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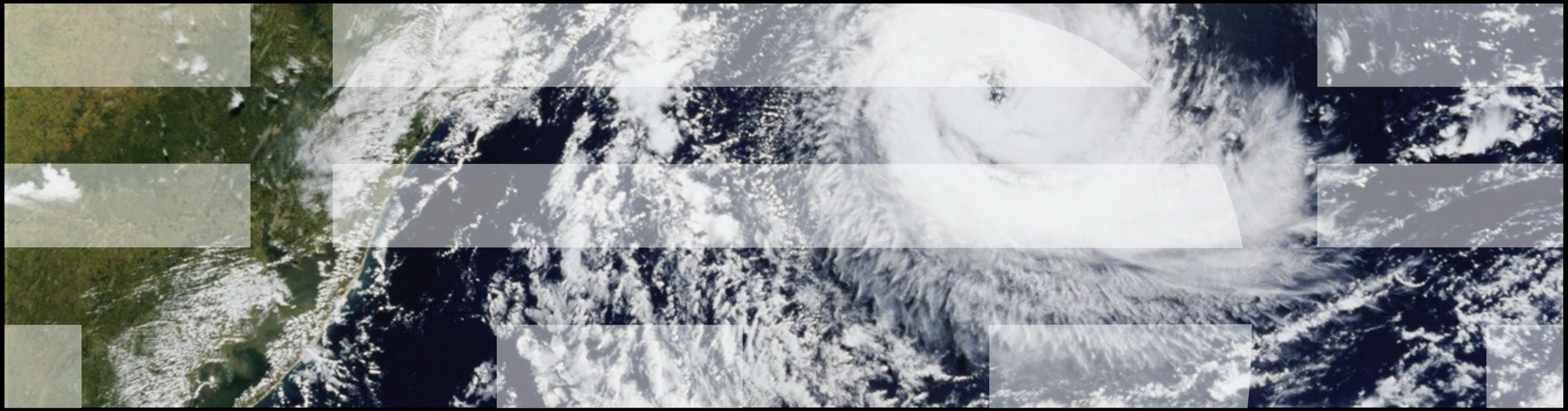
Tracing and Linux-Kernel RCU



Overview

- Two Definitions and a Consequence
- Avoiding Bugs
- Triggering Bugs Quickly
- Locating Bugs Once Triggered (Tracing Is Here)
- Recent Improvements In Use of Tracing
- Possible Future Improvements (Not Just Tracing)
- Summary

Two Definitions and a Consequence

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- A non-trivial software system contains at least one bug
- A reliable software system contains no known bugs

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- A non-trivial software system contains at least one bug
- A reliable software system contains no known bugs

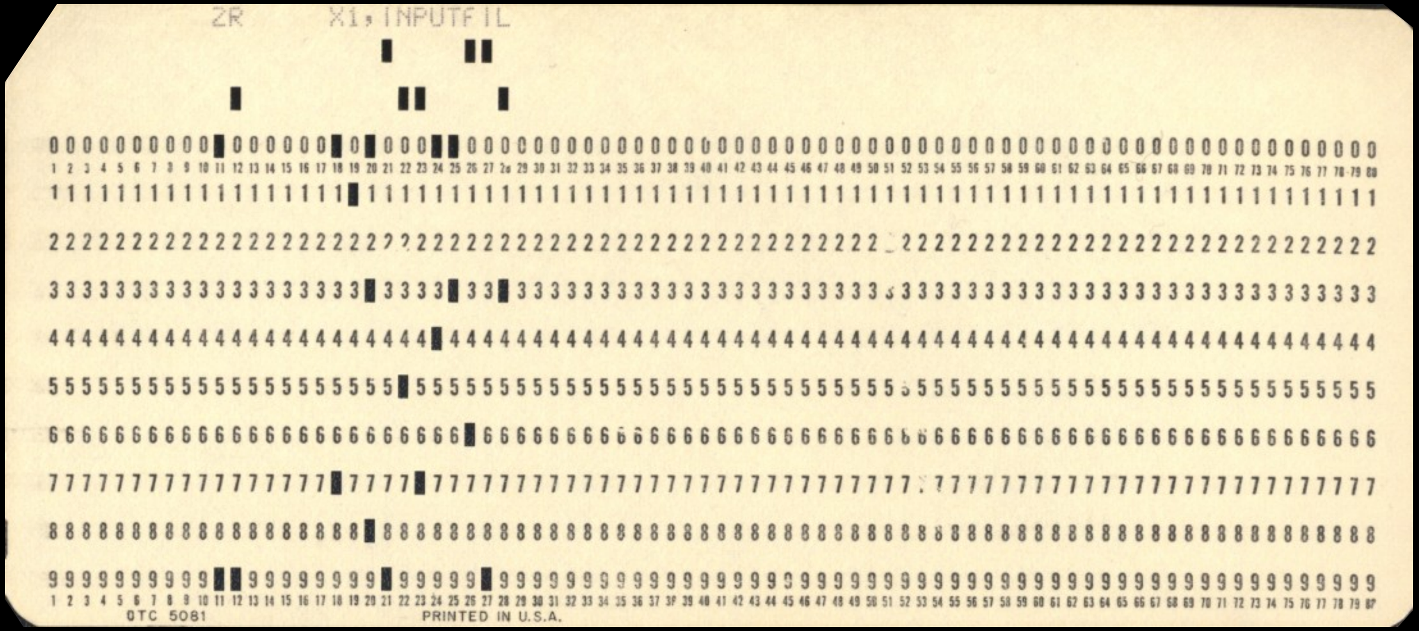
- Therefore, any non-trivial reliable software system contains at least one bug that you don't know about
- It is necessary to find that bug!

Avoiding Bugs

Avoiding Bugs: Design Time

- To the extent possible, establish requirements
  - Hint: It never is completely possible!
- Understand the hardware and underlying software
  - Shameless plug: “Is Parallel Programming Hard, And, If So, What Can You Do About It?”
    - https://www.kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html
- Set down design (text, figures, discussion, whatever)
- In some cases, formal verification in design, for example:
  - http://lwn.net/Articles/243851/, https://lwn.net/Articles/470681/, https://lwn.net/Articles/608550/
  - But need for formal verification often means too-complex design!

Avoiding Bugs: Coding Time



Avoiding Bugs: Coding Time

- Review your code carefully (can't always count on others!)
  - Write the code long hand in pen on paper
  - Correct bugs as you go
  - Copy onto a clean sheet of paper
  - Repeat until the last two versions are identical
- What constitutes "not complex"?
  - Sequential code, *and*
  - You can test it line-by-line, as in a scripting language or via gdb

Avoiding Coding Bugs: Case Study

static void rcu_preempt_offline_tasks(struct rcu_state *rsp,
struct rcu_node *rnp)
{
struct rcu_node *rnp_root = rcu_get_root();
~~if (!list_empty~~
~~struct task_struct *tp;~~ stet
int i;
~~struct list_head *lp;~~ stet
if (rnp == rnp_root) return;
for (i = 0; i < 2; i++) { lp =
while
~~if~~ (!list_empty(&rnp->blocked_tasks[i])) {
~~continue;~~
safe
~~list_for_each_entry(tp, &rnp->~~
tp = list_entry(

```
static void rcu_preempt_offline_tasks(struct rcu_state *rsp,
                                      struct rcu_node *rnp)
{
    int i;
    struct list_head *lp;
    struct list_head *lp_root;
    struct rcu_node *rnp_root = rcu_get_root(rsp);
    struct task_struct *tp;

    if (rnp == rnp_root)
        return;

    for (i = 0; i < 2; i++) {
        lp = &rnp->blocked_tasks[i];
        lp_root = &rnp_root->blocked_tasks[i];
        while (!list_empty(lp)) {
            tp = list_entry(lp->next, typeof(*tp),
                            rcu_node_entry);
            spin_lock(&rnp_root->lock); /* irqs disabled */
            list_del(&tp->rcu_node_entry);
            list_add(&tp->rcu_node_entry, lp_root);
            tp->rcu_blocked_node = rnp_root;
            spin_unlock(&rnp_root->lock); /* irqs disabled */
        }
    }
}
```

```
static void rcu_preempt_offline_tasks(struct rcu_state *rsp,
                                      struct rcu_node *rnp)
{
        int i;
        struct list_head *lp;
        struct list_head *lp_root;
        struct rcu_node *rnp_root = rcu_get_root(rsp);
        struct task_struct *tp;

        if (rnp == rnp_root)
                return;
        for (i=0; i<2; i++) {
                lp = &rnp->blocked_tasks[i];
                lp_root = &rnp_root->blocked_tasks[i];
                while (!list_empty(lp)) {
                        tp = list_entry(lp->next, typeof(*tp), rcu_node_entry);
                        spin_lock(&rnp_root->lock); /* irqs disabled */
                        list_del(&tp->rcu_node_entry);
                        list_add(&tp->rcu_node_entry, lp_root);
                        tp->rcu_blocked_node = rnp_root;
                        spin_unlock(&rnp_root->lock); /* irqs disabled */
                }
        }
}
```

So, How Well Did I Do?

```
static void rcu_preempt_offline_tasks(struct rcu_state *rsp,
              struct rcu_node *rnp,
              struct rcu_data *rdp)
{
  int i;
  struct list_head *lp;
  struct list_head *lp_root;
  struct rcu_node *rnp_root = rcu_get_root(rsp);
  struct task_struct *tp;

  if (rnp == rnp_root) {
    WARN_ONCE(1, "Last CPU thought to be offlined?");
    return;
  }
  WARN_ON_ONCE(rnp != rdp->mynode &&
         (!list_empty(&rnp->blocked_tasks[0]) ||
          !list_empty(&rnp->blocked_tasks[1])));
  for (i = 0; i < 2; i++) {
    lp = &rnp->blocked_tasks[i];
    lp_root = &rnp_root->blocked_tasks[i];
    while (!list_empty(lp)) {
      tp = list_entry(lp->next, typeof(*tp), rcu_node_entry);
      spin_lock(&rnp_root->lock); /* irqs already disabled */
      list_del(&tp->rcu_node_entry);
      tp->rcu_blocked_node = rnp_root;
      list_add(&tp->rcu_node_entry, lp_root);
      spin_unlock(&rnp_root->lock); /* irqs remain disabled */
    }
  }
}
```

```
static int rcu_preempt_offline_tasks(struct rcu_state *rsp,
                                     struct rcu_node *rnp,
                                     struct rcu_data *rdp)
{
  int i;
  struct list_head *lp;
  struct list_head *lp_root;
  int retval;
  struct rcu_node *rnp_root = rcu_get_root(rsp);
  struct task_struct *tp;

  if (rnp == rnp_root) {
    WARN_ONCE(1, "Last CPU thought to be offlined?");
    return 0;  /* Shouldn't happen: at least one CPU online. */
  }
  WARN_ON_ONCE(rnp != rdp->mynode &&
         (!list_empty(&rnp->blocked_tasks[0]) ||
          !list_empty(&rnp->blocked_tasks[1])));
  retval = rcu_preempted_readers(rnp);
  for (i = 0; i < 2; i++) {
    lp = &rnp->blocked_tasks[i];
    lp_root = &rnp_root->blocked_tasks[i];
    while (!list_empty(lp)) {
      tp = list_entry(lp->next, typeof(*tp), rcu_node_entry);
      spin_lock(&rnp_root->lock); /* irqs already disabled */
      list_del(&tp->rcu_node_entry);
      tp->rcu_blocked_node = rnp_root;
      list_add(&tp->rcu_node_entry, lp_root);
      spin_unlock(&rnp_root->lock); /* irqs remain disabled */
    }
  }
  return retval;
}
```

```
static int rcu_preempt_offline_tasks(struct rcu_state *rsp,
                                     struct rcu_node *rnp,
                                     struct rcu_data *rdp)
{
  int i;
  struct lis
  struct l         _root;
  int r
  str          *rnp_root = rcu_get_root(rsp
  s            *tp;

         == rn
         _ONCE(1,          hought to be offlined?");
        rn 0;  /* Sh         ppen: at least one CPU o         */

        ON_ONCE(rnp != rd           &&
          (!list_empty(&rnp-          sks[0]) ||
           !list_empty(&rnp->b          s[1])));
          = rcu_preempted_readers
          = 0; i < 2; i++) {
          rnp->blocked_tasks[i];
            = &rnp_root->blocked_tasks[
             ist_empty(lp)) {
               entry(lp->next, typeof(*tp),          ry);
      s           p_root->lock); /* irqs al          led */
      lis           node entry);
      tp->rc
      list_add(&
      spin_unlock(&rnp_          irqs remain disabled */
    }
  }
  return retval;
}
```

Avoiding Coding Bugs: Case Study Evaluation

- The approach worked just fine for the actual coding
- However, I should have put more effort into arriving at a simpler design
- Of course, at some point you do have to start coding
- And there is a cost to refusing to move these lists: The grace-period detection code must look at rcu_node structures whose CPUs are all offline
  - This is the right tradeoff now, but might not have been back in 2009

Avoiding Coding Bugs When Under Pressure

When you are fixing a critical bug, speed counts

The difference is level of risk

- The code is *already* broken, so less benefit to using extremely dainty process steps
- But *only* if you follow up with careful process
- Which I repeatedly learn the hard way: http://paulmck.livejournal.com/14639.html
- Failure to invest a few days in early 2009 cost me more than a month in late 2009!!!

Long-term perspective required

- And that means *you* – leave the “blame it on management” game to Dilbert cartoons
- Align with whatever management initiatives present themselves

But I Did All This And There Are Still Bugs!!!

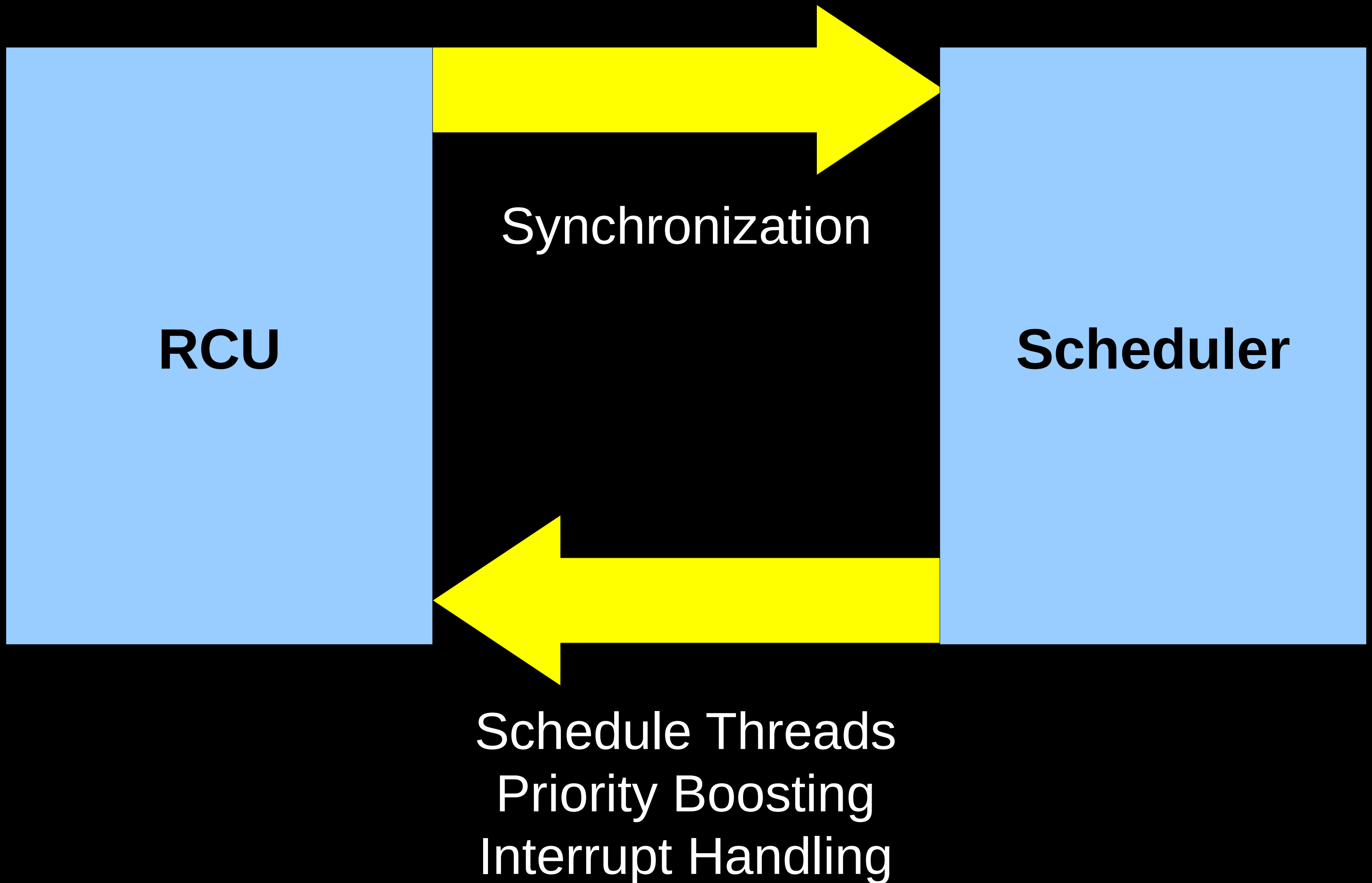
- “Be Careful!!! It Is A Real World Out There!!!”
- The purpose of careful software-development practices is to reduce risk
- And another part of risk reduction is testing!

Triggering Bugs Quickly

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”
  - https://lwn.net/Articles/514278/
- Integration testing: “linux-next tree”
  - https://lwn.net/Articles/571980/
- Test the test: Mutation testing
  - https://www.cs.cmu.edu/~agroce/ase15.pdf
- Some reports of automated formal verification of RCU
  - For but one example, https://arxiv.org/abs/1610.03052
- But let's look at some example bugs...

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

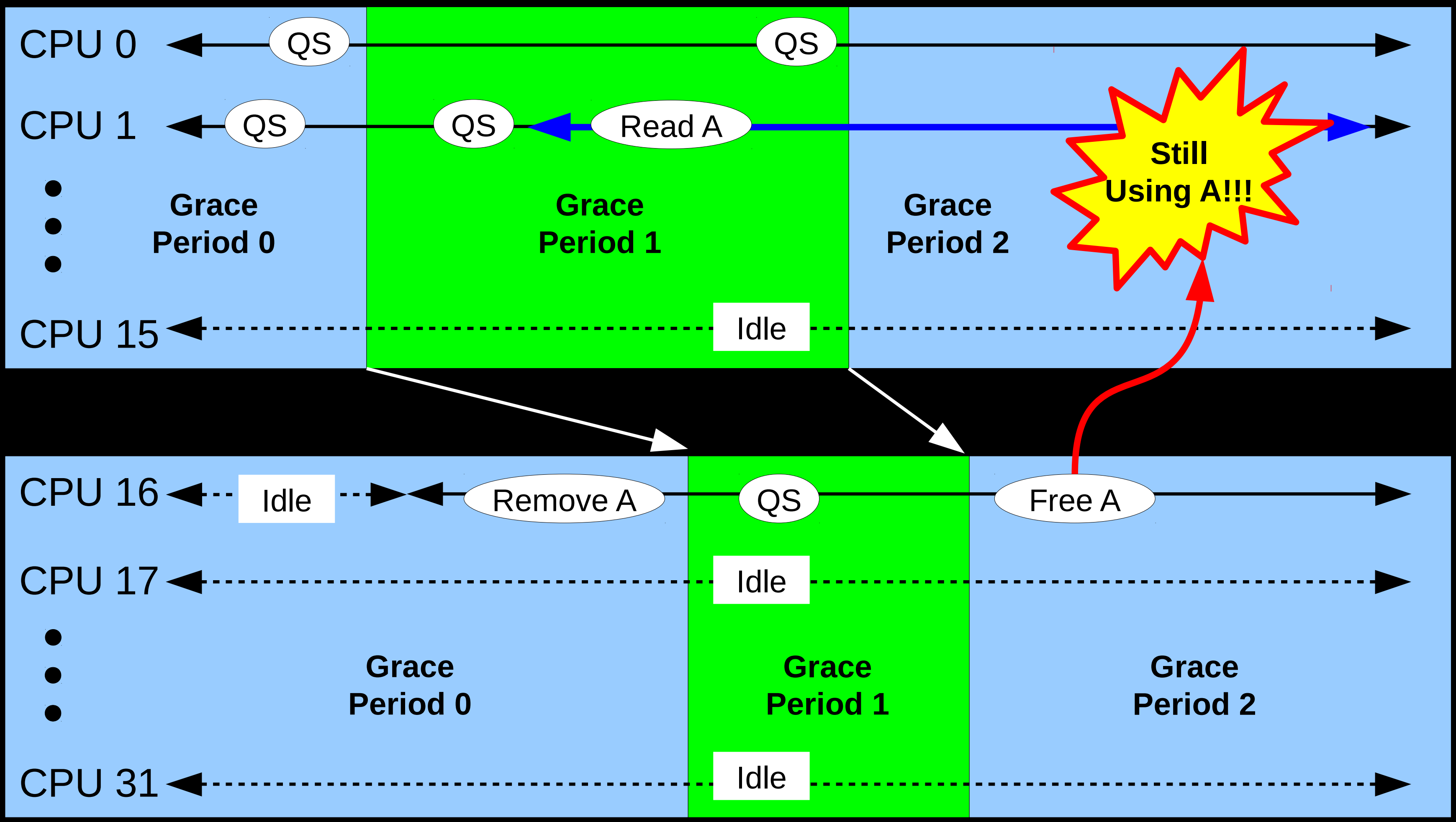
Example 1: Bug Was Located By Normal Testing

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***)

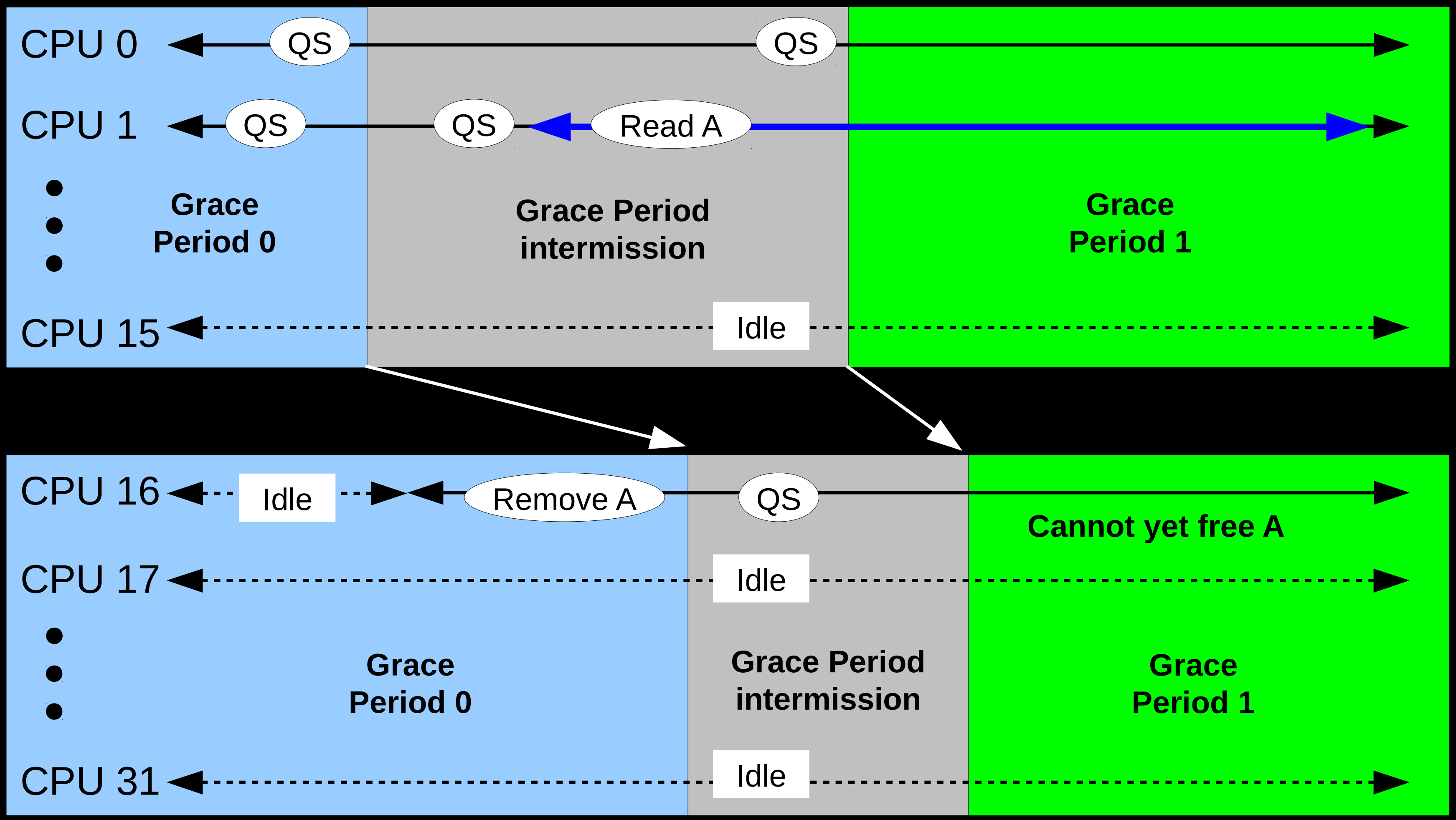
Not found via Linux-kernel validation: In production for 5 years!

Example 2: Grace Period Cleanup/Initialization Bug



Note: Remains a bug even under SC

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...
  - But as far as we know, this bug never did trigger in the field
- Both are bugs even under sequential consistency
  - Continued improvement in RCU's regression testing is clearly needed

Why Is Improvement Needed?

- A billion+ embedded Linux devices (1.4B smartphones)
  - 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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  - 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}
- At ***least*** 80 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
  - 40,000 system-years of RCU per year: p(RCU) = $5(10^{-4})$

https://www.quora.com/How-many-servers-exist-in-the-world

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  - 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
  - 40,000 system-years of RCU per year: $p(RCU) = 5(10^{-4})$
- Races between RCU event pairs, $p(bug)=p(RCU)^2$:
  - N-CPU probability of race: $1-(1-p(bug))^N-Np(1-p(bug))^{(N-1)}$
  - Assume rcutorture p(RCU)=1, compute rcutorture speedup:
    - Embedded: 10^{12}: 7.9 days of rcutorture testing covers one year
    - Server: $4(10^6)$: 21.9 *years* of rcutorture testing covers one year
    - Linux kernel releases are only about 60 days apart: RCU is moving target

https://www.quora.com/How-many-servers-exist-in-the-world

So Why Do RCU Failures Appear to be Rare?

- What is rcutorture's strategy for 80M server systems?
  - Other failures mask those of RCU, including hardware failures
    - I know of no human artifact with a million-year MTBF
    - But the Linux kernel is being used in applications that put the public at risk
  - Increasing CPUs on test system increases race probability
    - And many systems have relatively few CPUs
  - Rare but critical operations are forced to happen more frequently
    - Long-running RCU readers, CPU hotplug, expedited grace periods, RCU barrier operations, mass registration of RCU callbacks, irqs, mass return from idle, concurrent grace-period start, preemption, RCU priority boosting, quiescent-state forcing, conditional grace periods, sysidle, Tasks RCU, …
    - 16 test scenarios emphasizing different aspects of RCU
  - 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

Locating Bugs Once Triggered (Tracing Is Here)

Locating Bugs Once Triggered (Tracing Is Here)

- "What did I just change?" and review that code
- Break large commits into smaller commits
  - Difficulty of analyzing code grows exponentially (or worse) with size
- Look at conditions in which failure occurs, rule out bystanders
- Debug printk()s and WARN_ON()s
  - Especially if only executed after error is detected
- Pull code into userspace and use nicer debug tools
- Tracing
- Formal verification (more on this later if we have time)

The Common-Case RCU Bug is a Heisenbug!

The Common-Case RCU Bug is a Heisenbug! But Tracing Still Sometimes Useful

- Performance analysis of grace-period latencies
  - Automatic grace-period-duration analysis of rcuperf runs:
    - tools/testing/selftests/rcutorture/bin/kvm-recheck-rcuperf.sh
    - tools/testing/selftests/rcutorture/bin/kvm-recheck-rcuperf-ftrace.sh
- Non-heisenbugs in grace-period computation
  - There are scripts, but they will not be permitted to see the light of day
- Situations where something *doesn't* happen
  - Hard to place the printk()/WARN_ON() in such situations
  - Because rcutorture failed to detect an injected bug on TREE01!!!
    - But it did detect it on TREE02 through TREE08
- Learning what RCU actually does
  - Finding redundant execution (Frederic Weisbecker)

Tracing to Analyze Failure to Detect Injected Bug

- Injected bug: Each CPU seeing a new grace period clears other CPUs' bits, thus asserting that their quiescent states have already passed
  - Can result in too-short grace periods when other CPUs have not yet passed through a quiescent state
  - Can result in grace-period hangs by preventing up-tree propagation
    - But TREE01 has only one rcu_node structure, so no up-tree to prevent
- Note that TREE01 enables preemption, but tests RCU-bh
  - Readers need 50-ms delay to see bug, which are rare
  - Add tracing to determine when these delays are occurring
- Current result: Many ways for RCU to evade this bug!
  - Still looking for possible rcutorture improvements...

Recent Improvements In Use of Tracing

Recent Improvements In Use of Tracing

- Automatically dump ftrace buffer:
  - When rcuperf completes: Gather grace-period performance data
  - After rcutorture failures: Gather data on events leading to failure
  - When rcu_dynticks detects idle entry/exit misnesting
  - At RCU CPU stall warning time
- However, you still need to:
  - Build with CONFIG_RCU_TRACE=y
  - Enable relevant RCU trace events, preferably ***before*** the failure

Possible Future Improvements (Not Just Tracing)

Possible Future Improvements (Not Just Tracing)

- Run rcutorture in userspace (faster “hotplug” operations)
- Arrange to run rcutorture more often on a variety of arches
- Add more TBD nastiness to rcutorture
- More TBD self-defense checks in RCU
- Linux-kernel memory model
  - http://www.rdrop.com/users/paulmck/scalability/paper/LinuxMM.2016.10.04c.LCE.pdf
- Possibly formal verification in RCU regression testing...

Formal Verification and Regression Testing: Requirements

(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 **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!)
- Specifications are software and can have their own bugs

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

Promela/spin: Design-Time Verification

- 1993: Shared-disk/network election algorithm (pre-Linux)
  - Hadn't figured out bug injection: Way too trusting!!!
  - Single-point-of failure bug in specification: Fixed during coding
    - But fix had bug that propagated to field: Cluster partition
  - **Conclusion**: Formal verification is trickier than expected!!!
- 2007: RCU idle-detection energy-efficiency logic
  - (http://lwn.net/Articles/243851/)
  - Verified, but much simpler approach found two years later
  - **Conclusion**: The need for formal verification is a symptom of a too-complex design
- 2012: Verify userspace RCU, emulating weak memory
  - Two independent models (Desnoyers and myself), **bug injection**
- 2014: NMIs can nest!!! Affects energy-efficiency logic
  - Verified Andy's code, and no simpler approach apparent thus far!!!
  - Note: Excellent example of **empirical specification**

PPCMEM and Herd

- Verified suspected bug in Power Linux atomic primitives
- Found bug in Power Linus spin_unlock_wait()
- Verified ordering properties of locking primitives
- Excellent memory-ordering teaching tools
  - Starting to be used more widely within IBM as a design-time tool
- PPCMEM: (http://lwn.net/Articles/470681/)
  - Accurate but slow
- Herd: (http://lwn.net/Articles/608550/)
  - Faster, but some correctness issues with RMW atomics and lwsync
  - Work in progress: Formalize Linux-kernel memory model
    - With Alglave, Maranget, Parri, and Stern, plus lots of architects
    - Hopefully will feed into improved tooling

Alglave, Maranget, Pawan, Sarkar, Sewell, Williams, Nardelli:
"PPCMEM/ARMMEM: A Tool for Exploring the POWER and ARM Memory Models"
Alglave, Maranget, and Tautschnig: "Herding Cats: Modelling, Simulation, Testing, and Data-mining for Weak Memory"

C Bounded Model Checker (CBMC)

- Nascent concurrency and weak-memory functionality
- Valuable property: “Just enough specification”
  - Assertions in code act as specifications!
  - Can provide additional specifications in “verification driver” code
- Verified very small portions of RCU
  - Daniel Kroening, Oxford (publish/subscribe), myself (Tiny RCU)
- Has been used to verify substantial portion of Tree RCU
  - Lihao Liang, University of Oxford
- And of SRCU's core algorithm (plus an improved version)
  - Lance Roy, unaffiliated (improvements from Mathieu Desnoyers)
- Conclusion: Promising, especially if SAT progress continues

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.

Nidhugg (Preview, Still Learning)

- Not a full state-space exploration
  - Must be paired with testing?
- Finds situations where scheduling decisions and memory-order changes could produce a significantly different result
- More scalable than full state-space tools
- Probably vulnerable to incomplete test suites

Scorecard For Linux-Kernel C Code (Incomplete)

	Promela	PPCMEM	Herd	CBMC
(1) Automated				
(2) Handle environment	(MM)		(MM)	(MM)
(3) Low overhead				SAT?
(4) Map to source code				
(5) Modest input				
(6) Relevant bugs	???	???	???	???
Paul McKenney's first use	1993	2011	2014	2015

Promela MM: Only SC: Weak memory must be implemented in model
Herd MM: Some PowerPC and ARM corner-case issues
CBMC MM: Only SC and TSO
Note: All four handle concurrency! (Promela has done so for 25 years!!!)

Scorecard For Linux-Kernel C Code

	Promela	PPCMEM	Herd	CBMC	Test
(1) Automated					
(2) Handle environment	(MM)		(MM)	(MM)	
(3) Low overhead				SAT?	
(4) Map to source code					
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(6) Relevant bugs	???	???	???	???	
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So why do anything other than testing?

Scorecard For Linux-Kernel C Code

	Promela	PPCMEM	Herd	CBMC	Test
(1) Automated					
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So why do anything other than testing?

- Low-probability bugs can require expensive infinite testing regimen
- Large installed base will encounter low-probability bugs
- Safety-criitcal applications are sensitive to low-probability bugs

Scorecard For Linux-Kernel C Code (Nidhugg TBD)

	Promela	PPCMEM	Herd	CBMC	Test
(1) Automated					
(2) Handle environment	(MM)		(MM)	(MM)	
(3) Low overhead				SAT?	
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- Safety-criitcal applications are sensitive to low-probability bugs

Summary

Summary

- Tracing is a small but critically important part of RCU development tooling
- RCU is becoming more tracing-friendly over time
- Other tools making progress as well, even formal verification

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"
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- 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
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  - 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/
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- 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)
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To Probe Deeper (1/5)

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  – http://events.linuxfoundation.org/sites/events/files/slides/BareMetal.2014.03.09a.pdf
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  – 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
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    - http://lca2013.linux.org.au/schedule/30168/view_talk
  - Thompson: “Mechanical Sympathy”
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  - 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”
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