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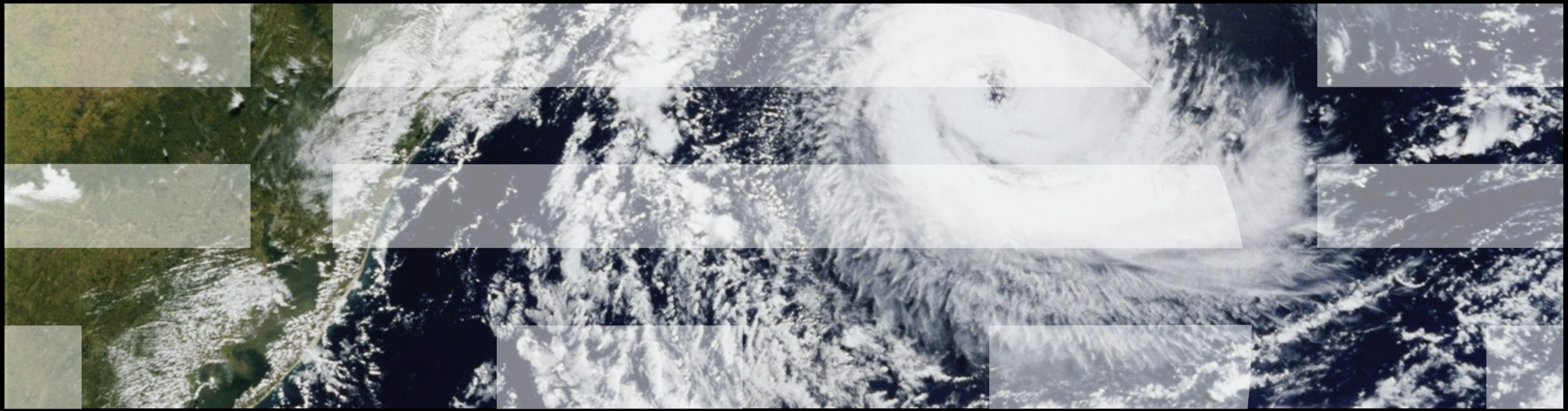
Beaver BarCamp, April 18, 2015

# 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

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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

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# 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

# The Conceptual Components of RCU

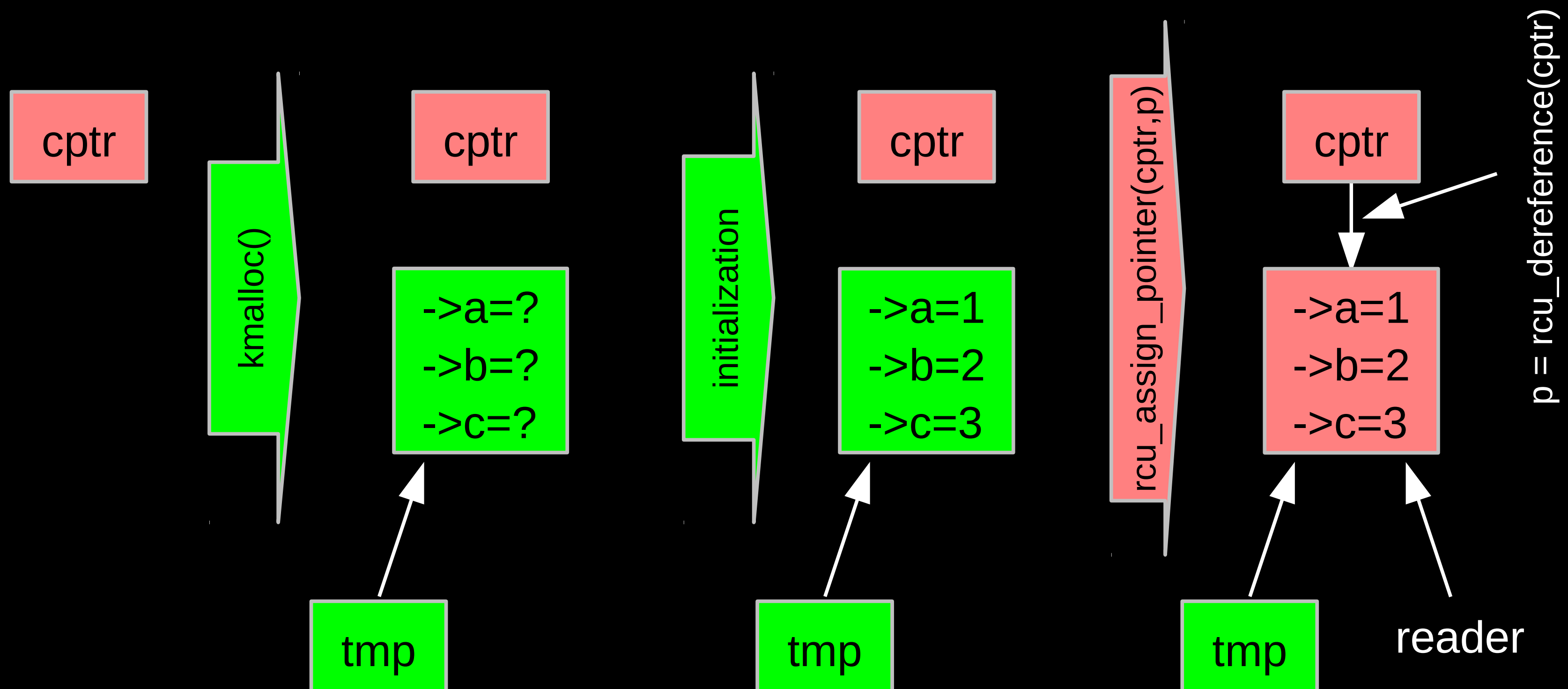
- Publishing of new data
- Subscribing to the current version of data
- Waiting for pre-existing RCU readers: Avoid disrupting readers by maintaining multiple versions of the data
  - Each *read*er continues traversing its *copy* of the data while a new *copy* might be being created concurrently by each *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
- In Linux kernel, frequently used to replace reader-writer locking
- 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
  - McKenney: “Structured Deferral: Synchronization via Procrastination”, July 2013 CACM

# 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 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

# Publication of And Subscription to New Data

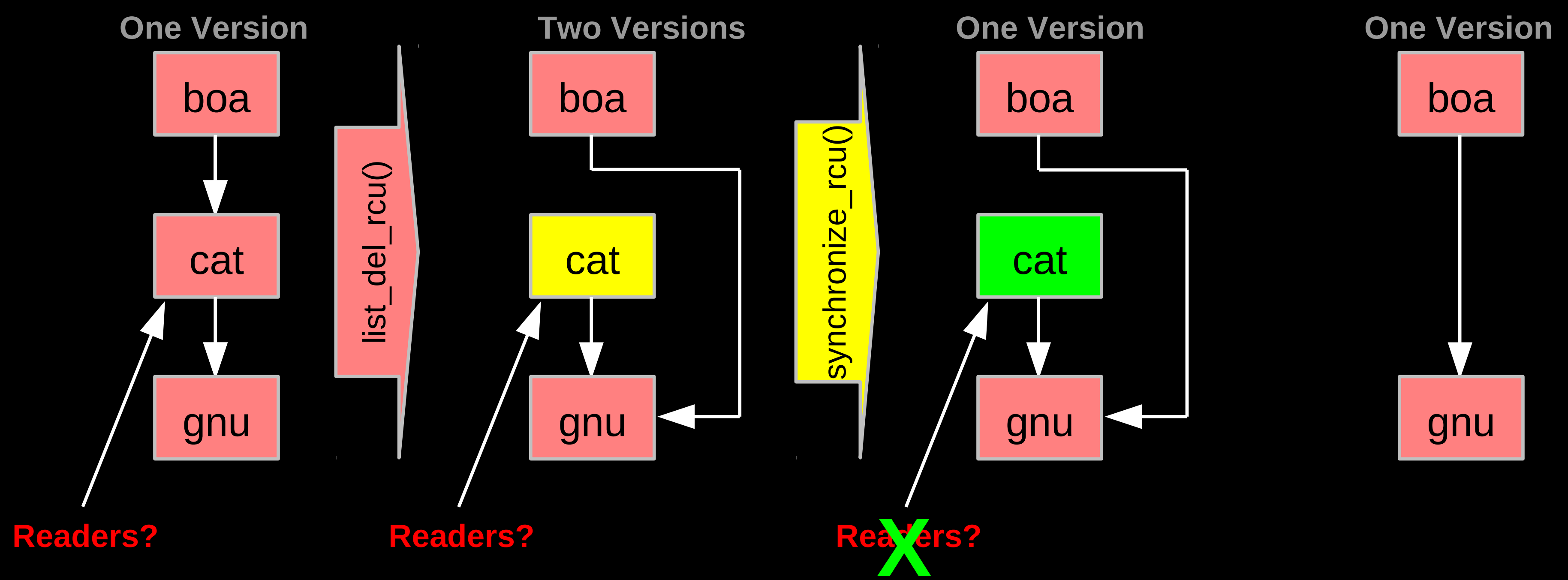
Key:
- Dangerous for updates: all readers can access
- Still dangerous for updates: pre-existing readers can access (next slide)
- Safe for updates: inaccessible to all readers




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

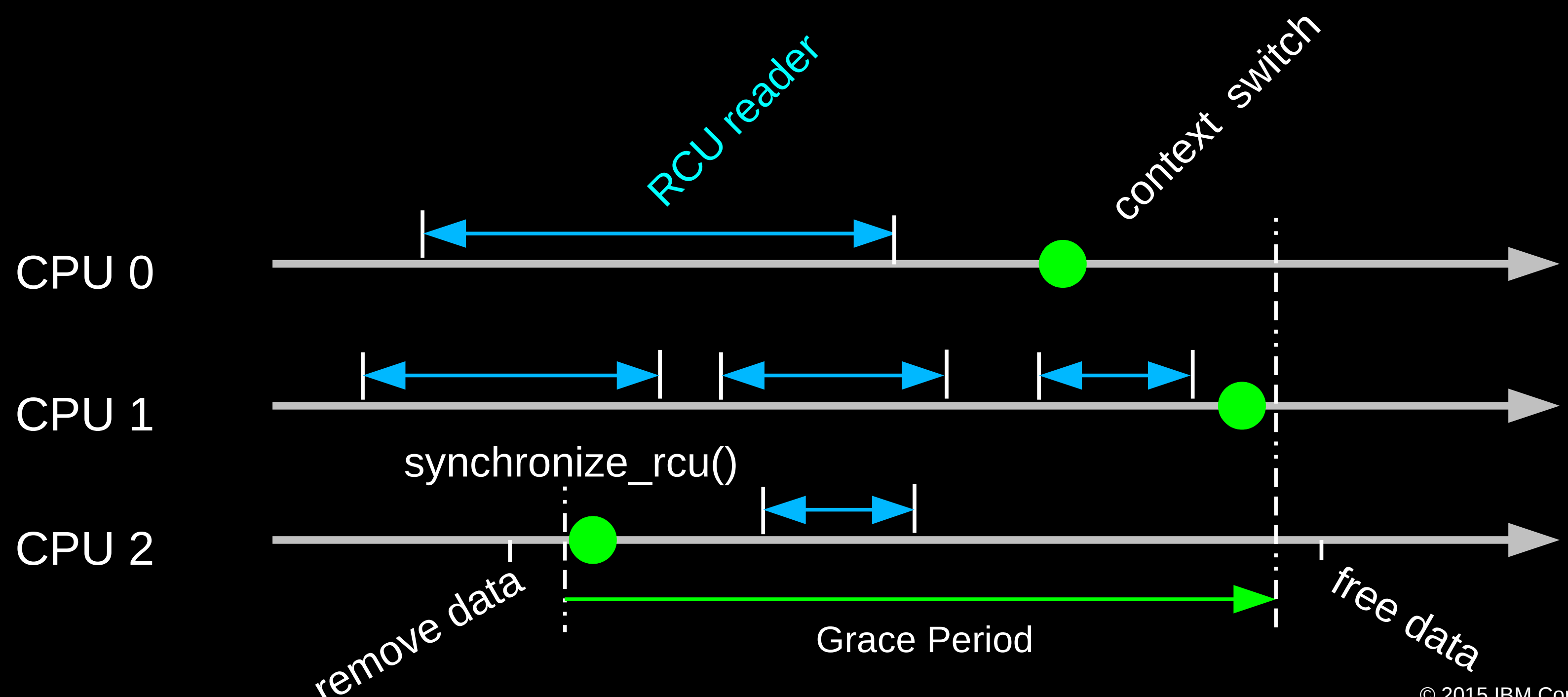
# RCU Removal From Linked List

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



# 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



# 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
- RCU is therefore synchronization via social engineering
- As are all other 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; \
})
```

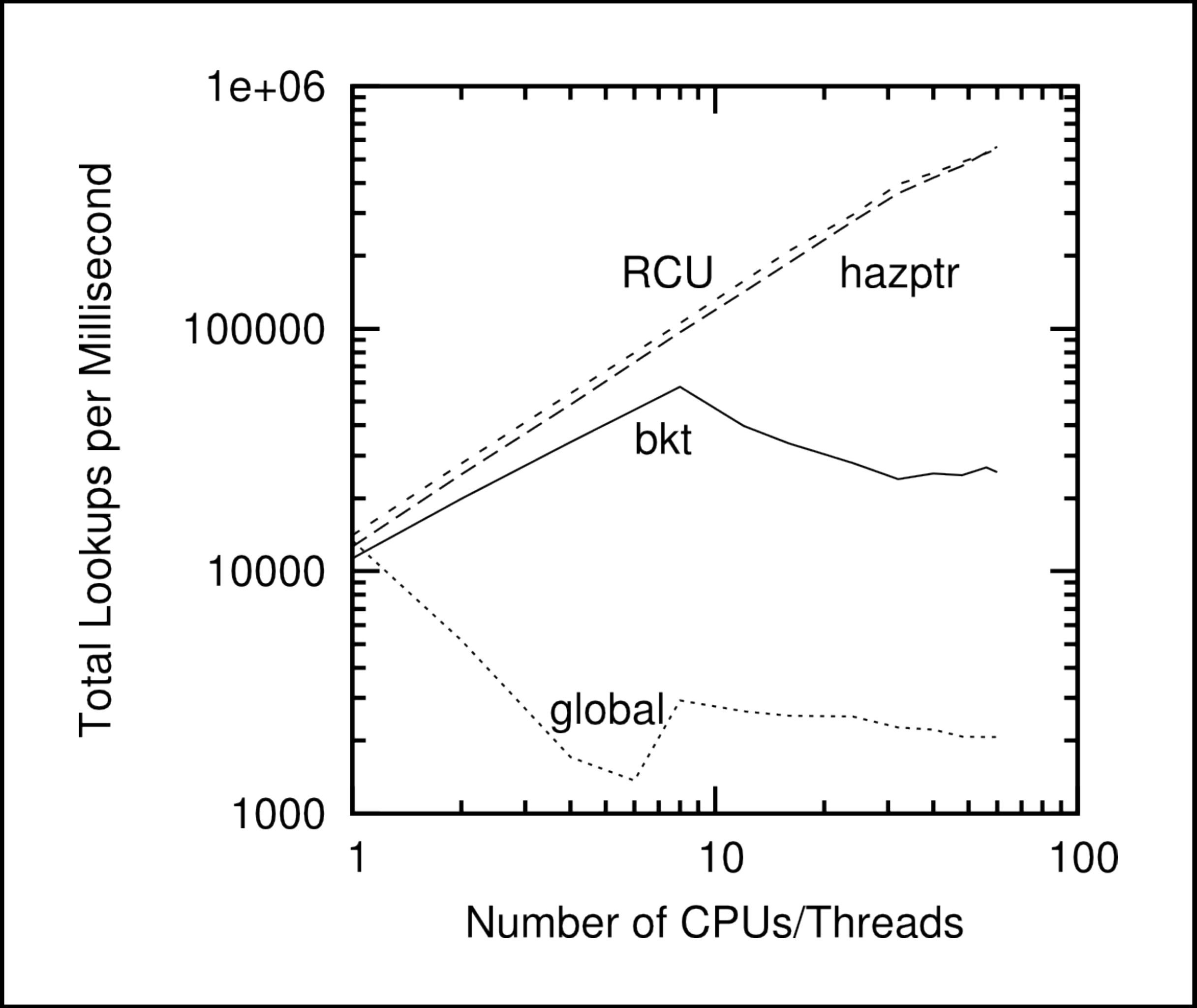
- Update-side primitives

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

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

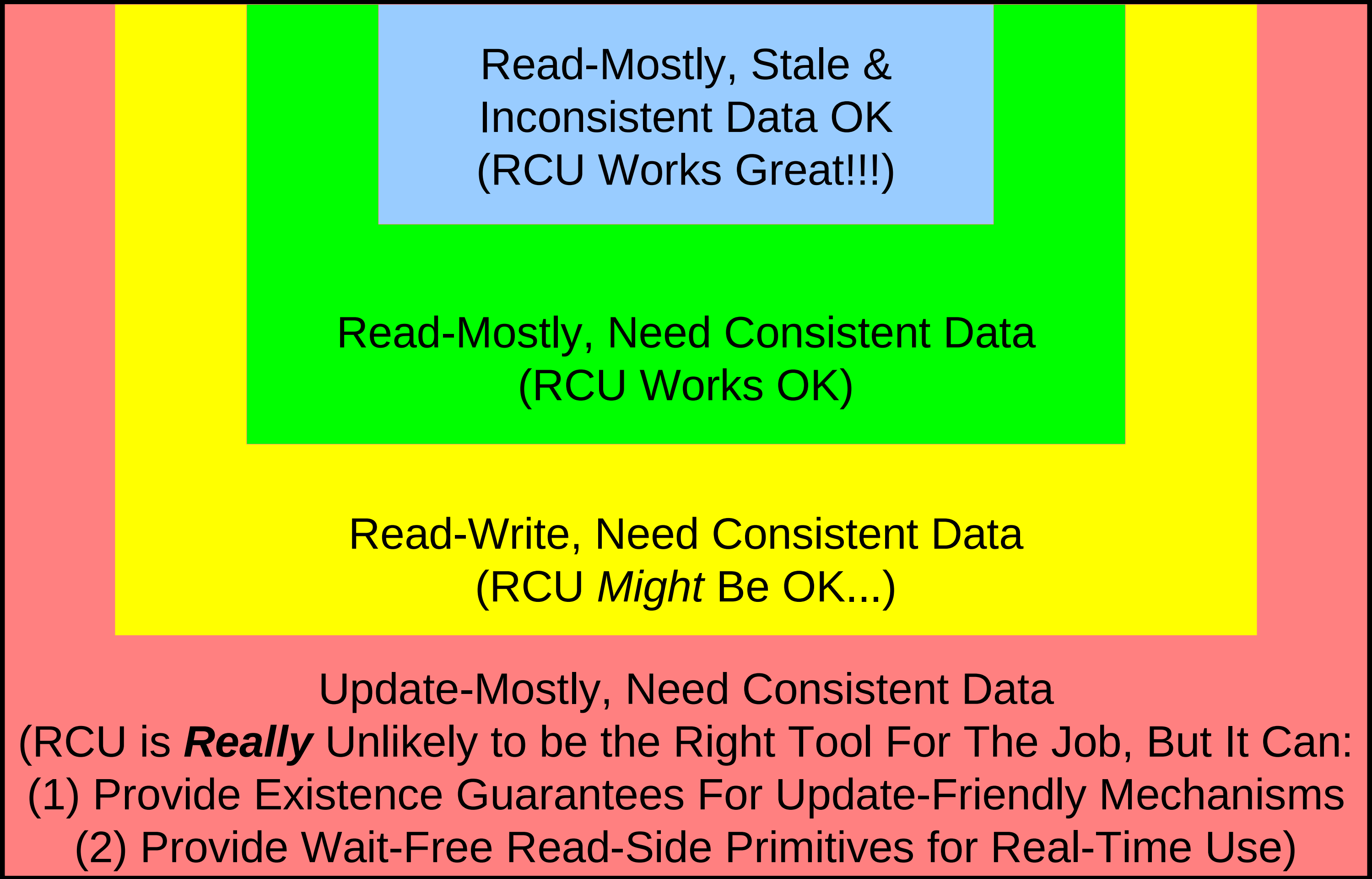
Only 9 of which are needed on sequentially consistent systems

# RCU Performance: Read-Only Hash Table

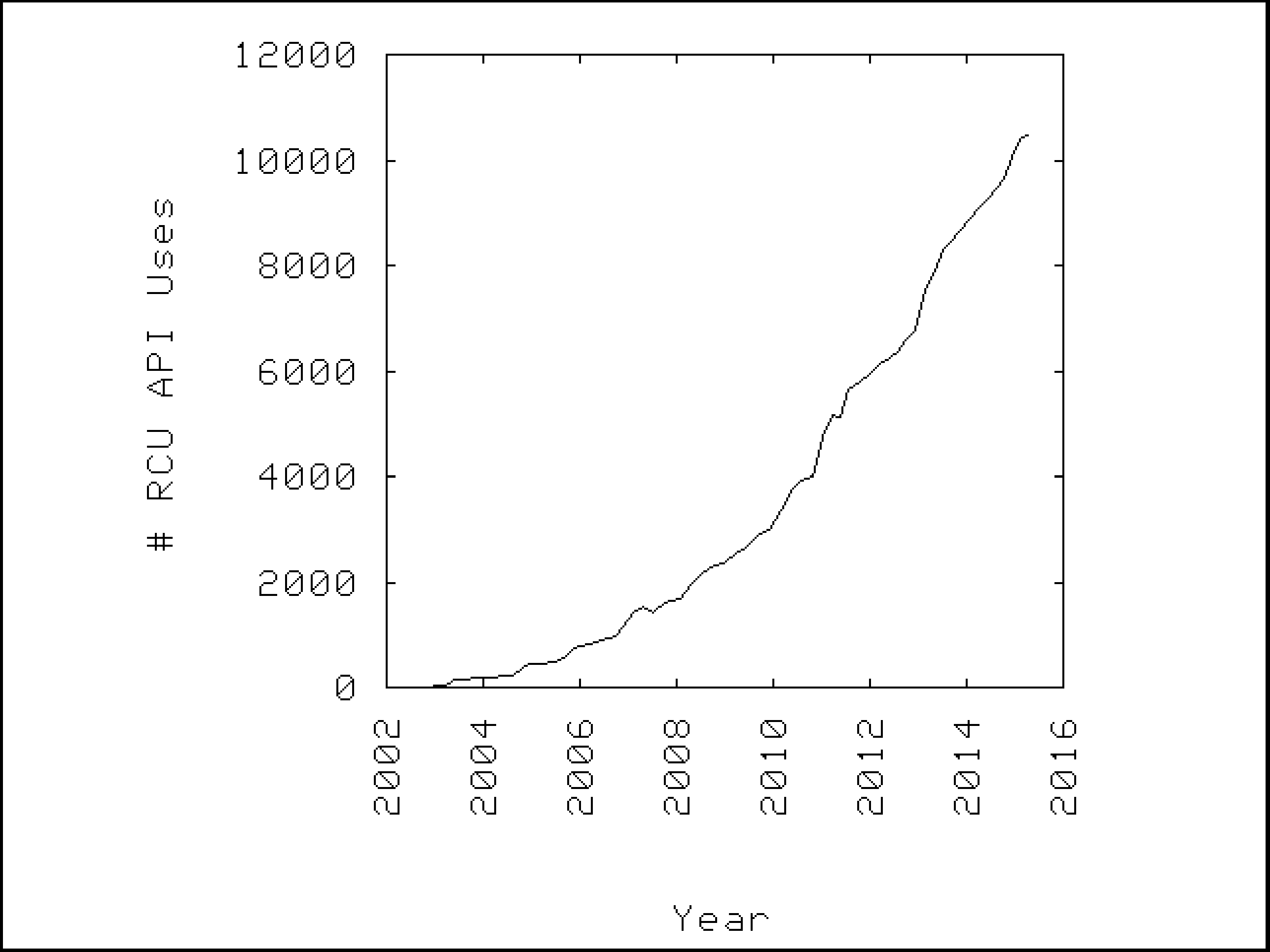



RCU and hazard pointers scale quite well!!!

# RCU Area of Applicability



# RCU Applicability to the Linux Kernel



# Current RCU Regression Testing

# The Nature of Testing

- One does not simply test correctness into one's program
- Common practice applies statistical inference to test results
  - For example, “These test results show that the change reduced the program's failure rate by at least two orders of magnitude, with 99.5% confidence.”
- Bugs can of course be deterministic in nature
  - One system deterministically crashed every evening just after backups
  - But attempts to reproduce in the lab resulted in 27-hour MTBF
  - Once the bug was identified, a 12-minute MTBF test was produced
- Not perfect, but commonly used in practice

# Current RCU Regression Testing

- 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”
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- Integration testing: “linux-next tree”
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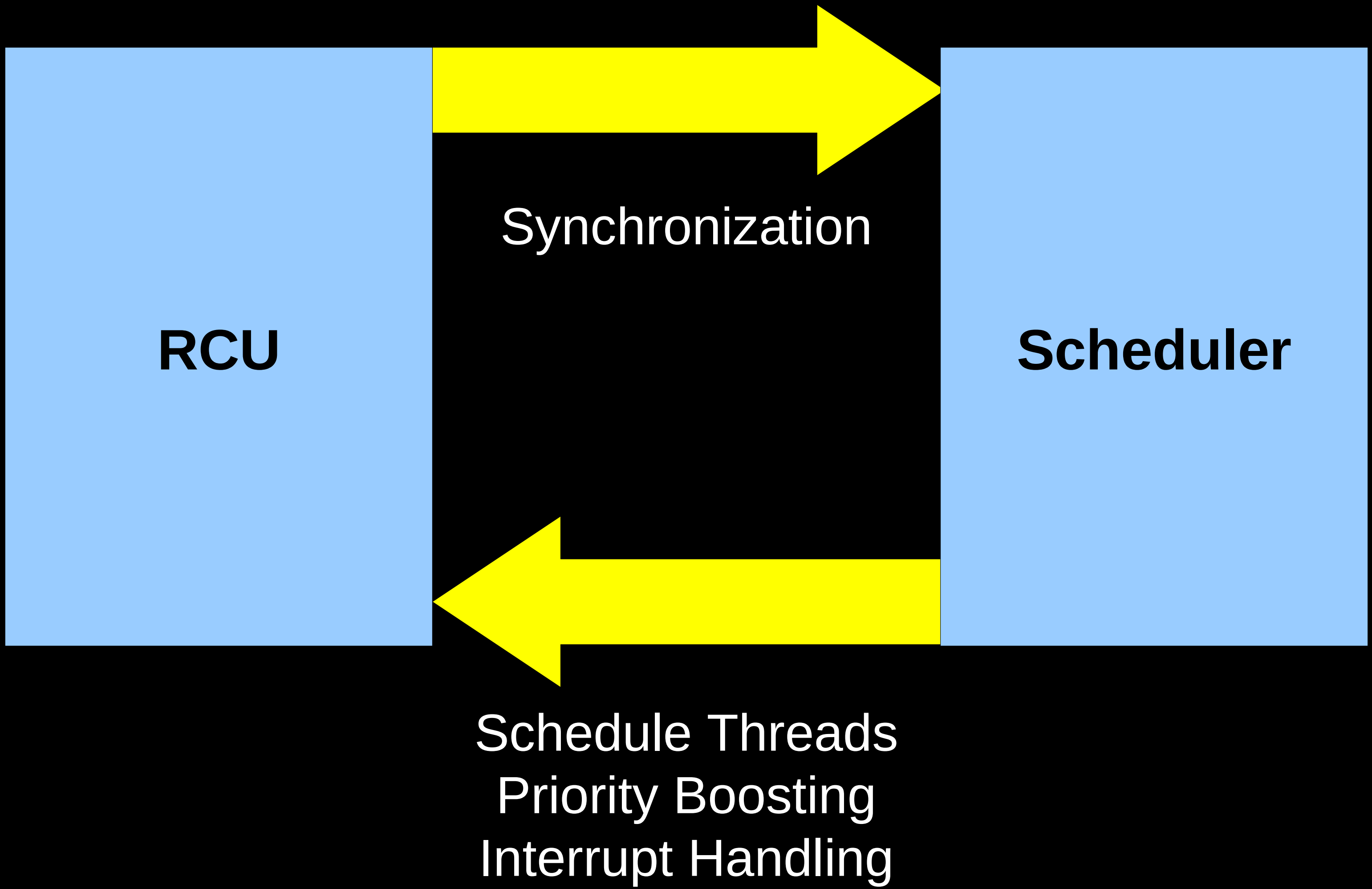
- Above is old technology – but not entirely ineffective
  - 2010: wait for -rc3 or -rc4. 2013: No problems with -rc1
- Formal verification in design, but not in regression testing
  - http://lwn.net/Articles/243851/, https://lwn.net/Articles/470681/, https://lwn.net/Articles/608550/

# 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 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!**

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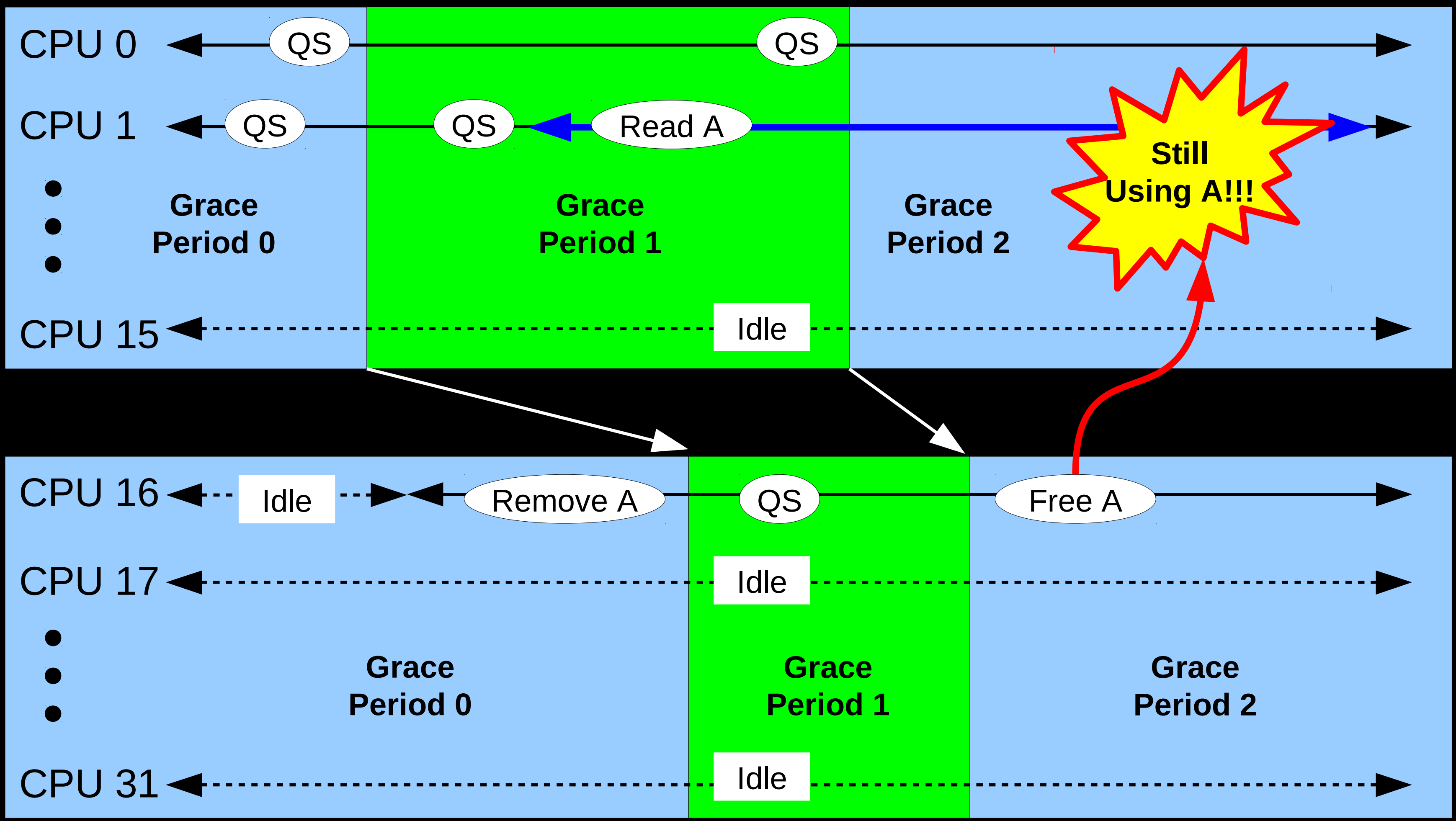


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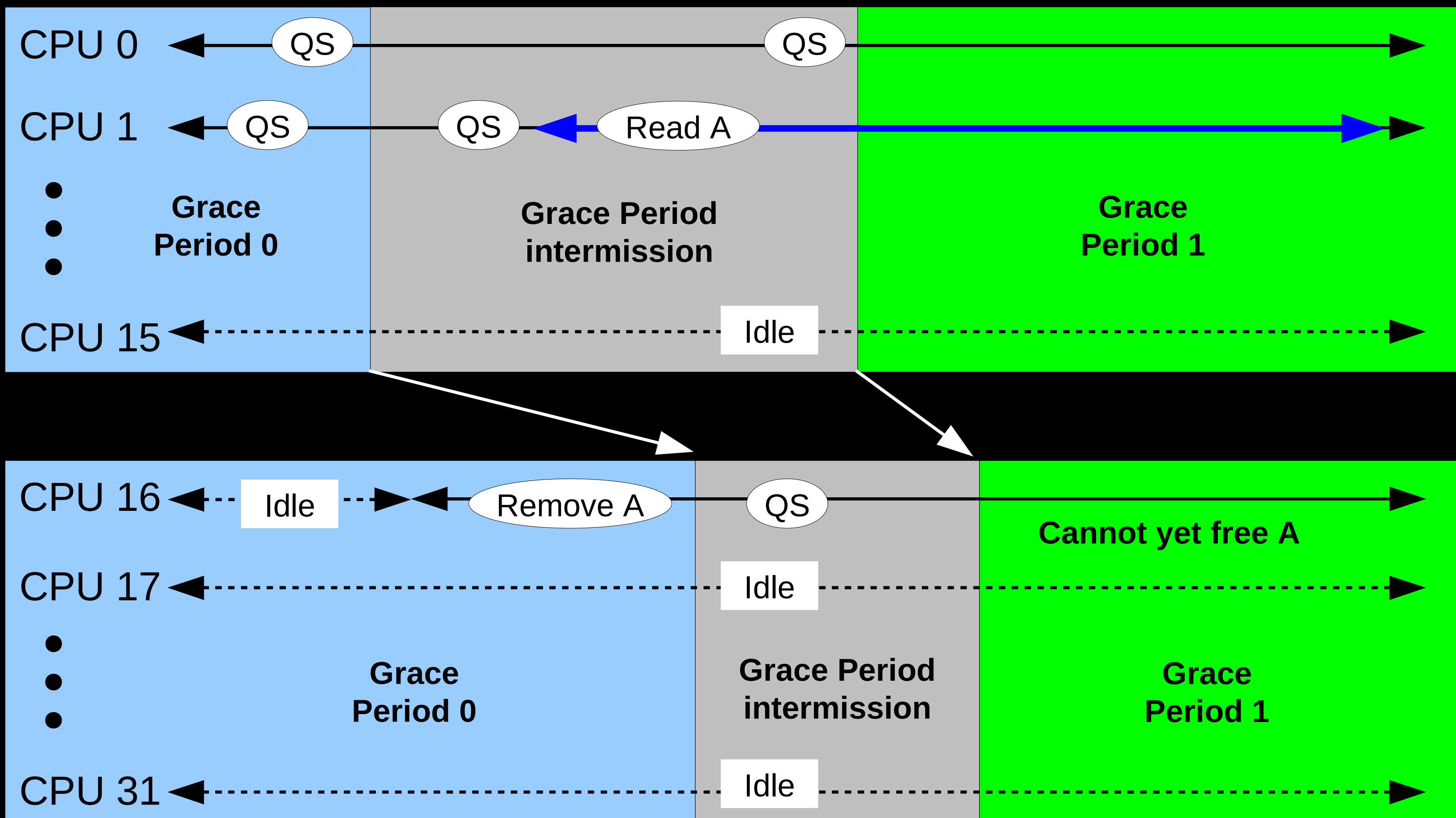


**Not found via Linux-kernel validation: In production for 5 years!**
**On systems with up to 4096 CPUs...**

# Why Formal Verification?

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  - 10,000 device-years of RCU per year: p(RCU) = $10^{-5}$
- 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?

- So why can so many people use Linux-kernel RCU?
  - 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 embedded systems have very 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
  - Formal verification ***is*** used for some aspects of RCU design
    - Dyntick idle, sysidle, NMI interactions

# Formal Verification and Regression Testing: Requirements

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(1) Either automatic translation or no translation required
- Manual translation provides opportunity for human error

(2) Automatic discarding of irrelevant portions of the code
- Manual discarding provides opportunity for human error

(3) Reasonable memory and CPU overhead
- Bugs must be located in practice as well as in theory
- Linux kernel is 20 million lines of code and life is short

(4) Map to source code line(s) containing the bug
- “Something is wrong somewhere” is not a helpful diagnostic

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

# 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
  - 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 (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

(2) Automatic discarding of irrelevant portions of the code
- Seems to do this quite well (sometimes too well)

(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

(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

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
- Tautschnig and Kroening: Experiments verifying RCU and uses of RCU using CBMC

# 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
- As far as I know, no independently developed formal-verification model has yet found a bug in Linux-kernel RCU

# 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

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# Questions?