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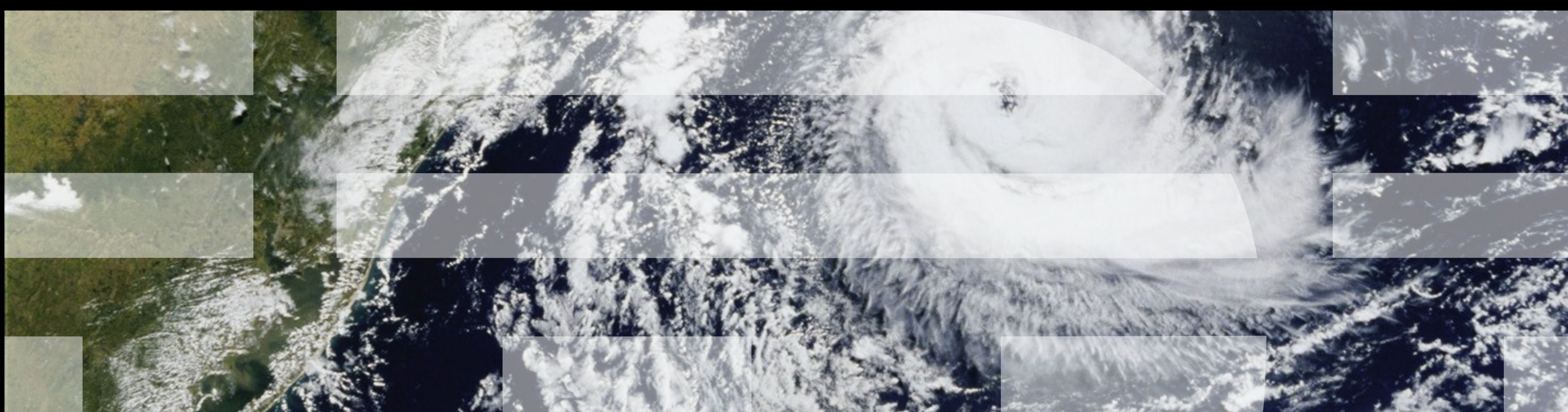
CS 569, Oregon State University, June 4, 2015

Formal Verification and Linux-Kernel Concurrency



Overview

- Two Definitions and a Consequence
- Current RCU Regression Testing
- How Well Does Linux-Kernel Testing Really Work?
- Why Formal Verification?
- Formal Verification and Regression Testing: Requirements
- Formal Verification Challenge

Two Definitions and a Consequence

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  - In practice, validation is about reducing risk
  - Can formal verification now take a front-row seat in this risk reduction?

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  - In practice, validation is about reducing risk
  - Can formal verification now take a front-row seat in this risk reduction?
- ***What would need to happen for me to include formal verification in my RCU regression testing?***

Current RCU Regression Testing

Current RCU Regression Testing
But First, What Is RCU (Read-Copy Update)?

RCU Is A Synchronization Mechanism That Avoids Contention and Expensive Hardware Operations

Want to be here!

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
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

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

Typical synchronization mechanisms do this a lot, plus suffer from contention

RCU Has Exceedingly Lightweight Readers

- In non-preemptible (run-to-block) environments, lightest-weight conceivable read-side primitives
  - #define rcu_read_lock()
  - #define rcu_read_unlock()
  - RCU readers are clearly extremely weakly ordered

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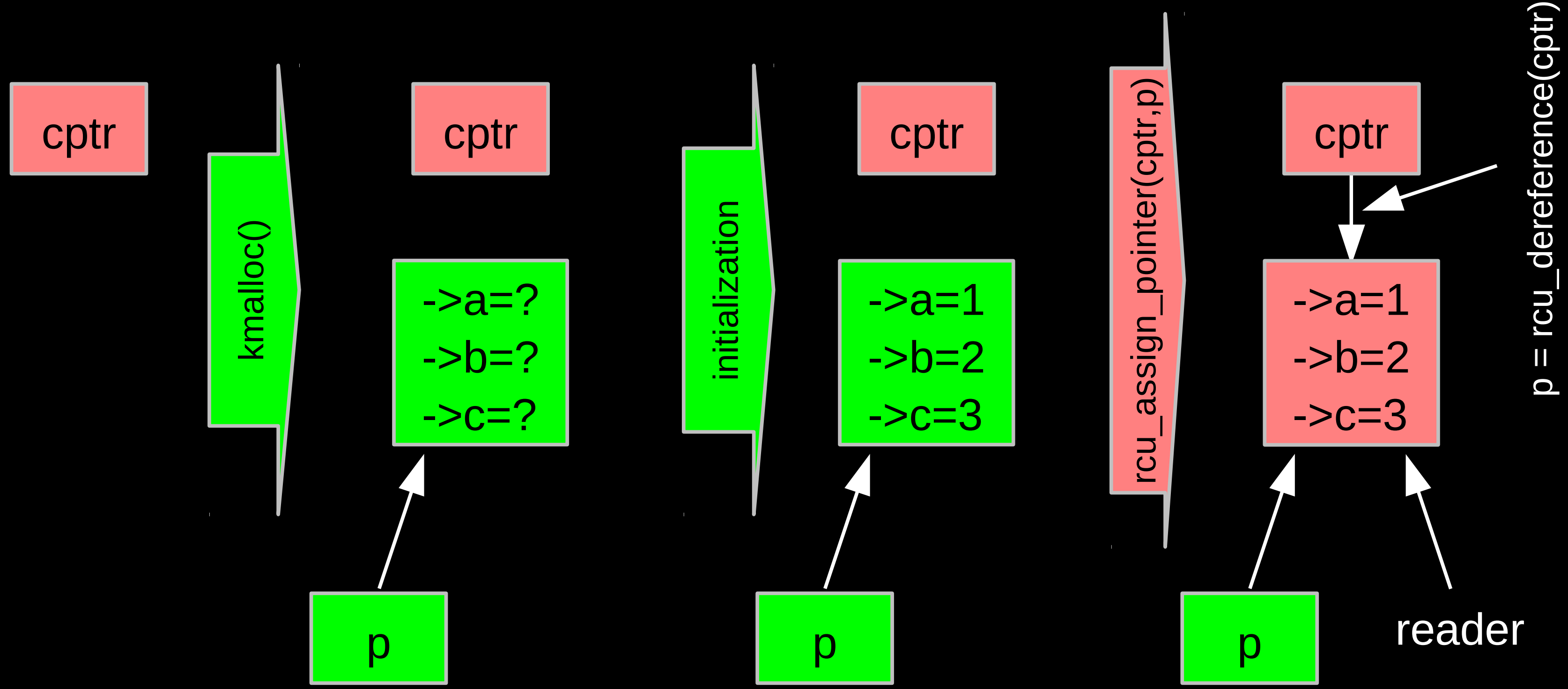
  - RCU readers are clearly extremely weakly ordered
- Best possible performance, scalability, real-time response, wait-freedom, and energy efficiency
- Uses indirect reasoning to determine when readers are done
  - In preemptible environments, rcu_read_lock() and rcu_read_unlock() manipulate per-thread variables
- References:
  - McKenney and Slingwine: “Read-Copy Update: Using Execution History to Solve Concurrency Problems”, PDCS 1998
  - Desnoyers, McKenney, Stern, Dagenais, and Walpole: “User-Level Implementations of Read-Copy Update”, Feb. 2012 IEEE TPDS
  - Additional references in backup slides

Publication of And Subscription to New Data

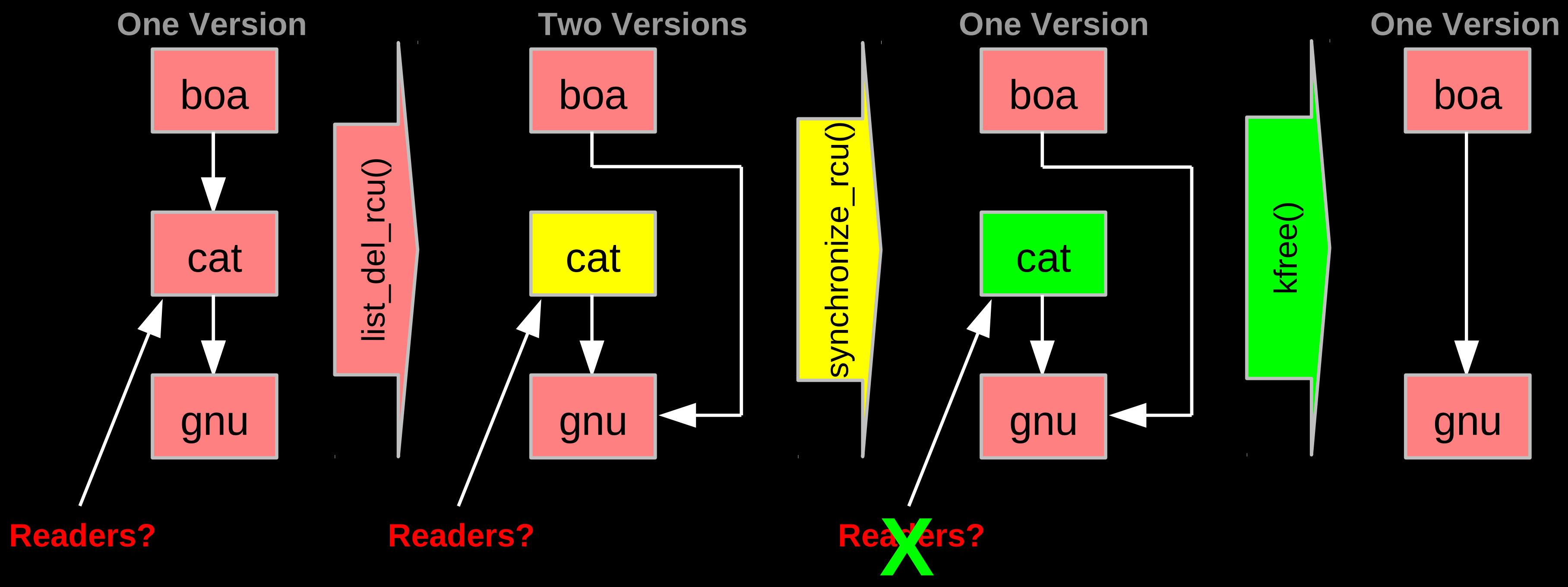
Key:
- Dangerous for updates: all readers can access
- Still dangerous for updates: pre-existing readers can access (backup)
- Safe for updates: inaccessible to all readers



See "To probe deeper" slides for more information

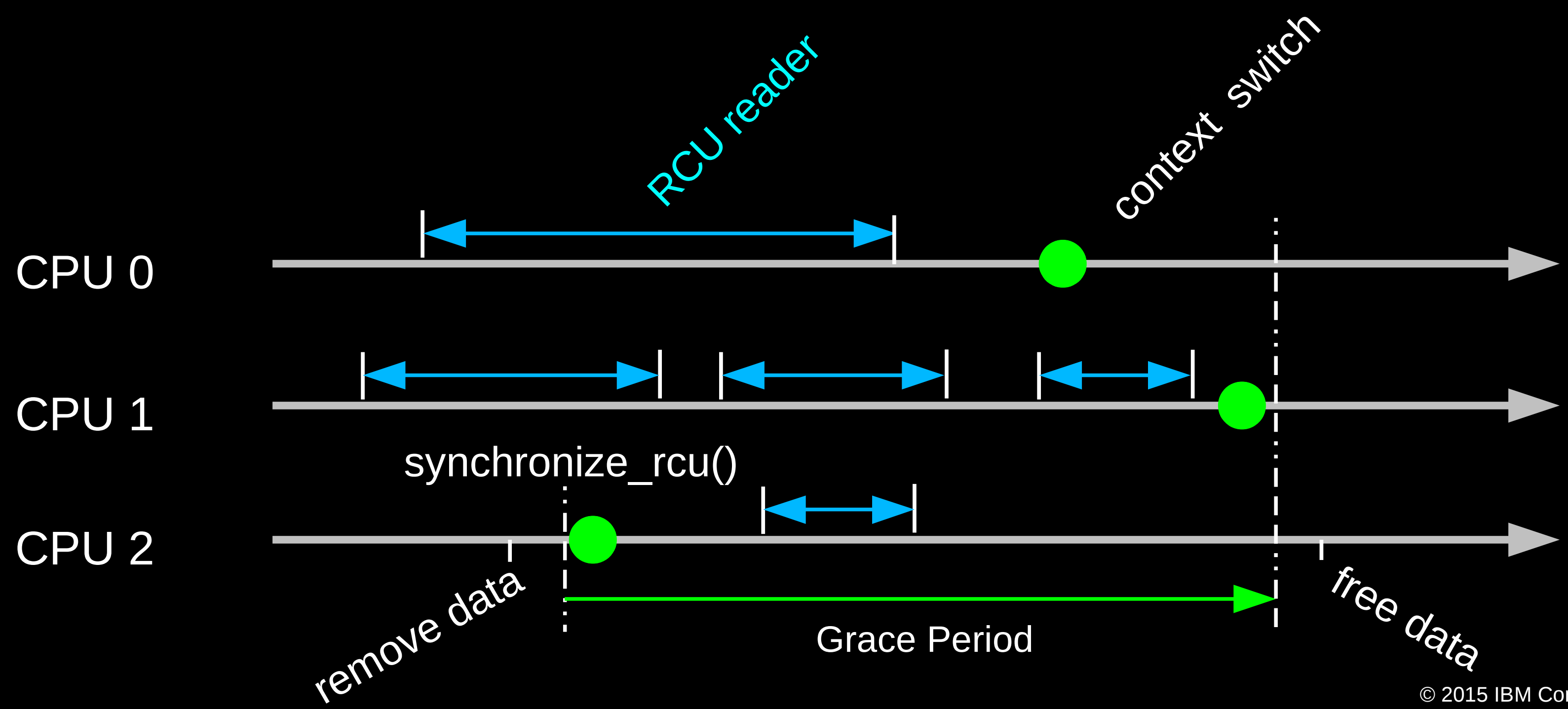
RCU Removal From Linked List

- 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())



Waiting for Pre-Existing Readers

- 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; \
})
```

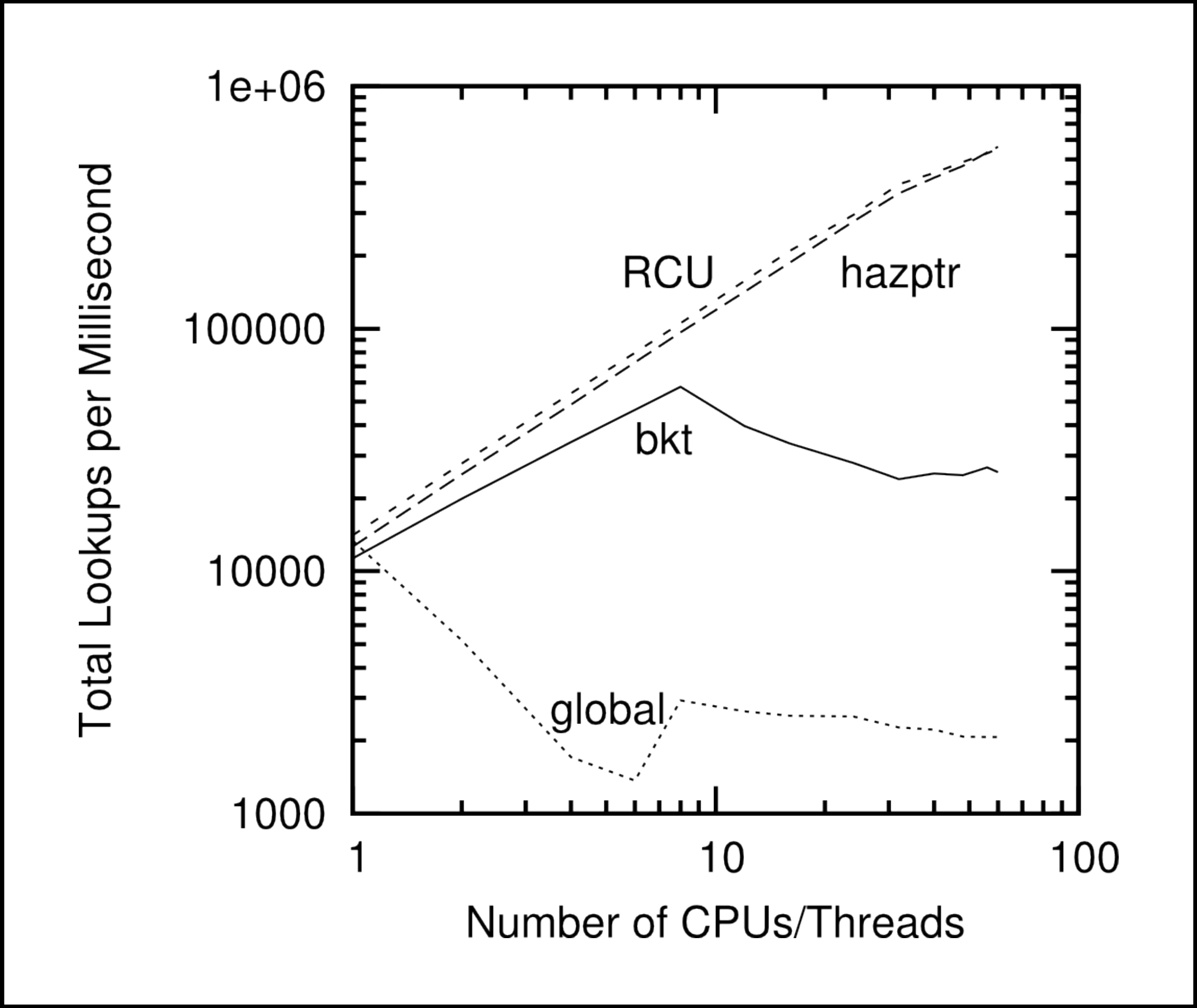
- Update-side primitives

```
#define rcu_assign_pointer(p, v) \
({ \
        smp_wmb(); \
        (p) = (v); \
})
void synchronize_rcu(void)
{
        int cpu;

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

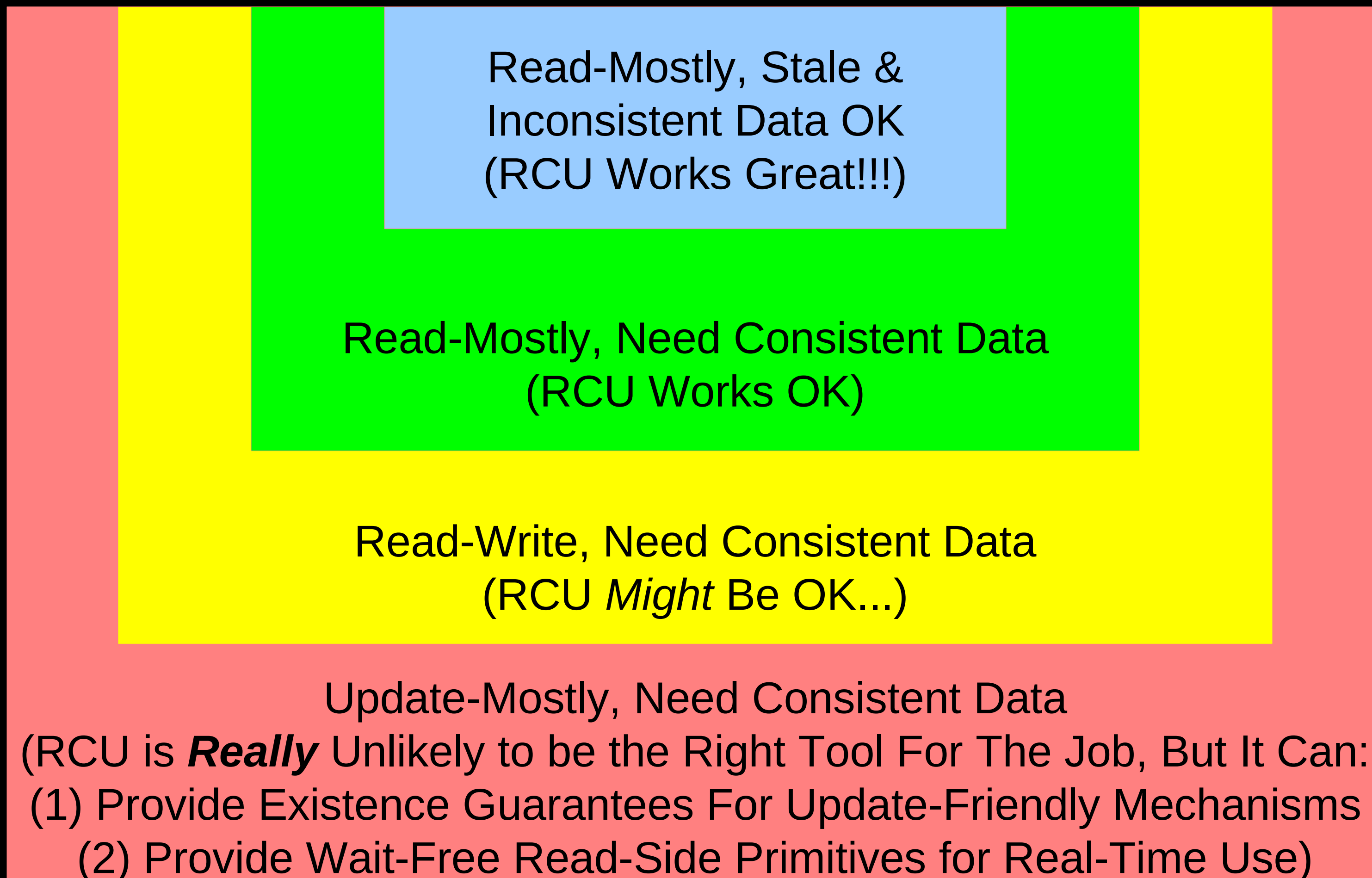
Only 9 of which are needed on sequentially consistent systems

RCU Performance: Read-Only Hash Table

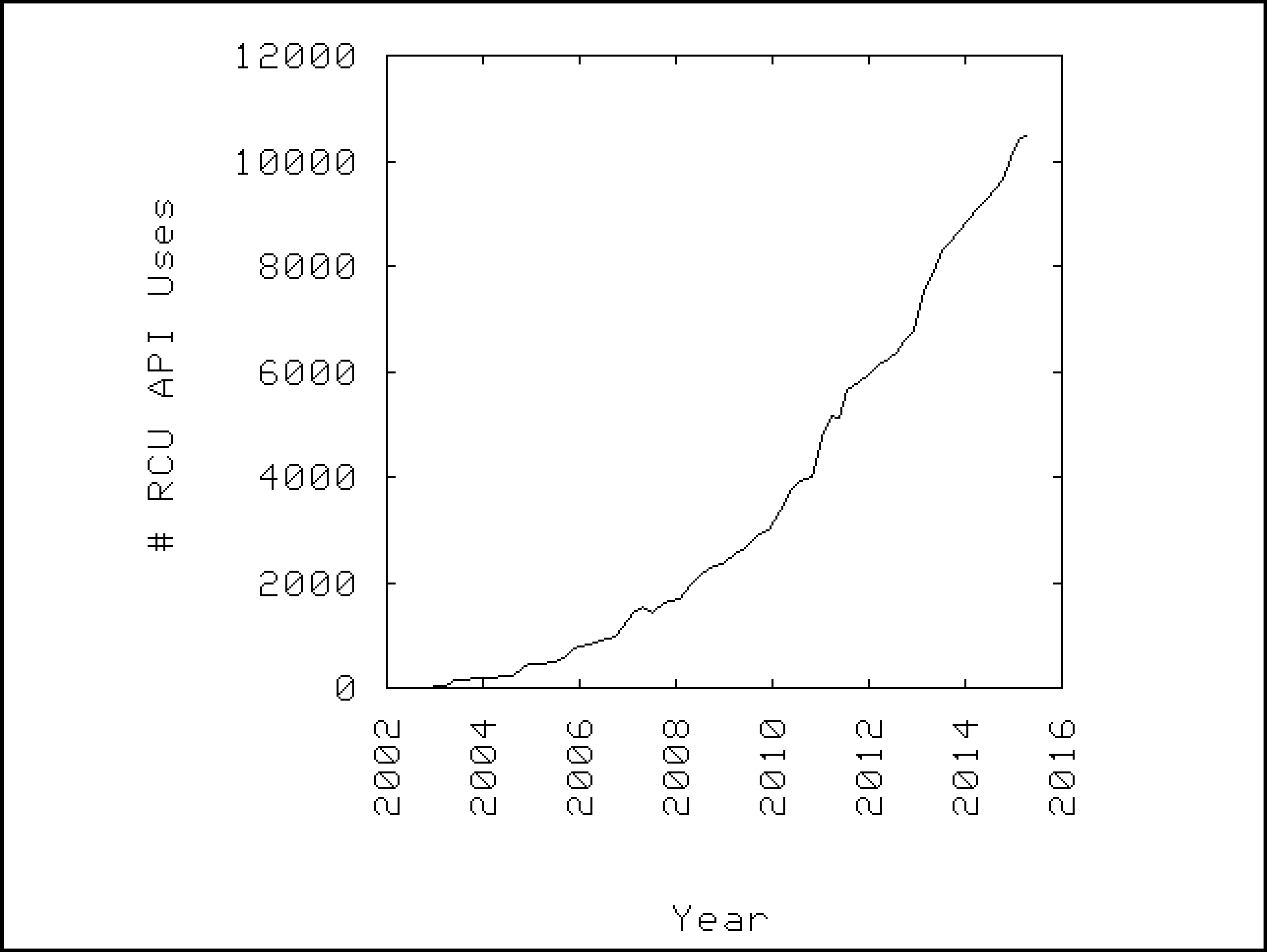


RCU and hazard pointers scale quite well!!!

RCU Area of Applicability



RCU Applicability to the Linux Kernel



Current RCU Regression Testing

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- Stress-test suite: “rcutorture”
  - http://lwn.net/Articles/154107/, http://lwn.net/Articles/622404/
- “Intelligent fuzz testing”: “trinity”
  - http://codemonkey.org.uk/projects/trinity/
- Test suite including static analysis: “0-day test robot”
  - https://lwn.net/Articles/514278/
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- Integration testing: “linux-next tree”
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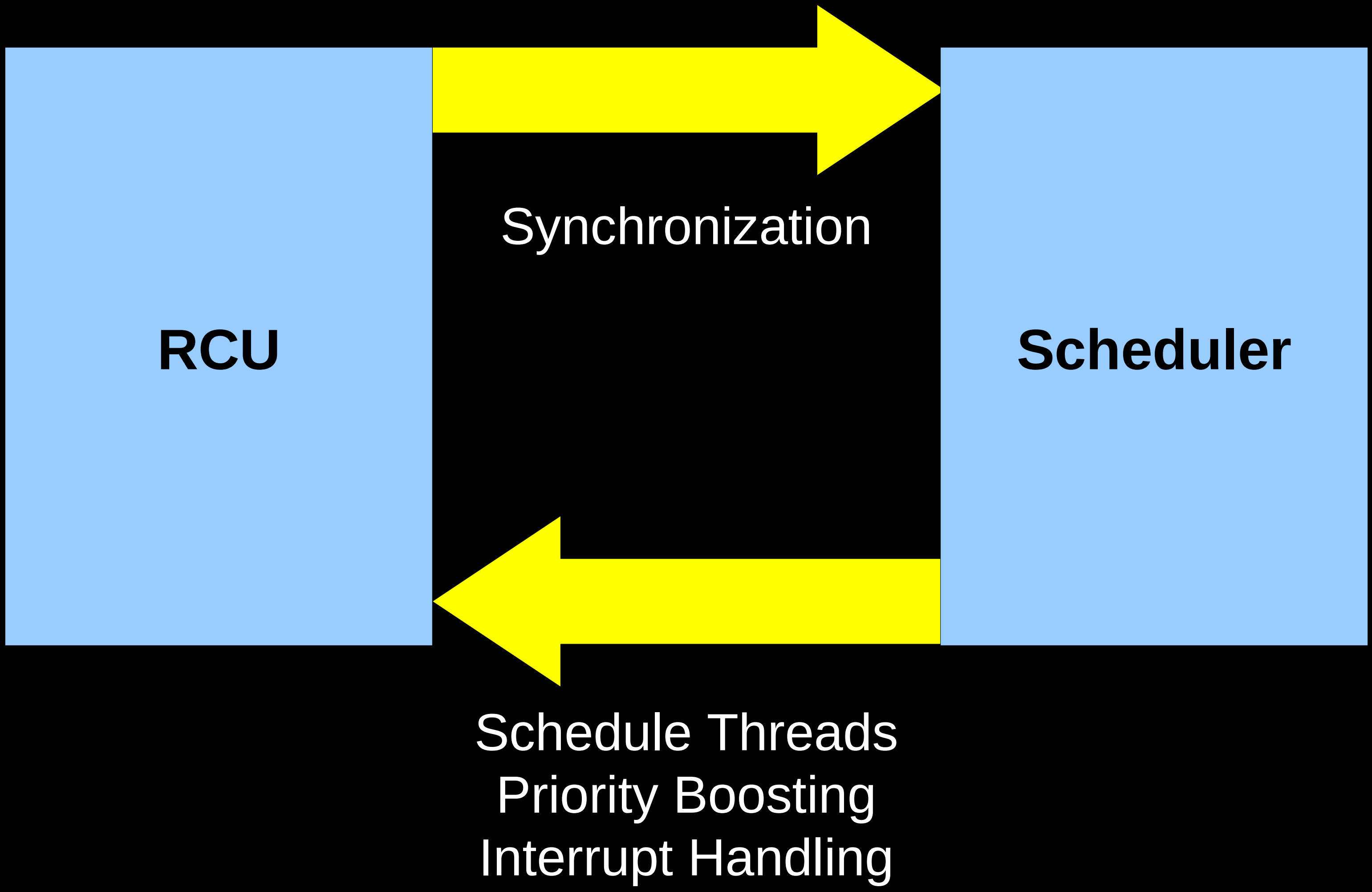
- Above is old technology – but not entirely ineffective
  - 2010: wait for -rc3 or -rc4. 2013: No problems with -rc1
- Formal verification in design, but not in regression testing
  - http://lwn.net/Articles/243851/, https://lwn.net/Articles/470681/, https://lwn.net/Articles/608550/

How Well Does Linux-Kernel Testing Really Work?

Example 1: RCU-Scheduler Mutual Dependency



So, What Was The Problem?

- Found during testing of Linux kernel v3.0-rc7:
  - RCU read-side critical section is preempted for an extended period
  - RCU priority boosting is brought to bear
  - RCU read-side critical section ends, notes need for special processing
  - Interrupt invokes handler, then starts softirq processing
  - Scheduler invoked to wake ksoftirqd kernel thread:
    - Acquires runqueue lock and enters RCU read-side critical section
    - Leaves RCU read-side critical section, notes need for special processing
    - Because in_irq() returns false, special processing attempts deboosting
    - Which causes the scheduler to acquire the runqueue lock
    - Which results in self-deadlock
  - (See http://lwn.net/Articles/453002/ for more details.)
- Fix: Add separate “exiting read-side critical section” state
  - Also validated my creation of correct patches – without testing!

Note: Remains a bug even under SC

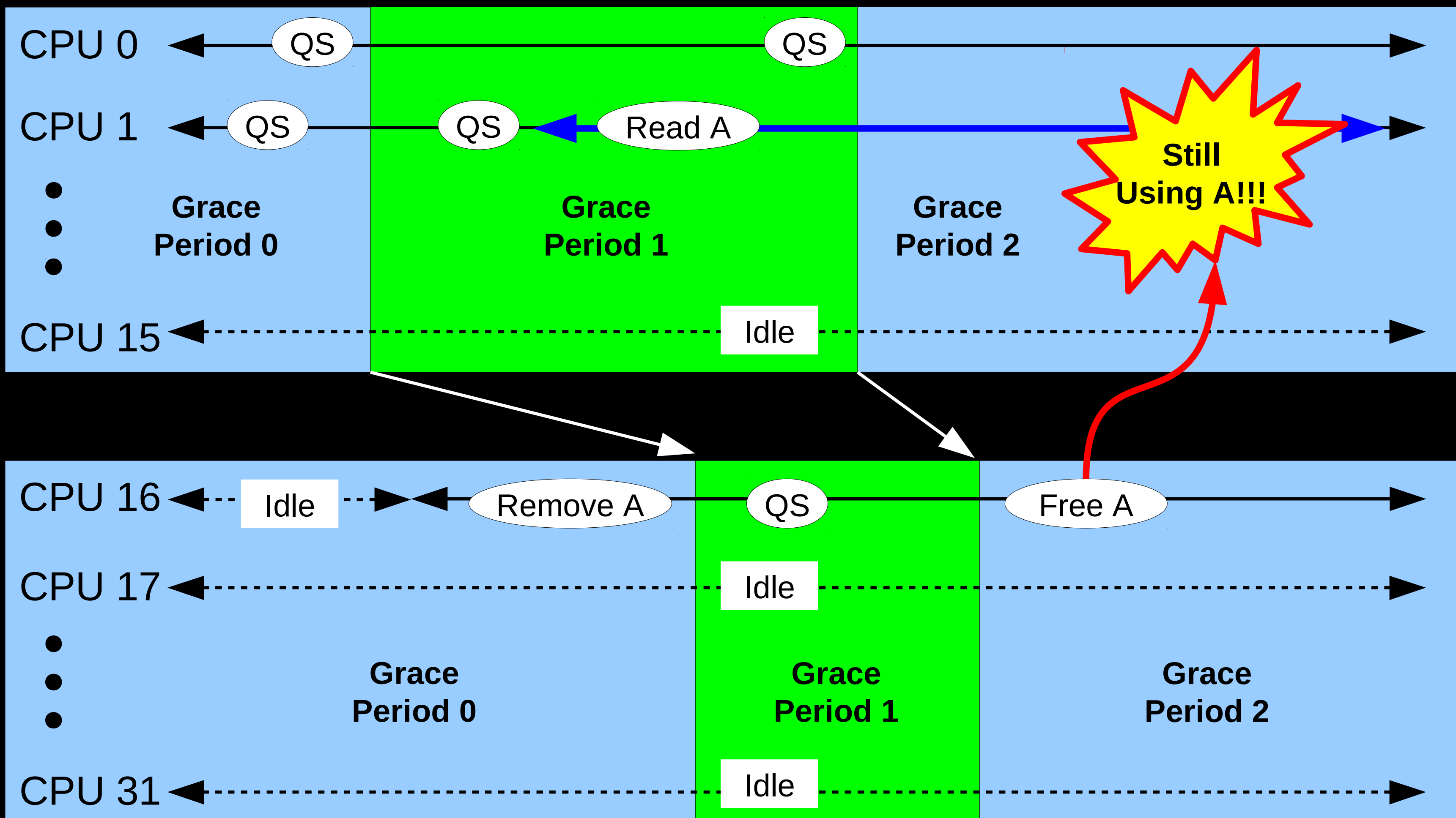
Example 1: Bug Was Located By Normal Testing

Example 2: Grace Period Cleanup/Initialization Bug

1. CPU 0 completes grace period, starts new one, cleaning up and initializing up through first leaf rcu_node structure
2. CPU 1 passes through quiescent state (new grace period!)
3. CPU 1 does rcu_read_lock() and acquires reference to A
4. CPU 16 exits dyntick-idle mode (back on ***old*** grace period)
5. CPU 16 removes A, passes it to call_rcu()
6. CPU 16 associates callback with next grace period
7. CPU 0 completes cleanup/initialization of rcu_node structures
8. CPU 16 callback associated with now-current grace period
9. All remaining CPUs pass through quiescent states
10. Last CPU performs cleanup on all rcu_node structures
11. CPU 16 notices end of grace period, advances callback to “done” state
12. CPU 16 invokes callback, freeing A (***too bad CPU 1 is still using it***)

Not found via Linux-kernel validation: In production for 5 years!

Example 2: Grace Period Cleanup/Initialization Bug



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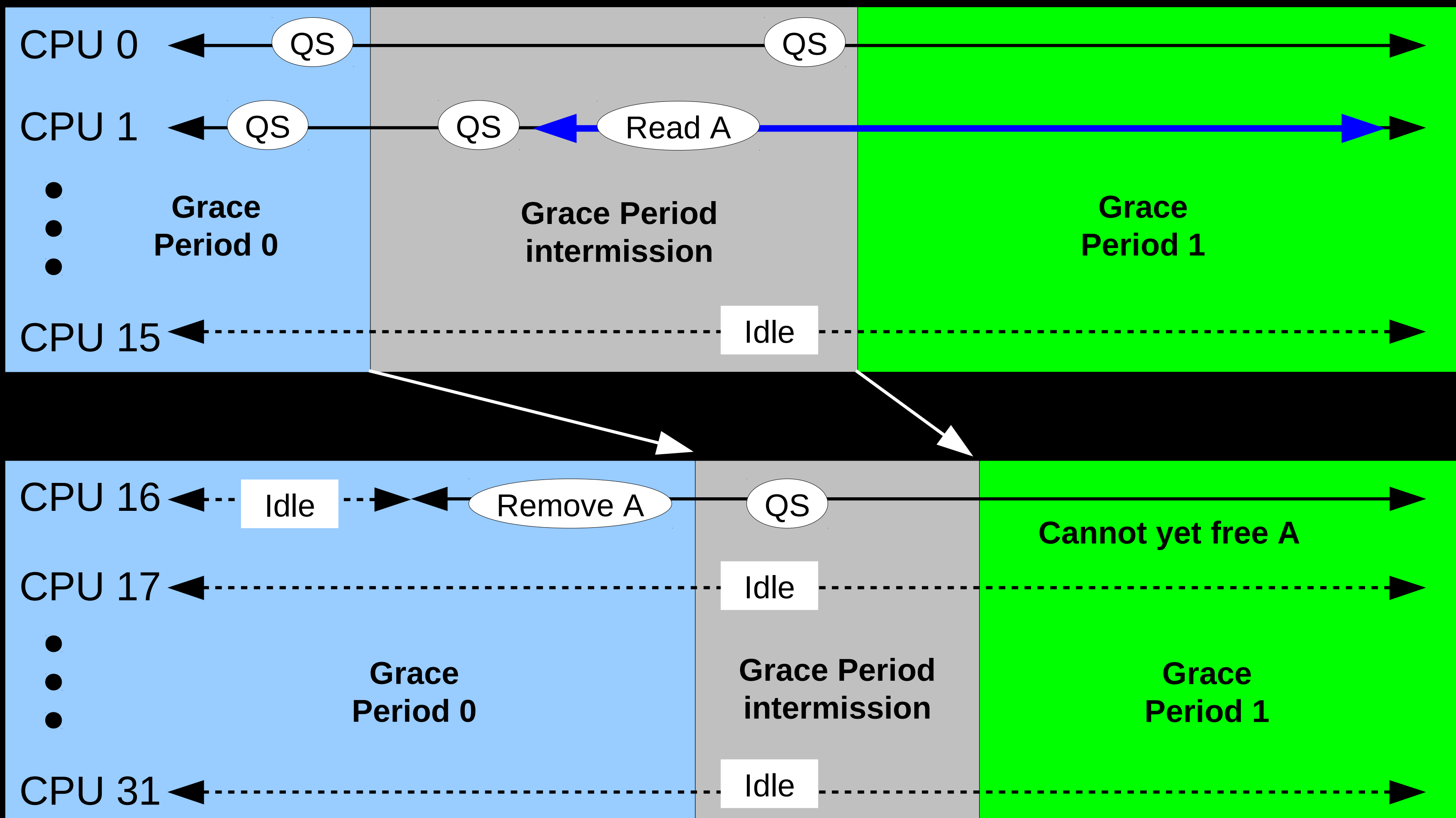
Example 2: Grace Period Cleanup/Initialization Fix



All agree that grace period 1 starts after grace period 0 ends

Example 1 & Example 2 Results

- Example 1: Bug was located by normal Linux test procedures
- Example 2: Bug was missed by normal Linux test procedures
  - Not found via Linux-kernel validation: In production for 5 years!
  - On systems with up to 4096 CPUs...
- Both are bugs even under sequential consistency
- Can formal verification do better?

Why Formal Verification?

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- At least one billion embedded Linux devices
  - A bug that occurs once per million years manifests three times per day
  - But assume a 1% duty cycle, 10% in the kernel, and 1% of that in RCU
  - 10,000 device-years of RCU per year: p(RCU) = 10^{-5}

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- At least 20 million Linux servers
  - A bug that occurs once per million years manifests twice per month
  - Assume 50% duty cycle, 10% in the kernel, and 1% of that in RCU
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  - Assume 50% duty cycle, 10% in the kernel, and 1% of that in RCU
  - 10,000 system-years of RCU per year: p(RCU) = $5(10^{-4})$
- But assume bugs are races between pairs of random events
  - N-CPU probability of RCU race bug: $p(bug)=(p(RCU)/N)^2 N(N-1)/2$
  - Assume rcutorture p(RCU)=1, compute rcutorture speedup:
    - Embedded: 10^{10}: 36.5 days of rcutorture testing covers one year
    - Server: $4(10^6)$: 250 *years* of rcutorture testing covers one year
    - Linux kernel releases are only about 60 days apart: RCU is moving target

How Does RCU Work Without Formal Verification?

- What is validation strategy for 20M server systems?
  - Other failures mask those of RCU, including hardware failures
    - I know of no human artifact with a million-year MTBF
  - Increasing CPUs on test system increases race probability
    - And many systems have relatively few CPUs
  - Rare but critical operations can be forced to happen more frequently
    - CPU hotplug, expedited grace periods, RCU barrier operations...
  - Knowledge of possible race conditions allows targeted tests
    - Plus other dirty tricks learned in 25 years of testing concurrent software
    - Provide harsh environment to force software to evolve quickly
  - Formal verification ***is*** used for some aspects of RCU design
    - Dyntick idle, sysidle, NMI interactions
- But it would be valuable to use formal verification as part of RCU's regression testing!

Formal Verification and Regression Testing: Requirements

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(1)Either automatic translation or no translation required
- Automatic discarding of irrelevant portions of the code
- Manual translation provides opportunity for human error

(2)Correctly handle environment, including memory model
- The QRCU validation benchmark is an excellent cautionary tale

(3)Reasonable memory and CPU overhead
- Bugs must be located in practice as well as in theory
- Linux-kernel RCU is 15KLoC and release cycles are short

(4)Map to source code line(s) containing the bug
- “Something is wrong somewhere” is not a helpful diagnostic: I already know bugs exist

(5)Modest input outside of source code under test
- Preferably glean much of the specification from the source code itself (empirical spec!)

(6)Find relevant bugs
- Low false-positive rate, weight towards likelihood of occurrence (fixes create bugs!)

Formal Validation Tools Used and Regression Testing

- Promela and Spin
  - Holzmann: “The Spin Model Checker”
  - I have used Promela/Spin in design for more than 20 years, but:
    - Limited problem size, long run times, large memory consumption
    - Does not implement memory models (assumes sequential consistency)
    - Special language, difficult to translate from C
- ARMMEM and PPCMEM (2)
  - Alglave, Maranget, Pawan, Sarkar, Sewell, Williams, Nardelli: “PPCMEM/ARMMEM: A Tool for Exploring the POWER and ARM Memory Models”
    - Very limited problem size, long run times, large memory consumption
    - Restricted pseudo-assembly language, manual translation required
- Herd (2, 3)
  - Alglave, Maranget, and Tautschnig: “Herding Cats: Modelling, Simulation, Testing, and Data-mining for Weak Memory”
    - Very limited problem size (but much improved run times and memory consumption)
    - Restricted pseudo-assembly language, manual translation required

Useful, but not for regression testing

Promela Model of Incorrect Atomic Increment (1/2)

```
#define NUMPROCS 2

byte counter = 0;
byte progress[NUMPROCS];

proctype incrementer(byte me)
{
  int temp;

  temp = counter;
  counter = temp + 1;
  progress[me] = 1;
}
```

Promela Model of Incorrect Atomic Increment (2/2)

```
init {
  int i = 0;
  int sum = 0;

  atomic {
    i = 0;
    do
    :: i < NUMPROCS ->
      progress[i] = 0;
      run incrementer(i);
      i++
    :: i >= NUMPROCS -> break
    od;
  }
  atomic {
    i = 0;
    sum = 0;
    do
    :: i < NUMPROCS ->
      sum = sum + progress[i];
      i++
    :: i >= NUMPROCS -> break
    od;
    assert(sum < NUMPROCS || counter == NUMPROCS)
  }
}
```

PPCMEM Example Litmus Test for IRIW

```
PPC IRIW.litmus
""
(* Traditional IRIW. *)
{
0:r1=1; 0:r2=x;
1:r1=1;         1:r4=y;
2:      2:r2=x; 2:r4=y;
3:      3:r2=x; 3:r4=y;
}
 P0            | P1            | P2                    | P3                    ;
 stw r1,0(r2)  | stw r1,0(r4)  | lwz r3,0(r2)          | lwz r3,0(r4)          ;
               |               | sync                  | sync                  ;
               |               | lwz r5,0(r4)          | lwz r5,0(r2)          ;

exists
(2:r3=1 /\ 2:r5=0 /\ 3:r3=1 /\ 3:r5=0)
```

Fourteen CPU hours and 10 GB of memory

Herd Example Litmus Test for Incorrect IRIW

```
PPC IRIW-lwsync-f.litmus
""
(* Traditional IRIW. *)
{
0:r1=1; 0:r2=x;
1:r1=1;         1:r4=y;
2:      2:r2=x; 2:r4=y;
3:      3:r2=x; 3:r4=y;
}
 P0            | P1            | P2                    | P3                    ;
 stw r1,0(r2)  | stw r1,0(r4)  | lwz r3,0(r2)          | lwz r3,0(r4)          ;
               |               | lwsync                | lwsync                ;
               |               | lwz r5,0(r4)          | lwz r5,0(r2)          ;

exists
(2:r3=1 /\ 2:r5=0 /\ 3:r3=1 /\ 3:r5=0)

. . .

Positive: 1 Negative: 15
Condition exists (2:r3=1 /\ 2:r5=0 /\ 3:r3=1 /\ 3:r5=0)
Observation IRIW Sometimes 1 15
```

Cautiously Optimistic For Future CBMC Version

(1)Either automatic translation or no translation required
- No translation required from C, discards irrelevant code quite well

(2)Correctly handle environment, including memory model
- SC and TSO, hopefully will do other memory models in the future

(3)Reasonable memory and CPU overhead
- OK for Tiny RCU and some tiny uses of concurrent RCU
- Jury is out for concurrent linked-list manipulations
- “If you live by heuristics, you will die by heuristics”

(4)Map to source code line(s) containing the bug
- Yes, reasonably good backtrace capability

(5)Modest input outside of source code under test
- Yes, modest boilerplate required, can use existing assertions

(6)Find relevant bugs
- Jury still out

Kroening, Clarke, and Lerda, “A tool for checking ANSI-C programs”, *Tools and Algorithms for the Construction and Analysis of Systems, 2004,* pp. 168-176.

Ongoing Work

- Ahmed, Groce, and Jensen: Use mutation generation and formal verification to find holes in rcutorture
- Liang, Tautschnig, and Kroening: Experiments verifying RCU and uses of RCU using CBMC
- Alglave: Derive formal memory model for Linux kernel
  - Including RCU

Formal Verification Challenge

Formal Verification Challenge

- Testing has many shortcomings
  - Cannot find bugs in code not exercised
  - Cannot reasonably exhaustively test even small software systems
- Nevertheless, a number of independently developed test harnesses have found bugs in Linux-kernel RCU
  - Trinity, 0-day test robot, -next testing
- As far as I know, no independently developed formal-verification model has yet found a bug in Linux-kernel RCU
  - Therefore, this challenge:

Formal Verification Challenge

- Can you verify SYSIDLE from C source?
  - Or, of course, find a bug
- This Verification Challenge 2:
  - http://paulmck.livejournal.com/38016.html
- Mathieu Desnoyers and I verified (separately) with Promela:
  - https://www.kernel.org/pub/linux/kernel/people/paulmck/Validation/sysidle/
- But neither Promela/spin is not suitable for regression testing
- Can your formal-verification tool regression-test SYSIDLE?

To Probe Deeper (RCU)

- https://queue.acm.org/detail.cfm?id=2488549
  - "Structured Deferral: Synchronization via Procrastination" (also in July 2013 CACM)
- 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 of Eddie Koher)
- http://www.rdrop.com/users/paulmck/RCU/ (More RCU information)

To Probe Deeper (1/5)

- Hash tables:
  - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook-e1.html Chapter 10
- Split counters:
  - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Chapter 5
  - http://events.linuxfoundation.org/sites/events/files/slides/BareMetal.2014.03.09a.pdf
- Perfect partitioning
  - Candide et al: "Dynamo: Amazon's highly available key-value store"
    - http://doi.acm.org/10.1145/1323293.1294281
  - McKenney: "Is Parallel Programming Hard, And, If So, What Can You Do About It?"
    - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Section 6.5
  - McKenney: "Retrofitted Parallelism Considered Grossly Suboptimal"
    - Embarrassing parallelism vs. humiliating parallelism
    - https://www.usenix.org/conference/hotpar12/retro%EF%AC%81tted-parallelism-considered-grossly-sub-optimal
  - McKenney et al: "Experience With an Efficient Parallel Kernel Memory Allocator"
    - http://www.rdrop.com/users/paulmck/scalability/paper/mpalloc.pdf
  - Bonwick et al: "Magazines and Vmem: Extending the Slab Allocator to Many CPUs and Arbitrary Resources"
    - http://static.usenix.org/event/usenix01/full_papers/bonwick/bonwick_html/
  - Turner et al: "PerCPU Atomics"
    - http://www.linuxplumbersconf.org/2013/ocw//system/presentations/1695/original/LPC%20-%20PerCpu%20Atomics.pdf

To Probe Deeper (2/5)

- Stream-based applications:
  - Sutton: “Concurrent Programming With The Disruptor”
    - http://www.youtube.com/watch?v=UvE389P6Er4
    - http://lca2013.linux.org.au/schedule/30168/view_talk
  - Thompson: “Mechanical Sympathy”
    - http://mechanical-sympathy.blogspot.com/
- Read-only traversal to update location
  - Arcangeli et al: “Using Read-Copy-Update Techniques for System V IPC in the Linux 2.5 Kernel”
    - https://www.usenix.org/legacy/events/usenix03/tech/freenix03/full_papers/arcangeli/arcangeli_html/index.html
  - Corbet: “Dcache scalability and RCU-walk”
    - https://lwn.net/Articles/419811/
  - Xu: “bridge: Add core IGMP snooping support”
    - http://kerneltrap.com/mailarchive/linux-netdev/2010/2/26/6270589
  - Triplett et al., “Resizable, Scalable, Concurrent Hash Tables via Relativistic Programming”
    - http://www.usenix.org/event/atc11/tech/final_files/Triplett.pdf
  - Howard: “A Relativistic Enhancement to Software Transactional Memory”
    - http://www.usenix.org/event/hotpar11/tech/final_files/Howard.pdf
  - McKenney et al: “URCU-Protected Hash Tables”
    - http://lwn.net/Articles/573431/

To Probe Deeper (3/5)

- Hardware lock elision: Overviews
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