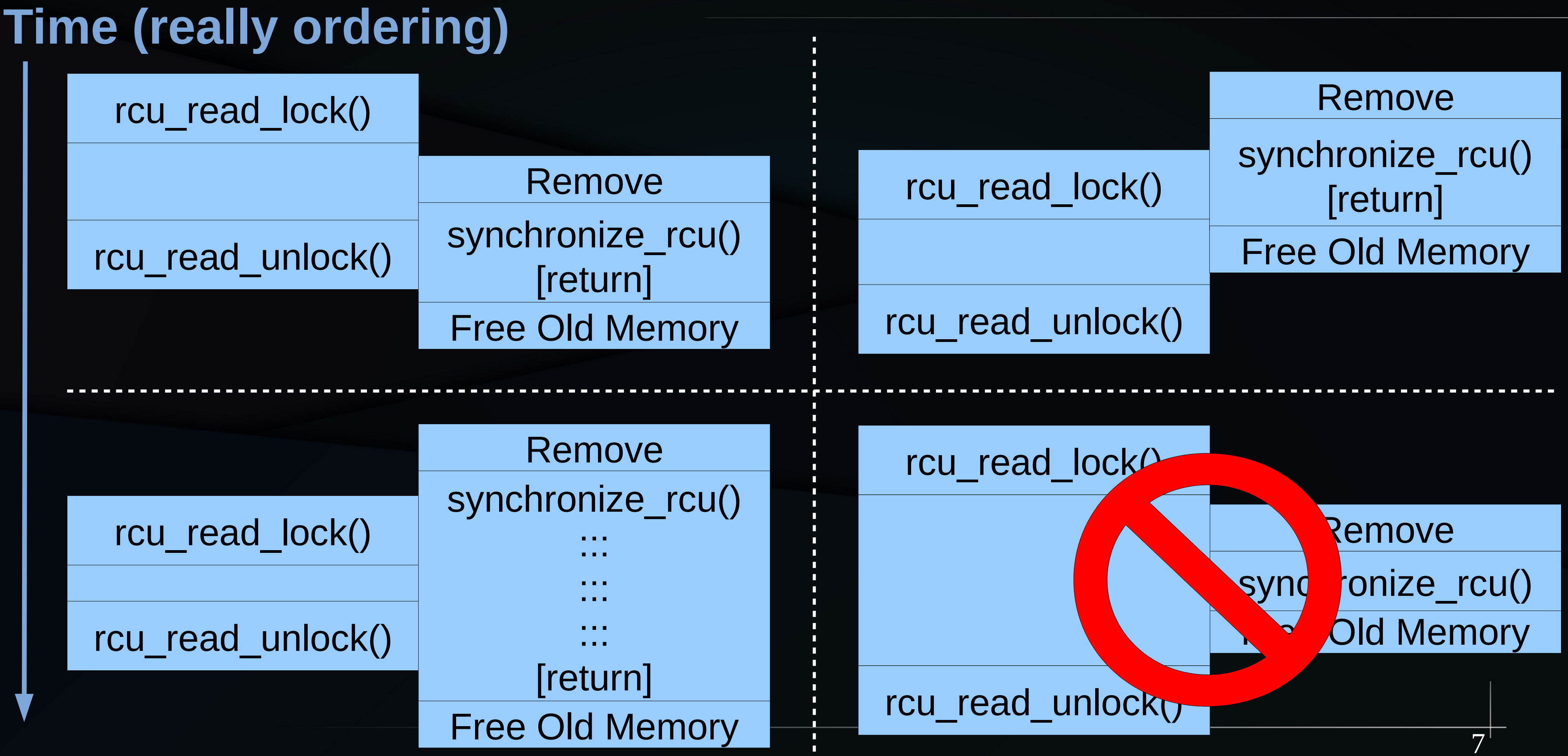
RCU Review: Purpose

- Global agreement is expensive
  - Finite speed of light and non-zero-sized atoms...
- So use both spatial & temporal synchronization
- RCU is one way to do this
  - Hazard pointers provide another way

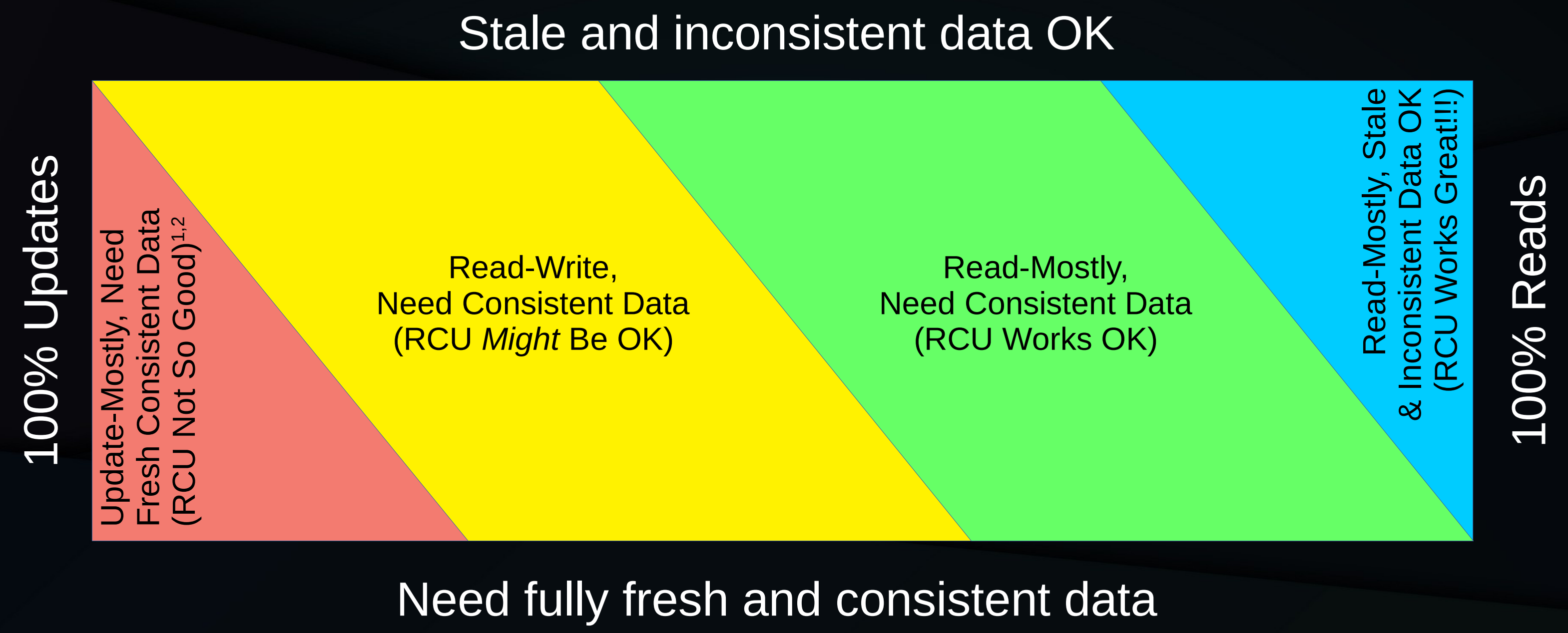
RCU Review: Core API (Space/Time)

- `rcu_read_lock()`: Begin reader
- `rcu_read_unlock()`: End reader
- `synchronize_rcu()`: Wait for pre-existing readers
- `call_rcu()`: Invoke function after pre-existing readers complete
- `rcu_dereference()`: Load RCU-protected pointer
- `rcu_dereference_protected()`: Ditto, but update-side locked
- `rcu_assign_pointer()`: Update RCU-protected pointer

RCU Review: Semantics (Graphical)



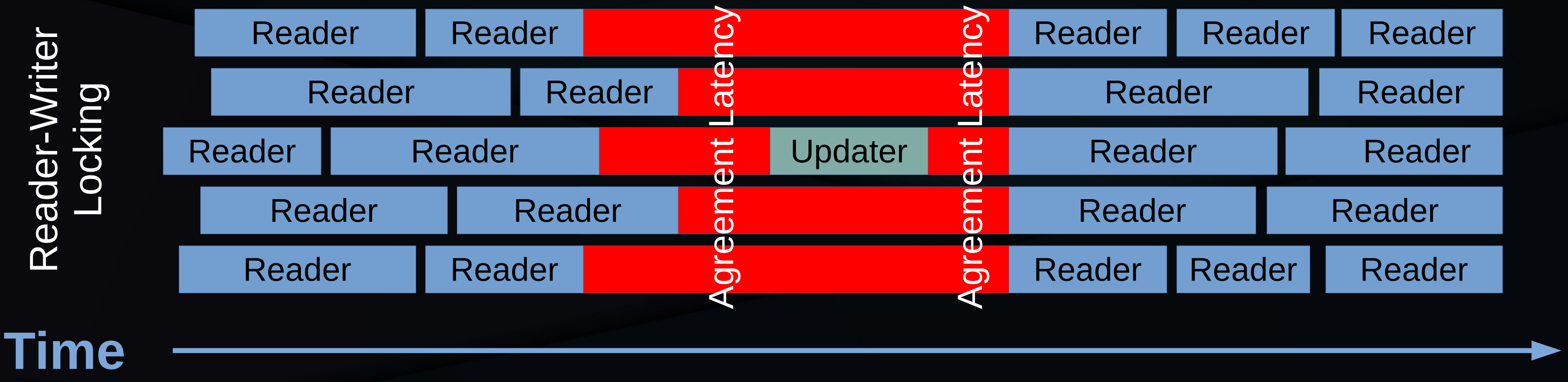
RCU Review: Restrictions


Stale and inconsistent data OK
100% Updates
Update-Mostly, Need Fresh Consistent Data (RCU Not So Good)[1,2]
Read-Write, Need Consistent Data (RCU *Might* Be OK)
Read-Mostly, Need Consistent Data (RCU Works OK)
Read-Mostly, Stale & Inconsistent Data OK (RCU Works Great!!!)
100% Reads
Need fully fresh and consistent data

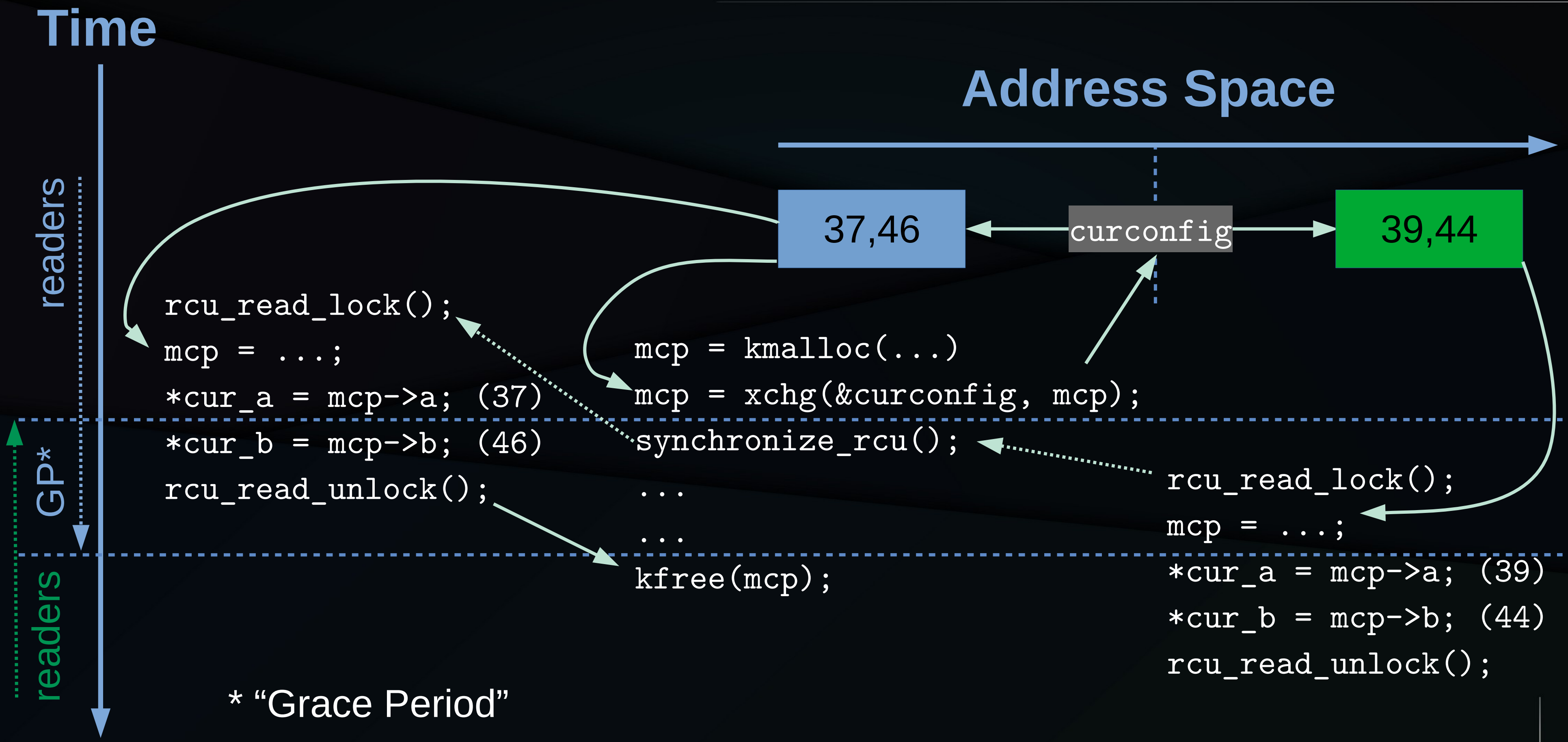
1. RCU provides ABA protection for update-friendly mechanisms (light-weight garbage collector)
2. RCU provides bounded wait-free read-side primitives for real-time use

And RCU is most frequently used for linked data structures.

RCU Review: Global Agreement Cost



RCU Review: Code Animation



```
rcu_read_lock();
mcp = ...;
*cur_a = mcp->a; (37)
*cur_b = mcp->b; (46)
rcu_read_unlock();
```

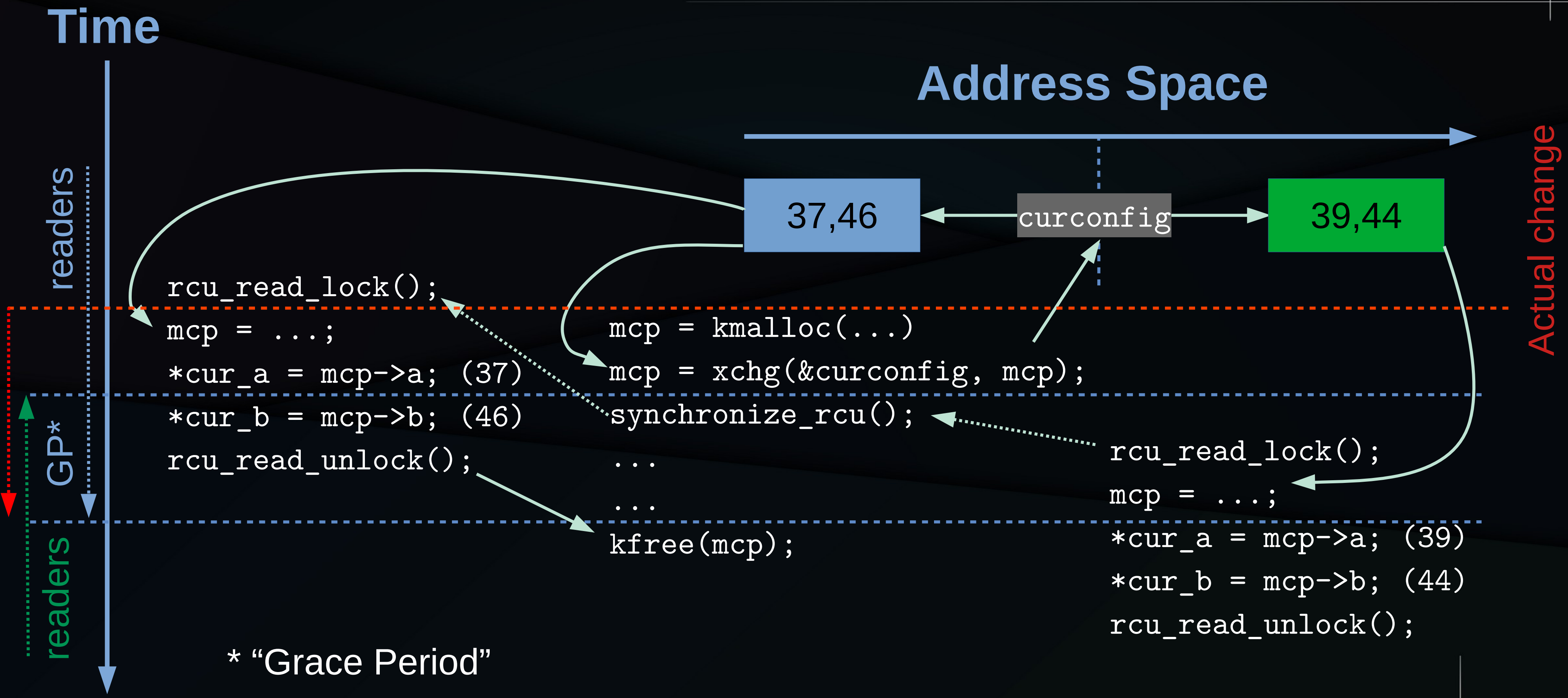
```
mcp = kmalloc(...)
mcp = xchg(&curconfig, mcp);
synchronize_rcu();
...
...
kfree(mcp);
```

```
rcu_read_lock();
mcp = ...;
*cur_a = mcp->a; (39)
*cur_b = mcp->b; (44)
rcu_read_unlock();
```

* “Grace Period”

First space/time articulation for RCU (to the best of my knowledge): Jonathan Walpole and his students Josh Triplett and Phil Howard

RCU Review: Code Animation



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mcp = kmalloc(...)
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synchronize_rcu();
...
...
kfree(mcp);
```

```
rcu_read_lock();
mcp = ...;
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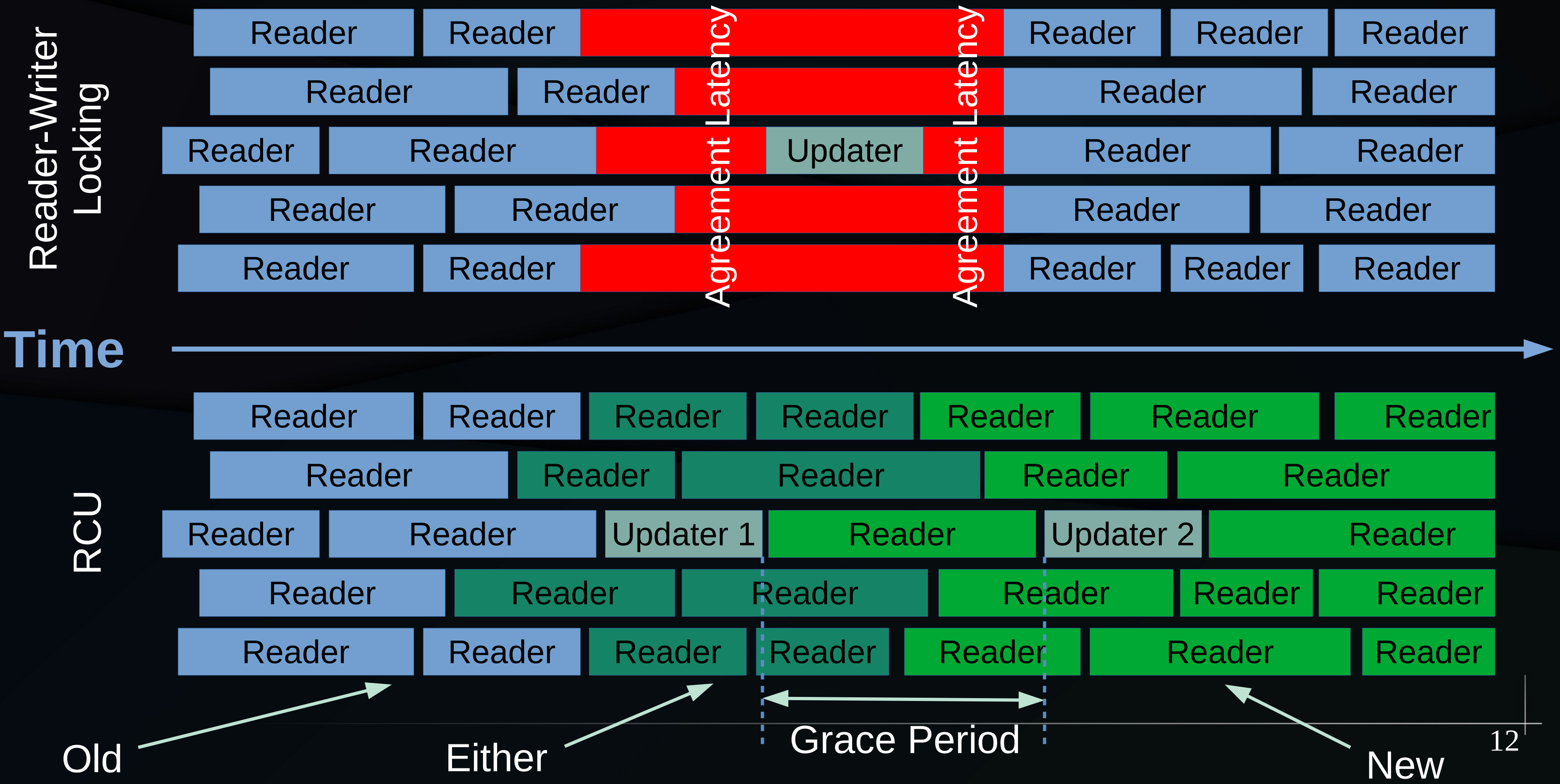
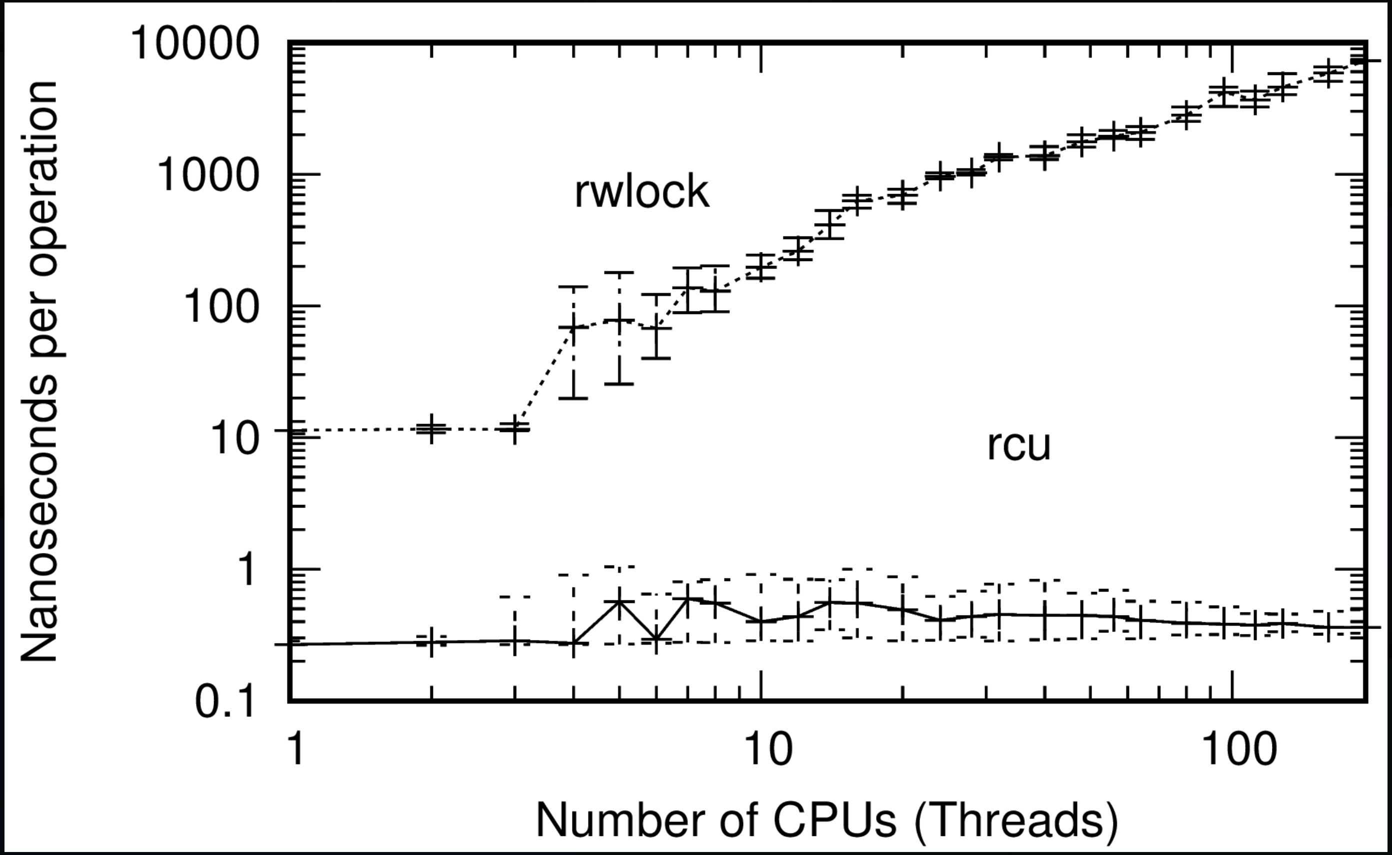


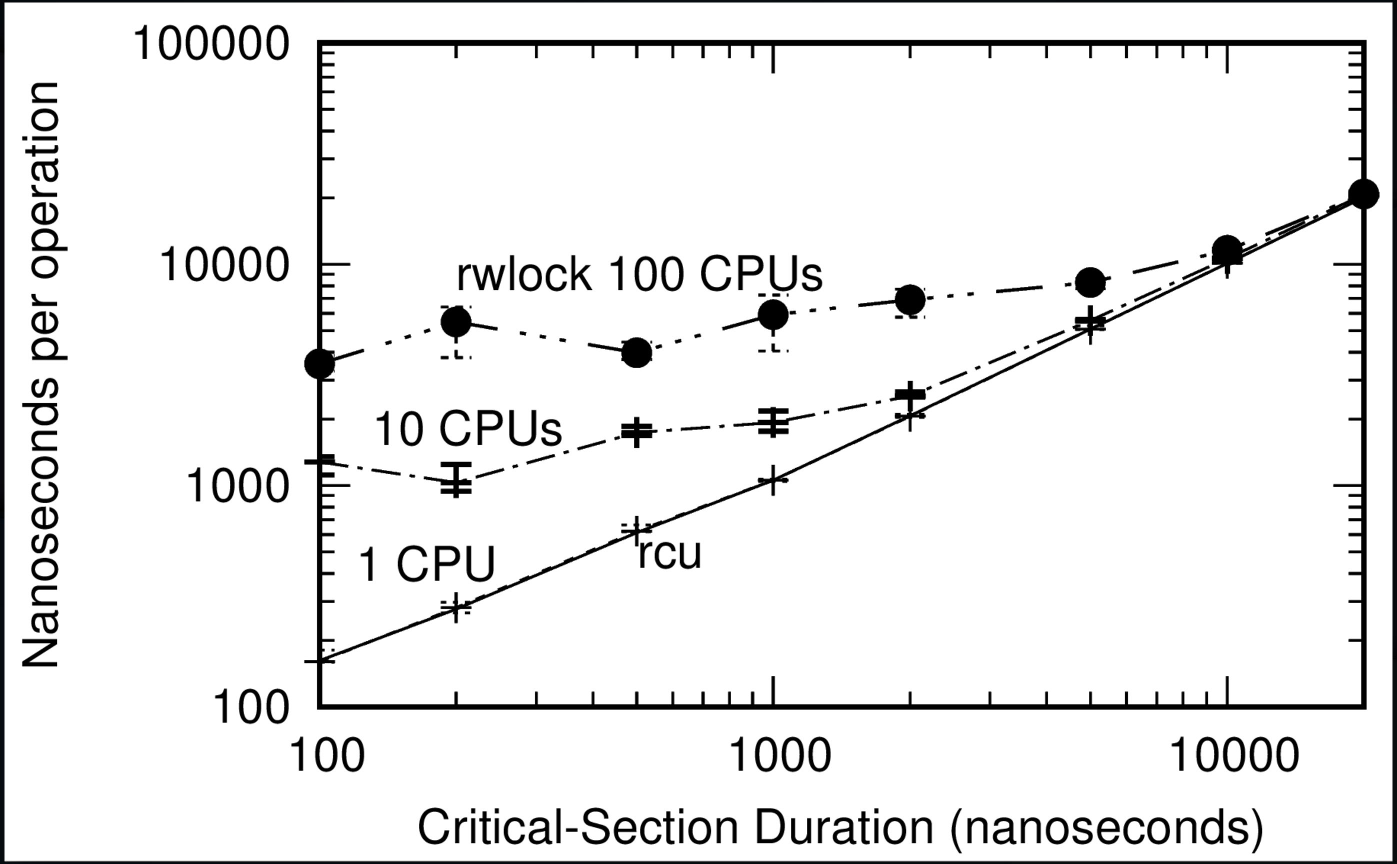
RCU Review: Scalability (Empty)



Intel(R) Xeon(R) Platinum 8176 CPU @ 2.10GHz

perfbook CodeSamples/defer/data/rcuscale.hps.2020.05.28a/rwlockperf.eps

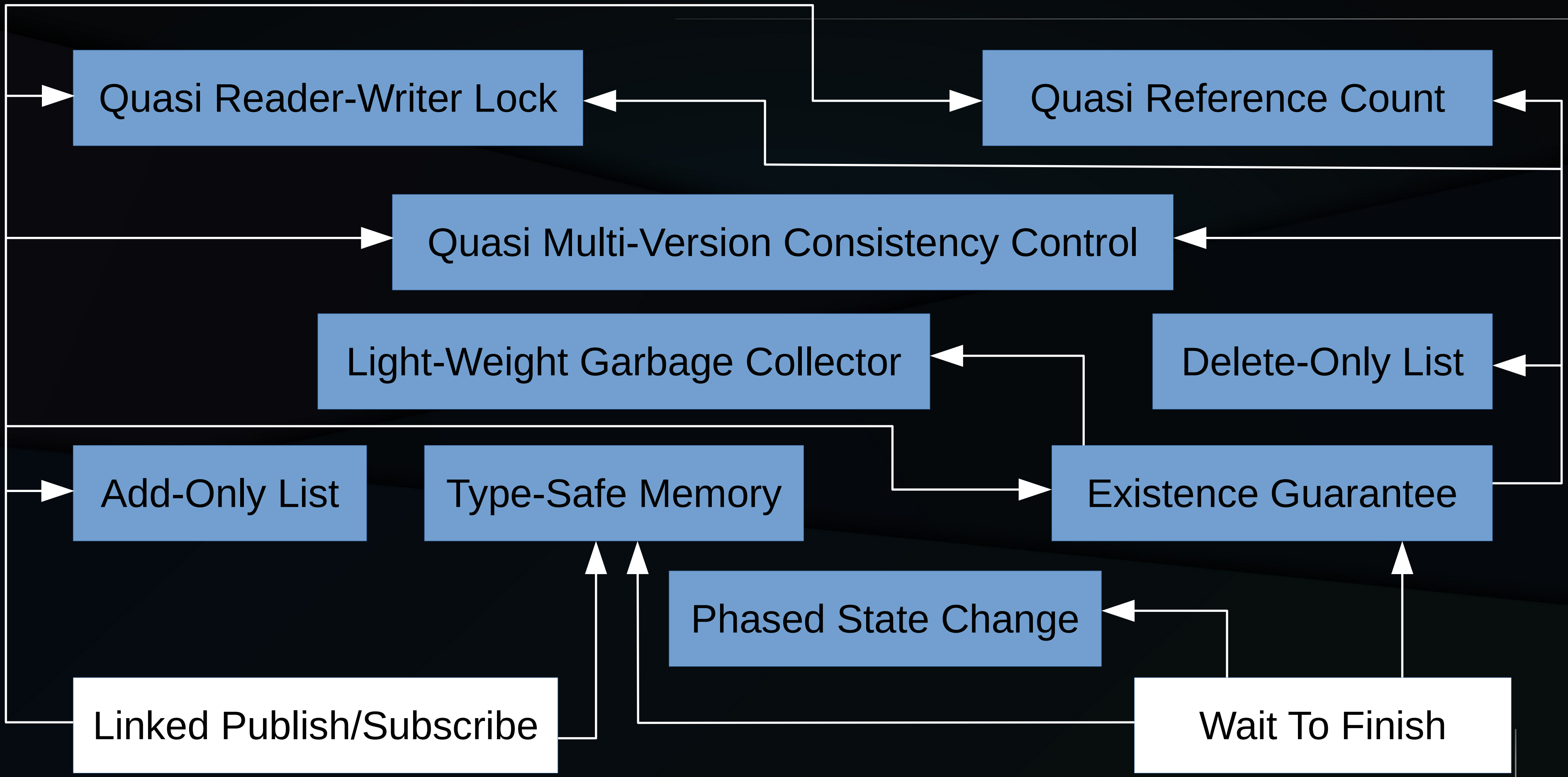
RCU Review: Scalability (Non-Empty)



Intel(R) Xeon(R) Platinum 8176 CPU @ 2.10GHz

perfbook CodeSamples/defer/data/rcuscale.hps.2020.05.28a/rwlockperf.eps

RCU Review: Use Cases



https://linuxfoundation.org/webinars/unraveling-rcu-usage-mysteries/
https://linuxfoundation.org/webinars/unraveling-rcu-usage-mysteries-additional-use-cases/

RCU Changes

RCU Changes

- Flavor consolidation
- Optional lockdep expression for list_for_each_entry_rcu()
- Single-argument kfree_rcu() and kvfree_rcu()
- Tasks Trace RCU and Tasks Rude RCU
- Polled grace-period APIs
- Runtime RCU callback (de-)offloading
- SRCU memory-footprint diet
- Real-time expedited grace periods

RCU Flavor Consolidation

RCU Flavor Consolidation: Impetus

```
Date: Sat, 3 Mar 2018 17:50:44 -0800
From: Linus Torvalds <torvalds@linux-foundation.org>
To: Jann Horn <jannh@google.com>, Tejun Heo <tj@kernel.org>, Paul McKenney
        <paulmck@linux.vnet.ibm.com>
Cc: Benjamin LaHaise <bcrl@kvack.org>, security@kernel.org, Al Viro
        <viro@zeniv.linux.org.uk>
Subject: Re: AIO locking bug in lookup_ioctx()
From linus971@gmail.com  Sat Mar  3 17:54:39 2018

[ Adding Al, Paul and Tejun and to the cc too for various reasons ]

On Fri, Mar 2, 2018 at 3:14 PM, Jann Horn <jannh@google.com> wrote:

[ . . . ]

> I'm not sending a patch because I'm not sure whether the intent here is to
> use RCU, and if so, whether it should be RCU-sched or normal RCU.

It's meant to use regular RCU.

But then in commit a4244454df12 ("percpu-refcount: use RCU-sched
insted of normal RCU") the percpu refcounts were changed to use
RCU-sched.

.. and in the process apparently broke the AIO RCU locking.

Tejun, Paul, please tell me why I'm wrong.

               Linus
```

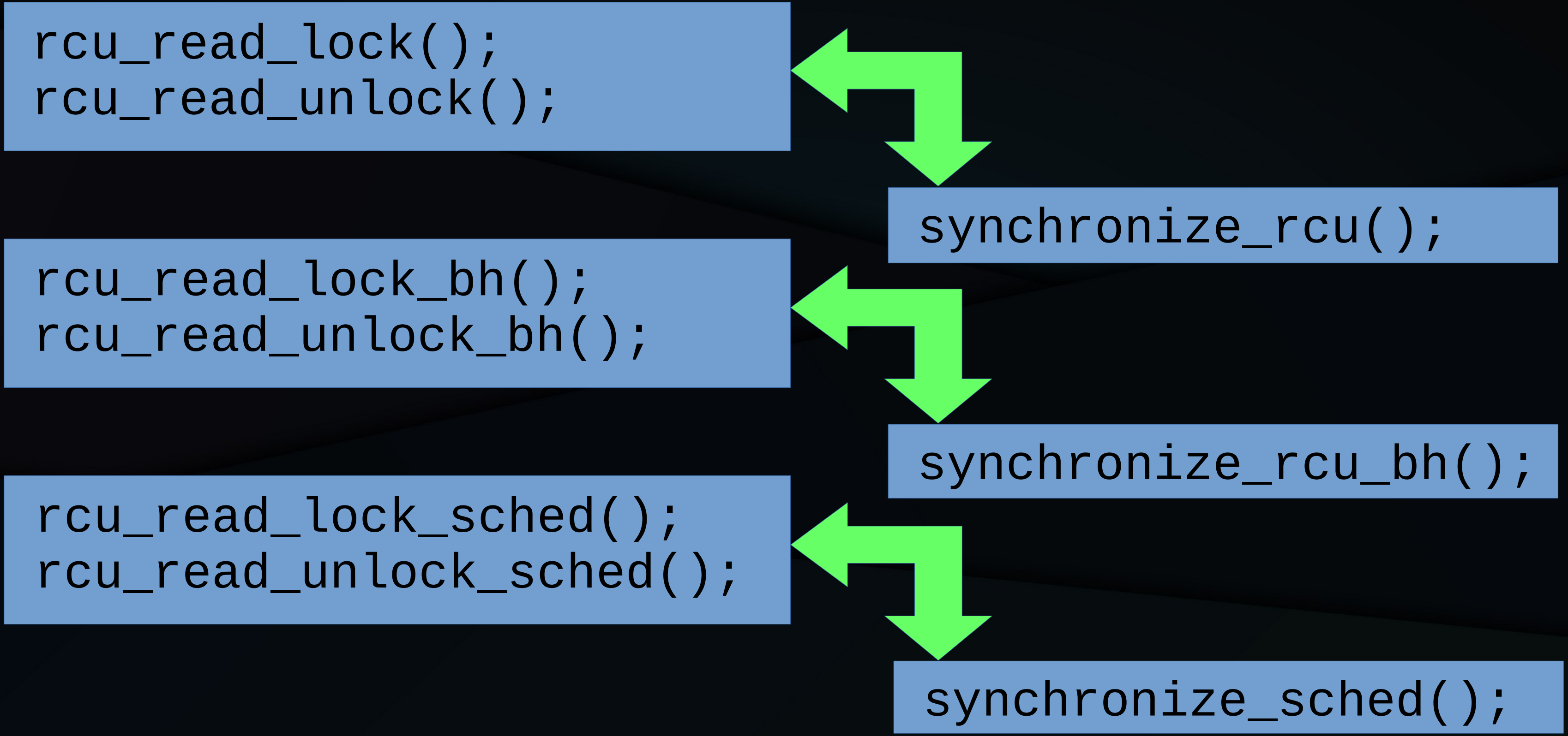
security@kernel.org

Root Cause Of Exploit

```
void reader(void)
{
  rcu_read_lock_sched();
  /*
   * Access RCU-
   * protected data.
   */
  rcu_read_unlock_sched();
}
```

```
void updater(void)
{
  /* Remove old data. */
  synchronize_rcu();
  /* Free old data. */
}
```

Need Consistency, Except That...



```
rcu_read_lock();
rcu_read_unlock();
```

```
synchronize_rcu();
```

```
rcu_read_lock_bh();
rcu_read_unlock_bh();
```

```
synchronize_rcu_bh();
```

```
rcu_read_lock_sched();
rcu_read_unlock_sched();
```

```
synchronize_sched();
```

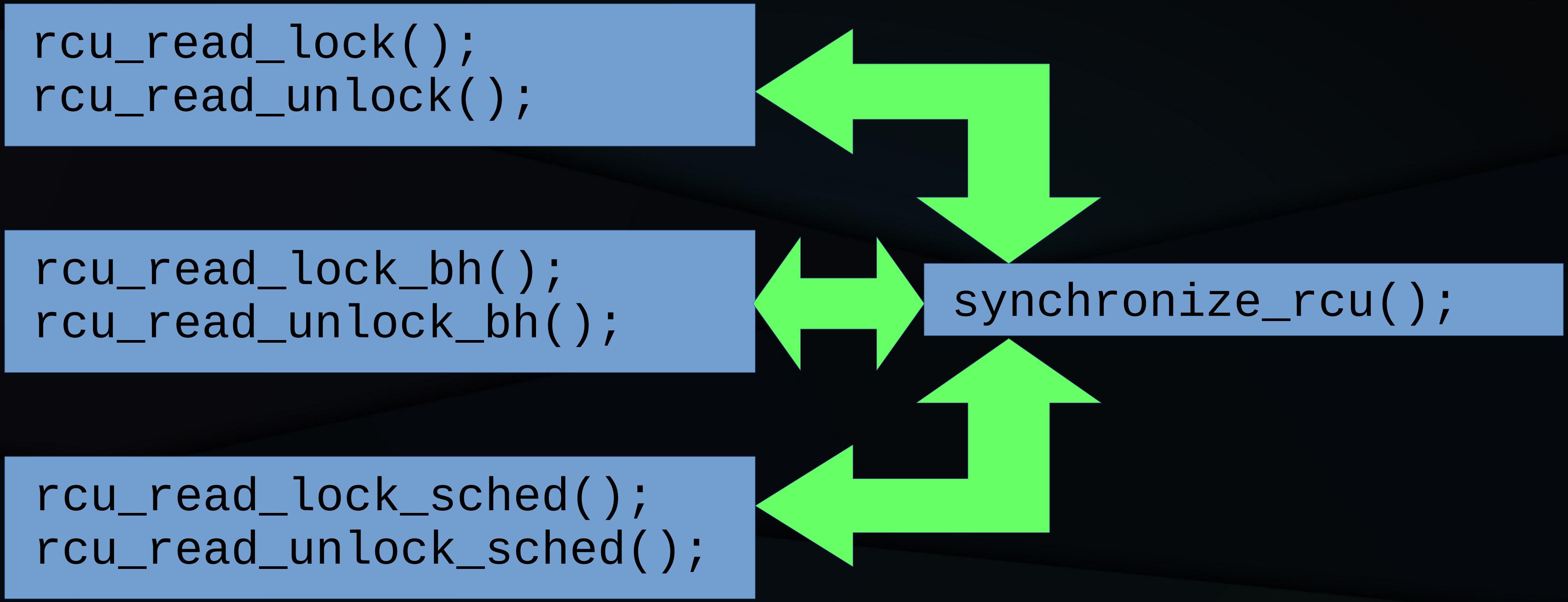
...to err is human!
Plus userspace controls content of much kernel data!!!

And the Call to Action

```
Date: Sun, 4 Mar 2018 10:53:54 -0800
From: Linus Torvalds <torvalds@linux-foundation.org>
To: Tejun Heo <tj@kernel.org>
Cc: Jann Horn <jannh@google.com>, Paul McKenney <paulmck@linux.vnet.ibm.com>,
        Benjamin LaHaise <bcrl@kvack.org>, security@kernel.org, Al Viro
        <viro@zeniv.linux.org.uk>
Subject: Re: AIO locking bug in lookup_ioctx()
From linus971@gmail.com  Sun Mar  4 10:56:59 2018

[ . . . ]

I've been confused before, and this time it was an actual security
bug. Admittedly one that is probably almost impossible to ever hit in
practice or mis-use, but still.

I repeat: I really love the traditional RCU, but I *despise* how there
are a million d
causes real pro

The only reason for rcu-sched to exist in the first place is that the
regular RCU had been made so much slower with PREEMPT_RCU. In other
words, the proliferation of different insane RCU implementations ends
up feeding on itself, and causing more and more of the proliferation.

Paul, is there really no way out of this mess?

                   Linus
```

Paul, is there really no way out of this mess?

Desired State (Usability/Security)



Aside from the need to backport to v4.19 or earlier...

Backport `synchronize_rcu()`

- v4.20 or later: Just backport with no change
- v4.19 or earlier:
  - Only waiting on `rcu_read_lock()`:
    - Use `synchronize_rcu()`, as in no change
  - Otherwise, use `synchronize_rcu_mult()`:
    `synchronize_rcu_mult(call_rcu, call_rcu_bh, call_rcu_sched);`
    - Using whichever `call_rcu*()` variants you need
    - Chain call_rcu(), call_rcu_bh(), and call_rcu_sched()

lockdep & list_for_each_entry_rcu()

Contributed by Joel Fernandes, available in v5.4

Lockdep & list_for_each_entry_rcu()

- Non-lockdep style (still supported):
  - list_for_each_entry_rcu(pos, head, member)
  - hlist_for_each_entry_rcu(pos, head, member)
- With lockdep support:
  - list_for_each_entry_rcu(pos, head, member[, cond])
  - hlist_for_each_entry_rcu(pos, head, member[, cond])
    - Example “cond”: “lockdep_is_held(&event_mutex)”

Contributed by Joel Fernandes, available in v5.4

Single-Argument kvfree_rcu()

Contributed by Uladzislau Rezki, available in v5.9

Single-Argument kvfree_rcu()

- Classic way: kvfree_rcu(p, rh)
  - Requires an rcu_head field named “rh” in object
  - Never sleeps
  - Will continue to be supported
- New way: kvfree_rcu(p)
  - No rcu_head required, but can sleep if OOM
- kfree_rcu() is a synonym for kvfree_rcu()
  - Uses kfree_bulk() for cache locality (since v5.7)

Contributed by Uladzislau Rezki, available in v5.9

RCU Tasks {,Rude,Trace}

RCU Tasks {,Rude,Trace}

- RCU Tasks and RCU Tasks Rude:
  – Used for tracing, e.g., freeing trampolines
- RCU Tasks Trace
  – Used for sleepable BPF trampolines
- All three variants are extremely specialized
  – Check with their other users before using them!!!

RCU Tasks {,Rude,Trace}

Voluntary context switch (v3.18):

```
synchronize_rcu_tasks()
call_rcu_tasks()
rcu_barrier_tasks()
```

Any context switch (v5.8):

```
synchronize_rcu_tasks_rude()
call_rcu_tasks_rude()
rcu_barrier_tasks_rude()
```

Explicit read-side markers (v5.8):

```
rcu_read_lock_trace()
rcu_read_unlock_trace()
rcu_read_lock_trace_held()
synchronize_rcu_tasks_trace()
call_rcu_tasks_trace()
rcu_barrier_tasks_trace()
```

Assisted by Neeraj Upadhyay

Polled Grace-Period APIs

Polled Grace-Period APIs

- `get_state_synchronize_rcu()`
- `cond_synchronize_rcu()`
  - v3.14 and later
- `start_poll_synchronize_rcu()`
- `poll_state_synchronize_rcu()`
  - v5.12 and later
- `get_completed_synchronize_rcu()`
- `start_poll_synchronize_rcu_expedited()`
- `cond_synchronize_rcu_expedited()`
  - Maybe v5.20 and later?

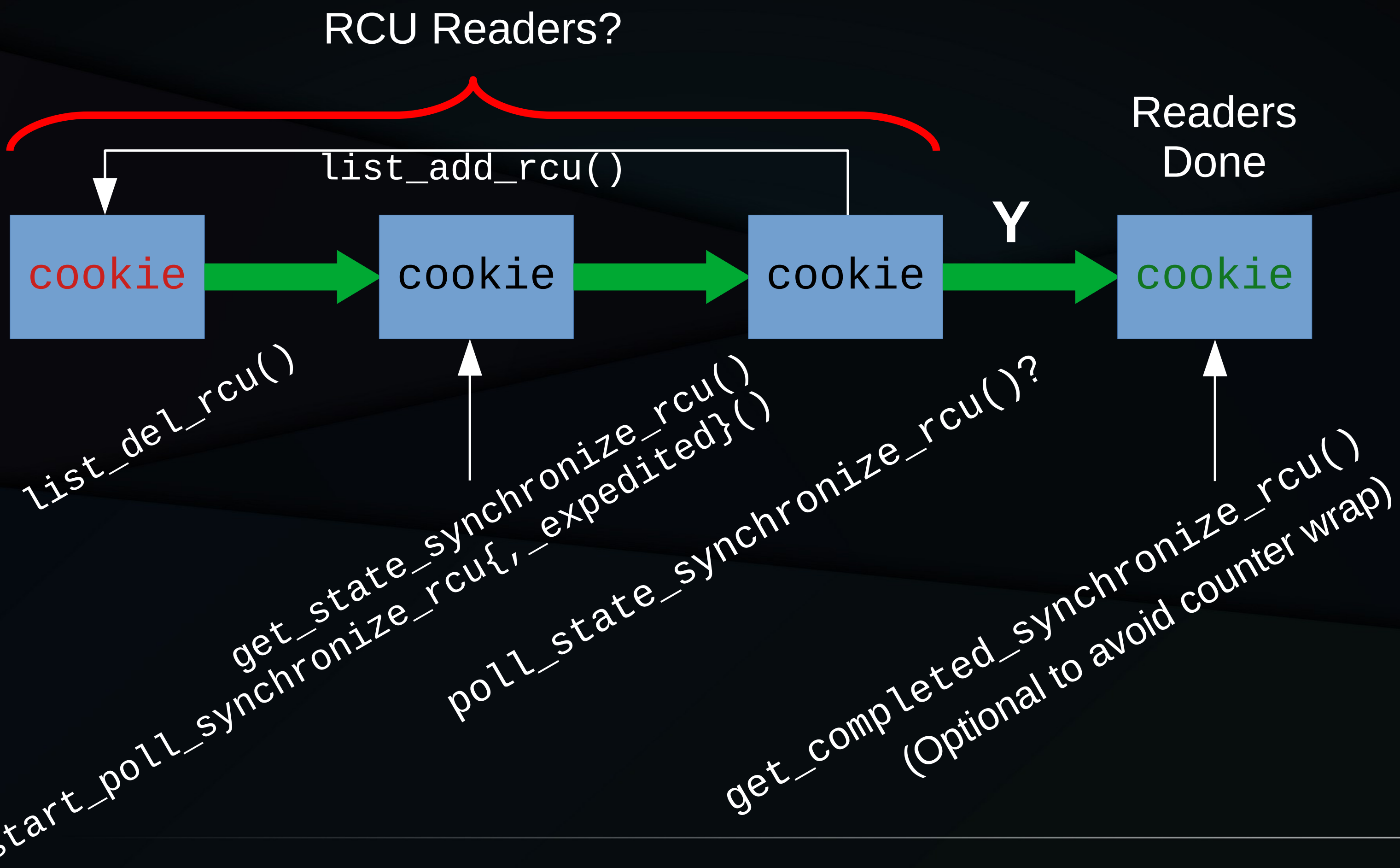
- `get_state_synchronize_srcu()`
- `start_poll_synchronize_srcu()`
- `poll_state_synchronize_srcu()`
  - v5.12 and later

Using Polled Grace-Period APIs (1/2)

```
/* Get grace-period cookie. */
cookie = get_state_synchronize_rcu();
/* Do other work. */
do_something();
/* If grace period not done, wait for the rest of it. */
cond_synchronize_rcu{,_expedited}(cookie);
```

Classic style going back to v3.14

Using Polled Grace-Period APIs (2/2)


RCU Readers?
list_add_rcu()
Readers Done
Y
cookie
cookie
cookie
cookie
list_del_rcu()
get_state_synchronize_rcu()
start_poll_synchronize_rcu{,_expedited}()
poll_state_synchronize_rcu()?
get_completed_synchronize_rcu()
(Optional to avoid counter wrap)

Polled Grace Period Caveat

```
/* Get grace-period cookie. */
cookie = get_state_synchronize_rcu();
synchronize_rcu{,_expedited}();

/*
 * Can trigger!!!  (1) Counter wrap.  (2) Races that
 * result in partially overlapping normal and expedited
 * grace periods.  Can eliminate #2, but with either
 * more storage (2 unsigned longs) or faster counter wrap.
 */
WARN_ON_ONCE(poll_state_synchronize_rcu(cookie));
```

rcutorture can make #2 happen, but unlikely in production workloads. (Famous last words...)

Polled Grace Period Guarantee

```
/* Get grace-period cookie. */
cookie = get_state_synchronize_rcu();

/* Only one grace period can be lost due to race. */
synchronize_rcu{,_expedited}();
synchronize_rcu{,_expedited}();

/* Can trigger!!!  But only due to counter wrap. */
WARN_ON_ONCE(poll_state_synchronize_rcu(cookie));
```

Runtime Callback (De-)Offloading

Contributed by Frederic Weisbecker, available in v5.12

Runtime Callback (De-)Offloading

- Requires CONFIG_RCU_NOCB_CPU=y
  - Implied by CONFIG_NO_HZ_FULL=y
- Requires rcu_nocbs kernel boot parameter
  - Implied by nohz_full kernel boot parameter
- Available only in kernel for rcu_nocbs CPUs:
  - rcu_nocb_cpu_offload(cpu)
  - rcu_nocb_cpu_deoffload(cpu)

Contributed by Frederic Weisbecker, available in v5.12

Putting SRCU on a Memory Diet

Putting SRCU on a Memory Diet

- Tree SRCU has a compile-time srcu_node tree
  - NR_CPUS=4096 means 261 array elements
    - About 100 bytes each, which is not a big deal, but...
  - Requires bigger instructions to access later fields
  - And big srcu_node arrays wasted on real systems, which rarely have thousands of CPUs!!!
    - And most srcu_struct instances don’t even need the srcu_node array at all!

Putting SRCU on a Memory Diet

- Separately allocate srcu_node tree
  - But only if requested or actually needed
    - srcutree.big_cpu_lim: # CPUs in “big” system (128)
    - srcutree.convert_to_big: When to allocate?
      - 0xX0: Never
      - 0xX1: At init_srcu_struct() time (AKA “always”)
      - 0xX2: When rcutorture so chooses
      - 0xX3: Decide 0/1 at boot based on big_cpu_lim (0x03 is default)
      - 0x1X: Above plus if lock contention is high and not OOM
  - Sized based on actual number of CPUs

Putting SRCU on a Memory Diet

- Default to allocate on contention (0x13)?
  - No: This has not yet earned our trust
  - No useful way to report allocation failure
    - Contention continues if OOM
    - Which is ***probably*** OK...

Assisted by Neeraj Upadhyay, slated for v5.19

Real-Time Expedited Grace Periods

Real-Time Expedited Grace Periods

- Brief history of RCU CPU stall warnings:
  - 1990s: Dynix/PTX 1.5 seconds
  - 2000s: Linux 60 seconds
  - 2010s: Linux 21 seconds
  - 2020s: 20 milliseconds proposed for expedited GPs
    - CONFIG_RCU_EXP_CPU_STALL_TIMEOUT
      - Defaults to 20 ms if CONFIG_ANDROID, 21000 ms otherwise
    - But how is this going to work???

Contributed by Uladzislau Rezki, slated for v5.19

Real-Time Expedited Grace Periods

- Expedited grace periods driven by workqueues
  - Normal SCHED_OTHER priority
- New CONFIG_RCU_EXP_KTHREAD=y:
  - kthread_create_worker() @ SCHED_FIFO
  - Less than 32 CPUs, no -rt, boosting enabled
  - Reduce max latency 3 OOM to ~2 ms!

Contributed by Kalesh Singh, slated for v5.19

Real-Time Expedited Grace Periods

- There are a few remaining issues
  - Currently requires also running callback invocation at SCHED_FIFO
  - Which results in unacceptable latency spikes
  - Work in progress to run only expedited grace periods and priority boosting at SCHED_FIFO
    - Let callbacks fight it out at SCHED_OTHER

Miscellaneous

Miscellaneous

- If CONFIG_PREEMPTION, RCU readers can be preempted
- No longer special restrictions on scheduler use of rcu_read_unlock() (Lai Jiangshan)
- RCU now watches almost all of the idle loop (Peter Zijlstra and Thomas Gleixner)

Looking to the Future

Possible Future Work

- Even better handling of callback floods (battery)
- Callback-invocation cache locality
- Consolidate RCU Tasks & RCU Tasks Rude
- Faster RCU Tasks Trace grace periods
- Consolidate RCU dynticks into context tracking (Peter Zijlstra and/or Frederic Weisbecker)
- A very long list of more speculative items
  - For example, de-offload in response to callback overload
- Common case: Stuff I don’t see coming!!!

But How Much Future?

Looking Back to the Past ...

```
288 paulmck@linux.vnet.ibm.com (74%)
 11 peterz@infradead.org
 10 agordeev@redhat.com
 10 boqun.feng@gmail.com
  6 mingo@kernel.org
  6 oleg@redhat.com
  4 paul.gortmaker@windriver.com
  3 dave@stgolabs.net
  3 tglx@linutronix.de
  2 aik@ozlabs.ru
  2 bigeasy@linutronix.de
  2 changbin.du@intel.com
```

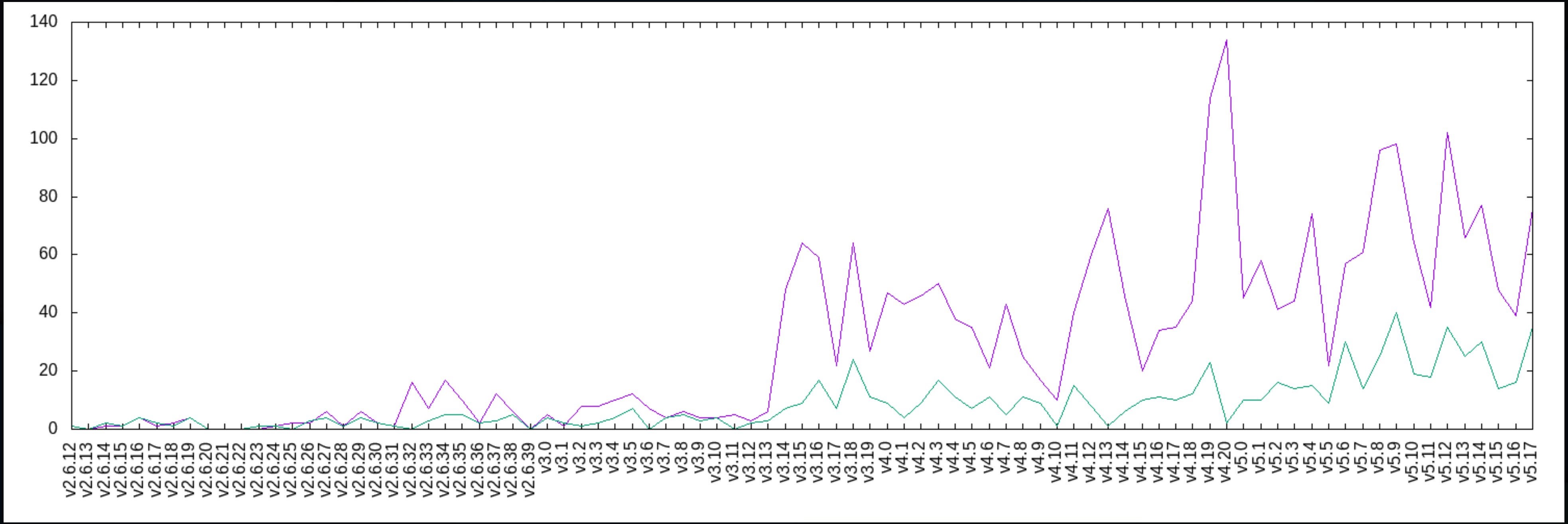
Number of RCU commits over the two years ending on April 24, 2017 from 46 contributors

… And Preparing for the Future

```
503 paulmck@kernel.org (63%)
 78 frederic@kernel.org
 26 urezki@gmail.com
 20 joel@joelfernandes.org
 14 peterz@infradead.org
 13 neeraju@codeaurora.org
 10 qiang1.zhang@intel.com
  7 mchehab+huawei@kernel.org
  7 zhouzhouyi@gmail.com
  6 bigeasy@linutronix.de
  6 tglx@linutronix.de
  5 quic_neeraju@quicinc.com
```

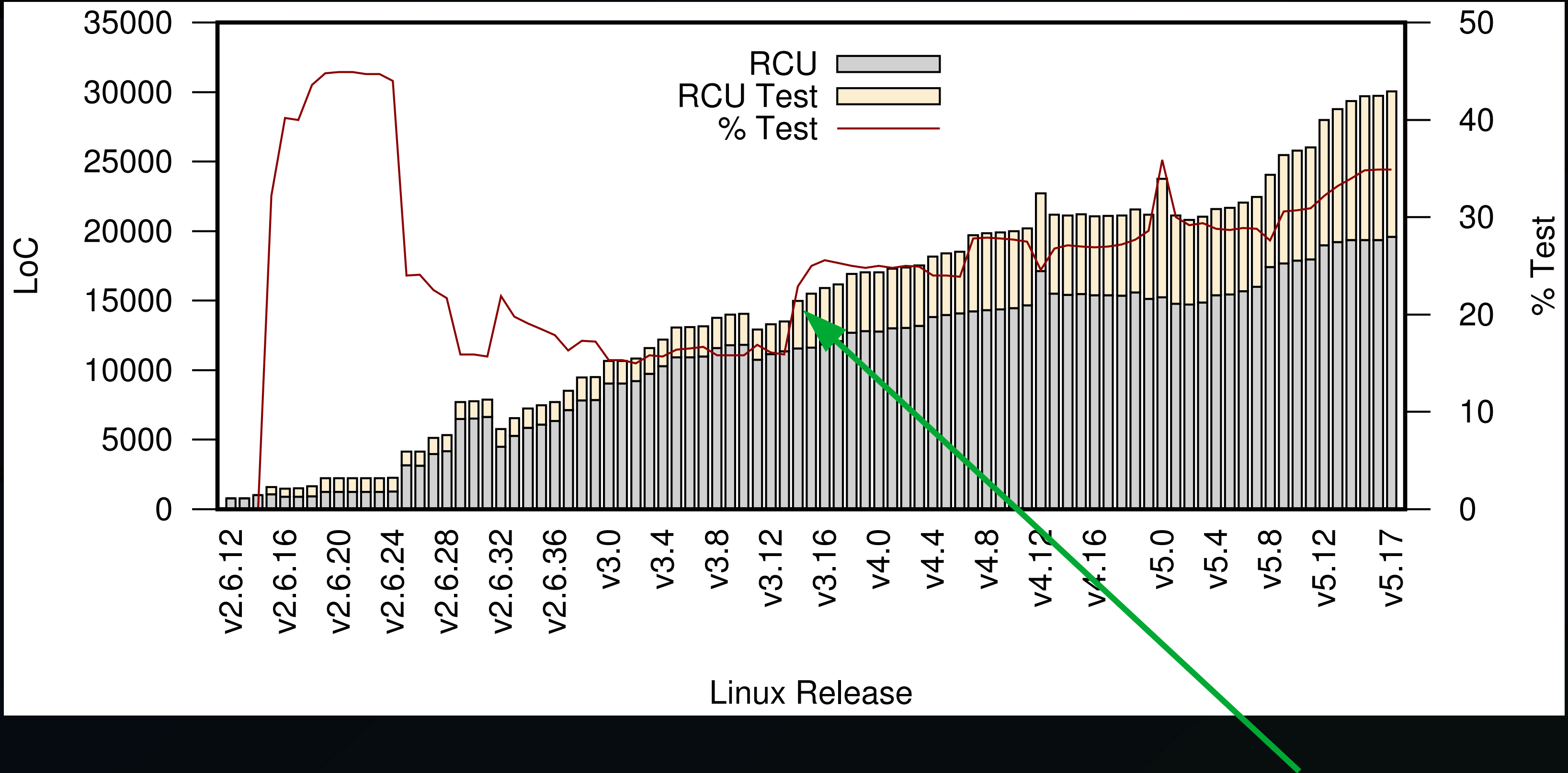
Number of RCU commits over the past two years as of April 24, 2022 from 79 contributors

Longer-Term Trends



Upper trace: All RCU commits. Lower trace: Non-paulmck RCU commits. What happened at v3.14???

What Happened at v3.14? A Train!!!



v3.14

Plot courtesy of Akira Yokosawa, taken from “Is Parallel Programming Hard, And, If So, What Can You Do About It?”

What Train Affected v3.14 RCU???

- Actually v3.0-rc7: https://lwn.net/Articles/453002/
- Understood bug in Nanjing, just before boarding 2-hour train to Shanghai
  - Without internet access, so two hours sweating bullets over alleged fix
  - No access to test grid and to cowardly to boot v3.0-rc7+fix on my only laptop
- Go from train to plane in Shanghai
  - Just enough internet access to send an email
- This experience motivated the rcutorture scripting, hence v3.14

Summary

Summary

- RCU is still under active development:
  - Driven by the needs of its users
- RCU synchronizes in space as well as time
  - But the time and space aspects are deeply intertwined
  - Enables near-zero-cost read-side synchronization
- RCU's dirty little secret:
  - RCU is dead simple, but in order to make good used of it, you must change the way that you think about your problem

For More Information

- Unraveling RCU Usage Mysteries
  - Part 1: https://www.linuxfoundation.org/webinars/unraveling-rcu-usage-mysteries/
  - Part 2: https://linuxfoundation.org/webinars/unraveling-rcu-usage-mysteries-additional-use-cases/
- “RCU Usage In the Linux Kernel: One Decade Later”:
  - http://www.rdrop.com/~paulmck/techreports/survey.2012.09.17a.pdf
  - http://www.rdrop.com/~paulmck/techreports/RCUUsage.2013.02.24a.pdf
  - 2020 update: https://dl.acm.org/doi/10.1145/3421473.3421481
- “Structured Deferral: Synchronization via Procrastination”: http://doi.acm.org/10.1145/2488364.2488549
- Linux-kernel RCU API, 2019 Edition: https://lwn.net/Articles/777036/
- “Stupid RCU Tricks: So you want to torture RCU?”: https://paulmck.livejournal.com/61432.html
- Documentation/RCU/* in kernel source
- “Is Parallel Programming Hard, And, If So, What Can You Do About It?”, “Deferred Processing” chapter: https://mirrors.edge.kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html
- Folly-library RCU implementation (also C-language user-space RCU)
- Large piles of information: http://www.rdrop.com/~paulmck/RCU/

Questions?