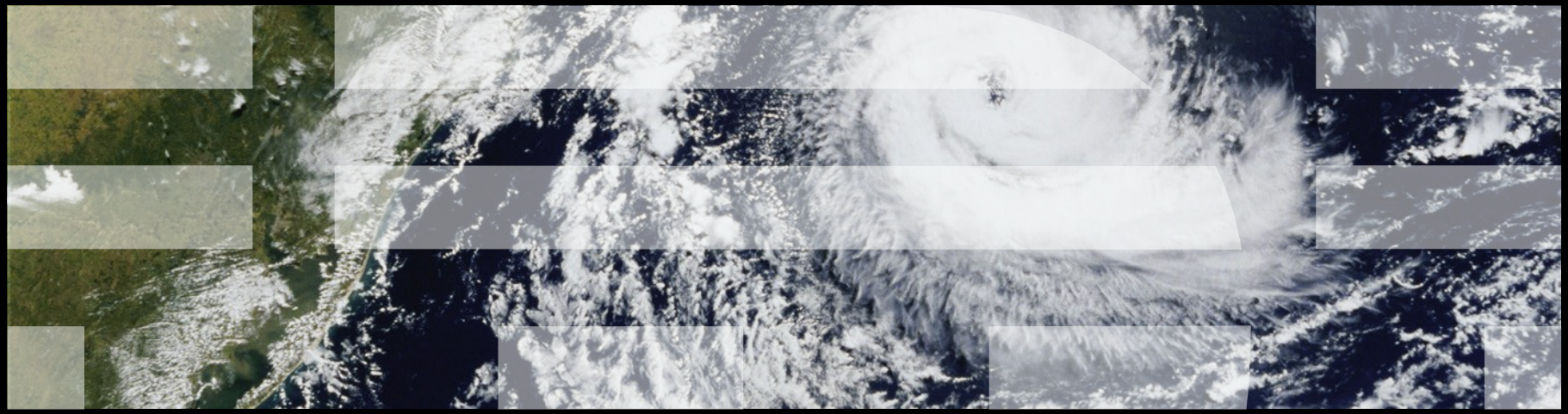
Paul E. McKenney, IBM Distinguished Engineer, Linux Technology Center
Member, IBM Academy of Technology
Facebook Concurrency Reasoning Workshop, January 18, 2018

Towards Synchronization-Primitive Regression Testing via Hard-Core Formal Verification

The Linux-Kernel RCU Experience



Reporting on Joint Work: Many Collaborators

- Alan Stern
- Alex Groce
- Andrea Parri
- Andy Lutomirski
- Bob Glossman
- Boqun Feng
- Carlos Jensen
- Daniel Kroening
- David Howells
- Dmitry Vyukov
- Iftekhar Ahmed
- Jade Alglave
- Konstantinos Sagonas
- Lance Roy
- Lihao Liang
- Luc Maranget
- Mathieu Desnoyers
- Michael Tautschnig
- Michalis Kokologiannakis
- Nick Piggin
- Peter Sewell
- Peter Zijlstra
- Steven Rostedt
- Susmit Sarkar
- Tom Melham
- Will Deacon

(Partial list over 25 years)

Why Bother With Formal Verification?

- It is said that 20 billion instances of the Linux kernel exist
- A bug with a million-year MTBF: >50 failures per *day*
- Kernel version every 2-3 months, each with RCU changes
- Testing really is feasible for low-duty-cycle devices
  - Especially for those with small numbers of CPUs
  - Household appliances, smartphones used as phones
    - But “as phone” use case is being overwhelmed by social-media use cases
- But not for the ~80 million servers!!!
  - Duty cycle is high, large numbers of CPUs
- Plus Linux kernels used in some safety-critical applications!!!

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- Plus Linux kernels used in some safety-critical applications!!!
- Why not apply formal verification to RCU regression testing?

Formal Verification & Regression Tests: 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 (plus 5KLoC tests) and release cycles are short

(4) Map to source code line(s) containing the bug
- "Something is wrong somewhere" is not helpful: I already **know** bugs exist
- Two bugs reported thus far this week!!!

(5) Modest input outside of source code under test
- Preferably glean much of the specification from the source code itself (empirical spec!)
- Specifications are large bodies of software and can therefore have their own bugs

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

How Do Formal Verification Tools Stack Up?

How Do Current Formal Verification Tools Stack Up?

- Promela/spin
- PPCMEM
- Herd
- CBMC
- Nidhugg

Promela/spin: Design-Time Verification

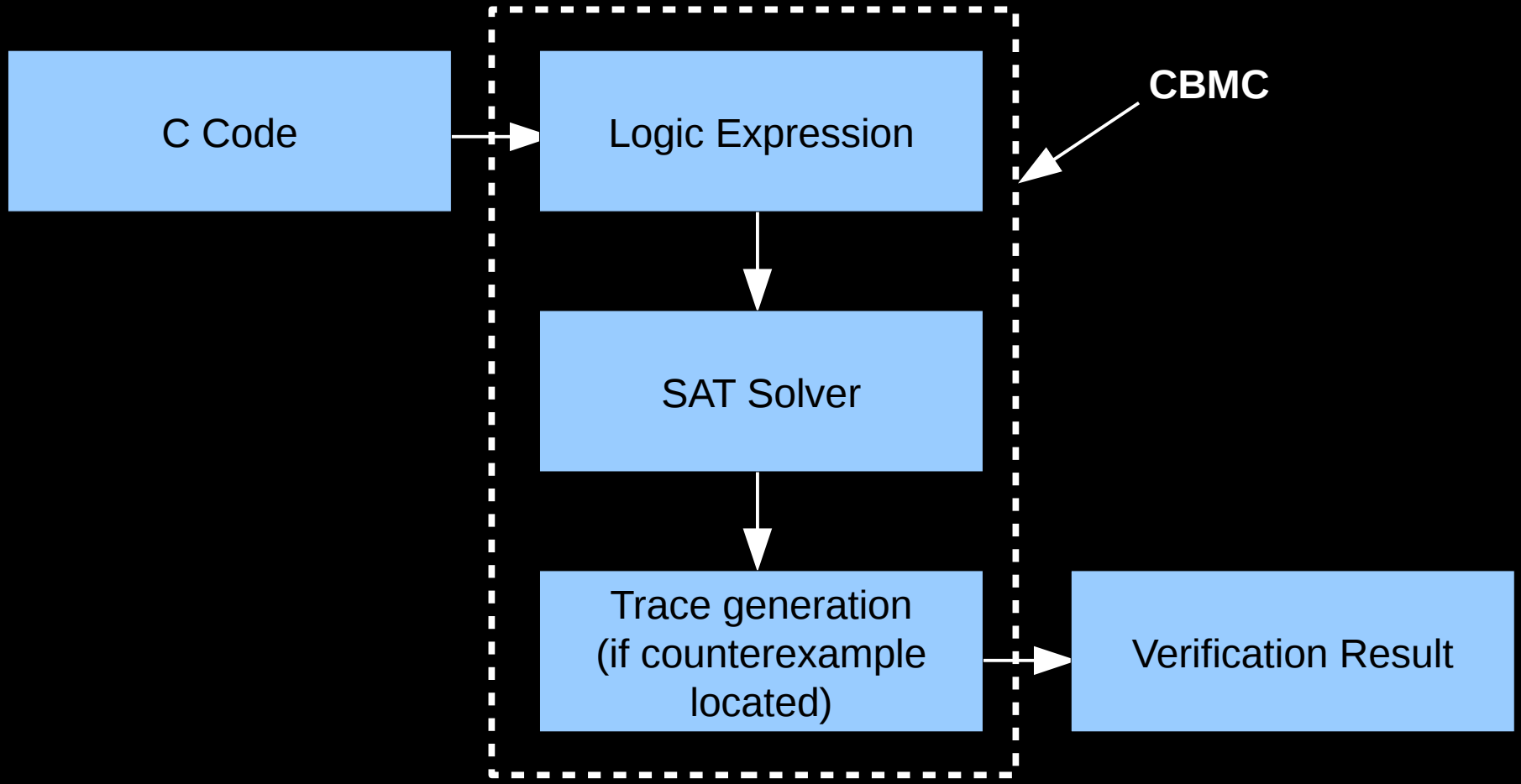
- 1993: Shared-disk/network election algorithm (pre-Linux)
  - Hadn't figured out bug injection: Way too trusting!!!
  - Single-point-of failure bug in specification: Fixed during coding
    - But fix had bug that propagated to field: Cluster partition
  - **Conclusion**: Formal verification is trickier than expected!!!
- 2007: "Quick" RCU (QRCU) – fast updaters
  - http://lwn.net/Articles/243851/, but never accepted into Linux kernel
- 2008: RCU idle-detection energy-efficiency logic
  - http://lwn.net/Articles/279077/
  - Verified, but much simpler approach found two years later
  - **Hypothesis**: Need for formal verification: Symptom of 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, 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 still not able to handle 10,000-line programs
  - 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"

CBMC (Very) Rough Schematic

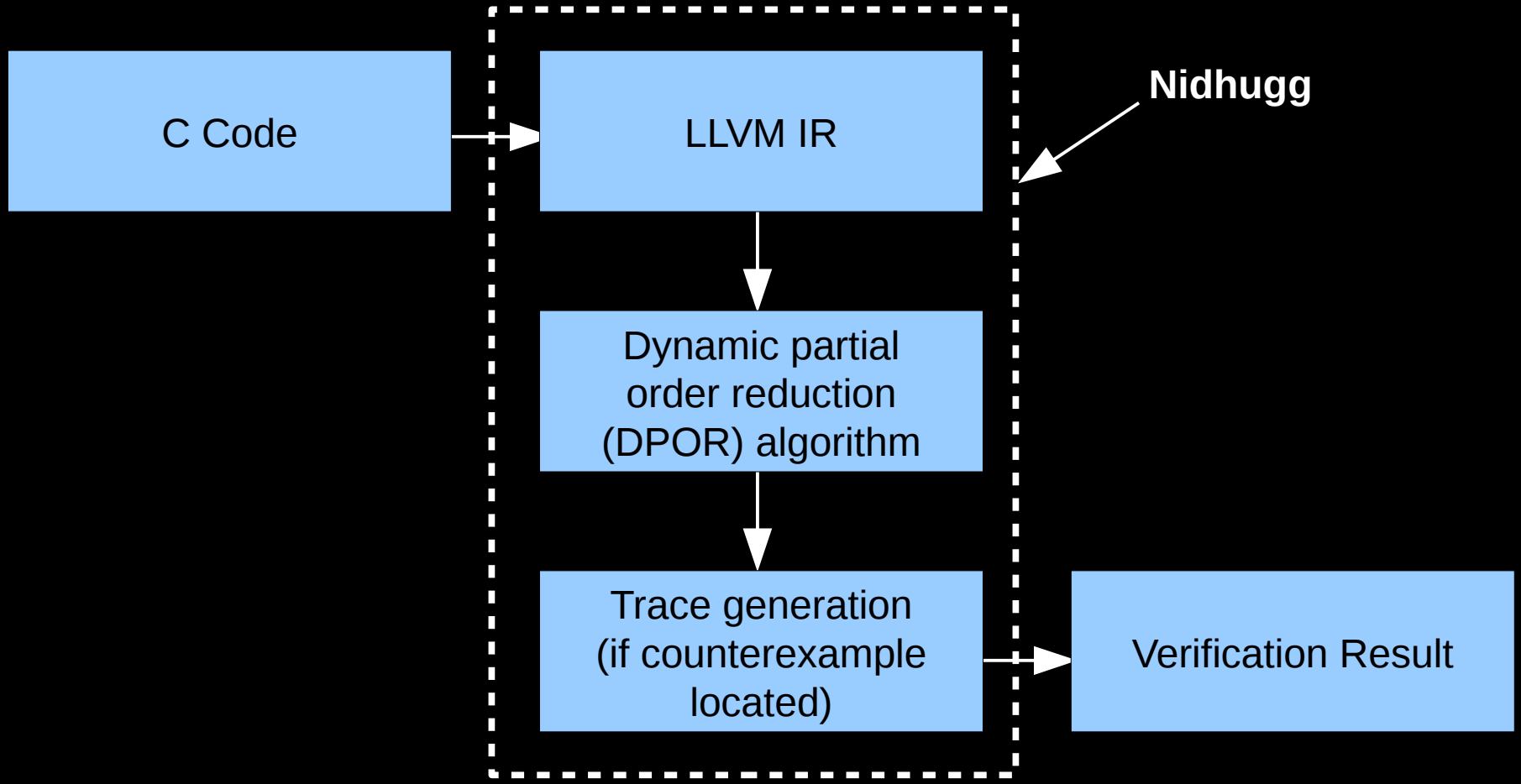


Kroening, Clarke, and Lerda, “A tool for checking ANSI-C programs”, *Tools and Algorithms for the Construction and Analysis of Systems, 2004,* pp. 168-176.
https://github.com/diffblue/cbmc

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 rcu_dereference() and rcu_assign_pointer()
  - Alglave et al.: https://dl.acm.org/citation.cfm?id=2526873
- I used CBMC to verify Tiny RCU
  - But when I say “Tiny”, I really do mean ***tiny!!!***
- Substantial portion of Tree RCU verified as tour de force
  - Lihao Liang, Oxford, et al.: https://arxiv.org/abs/1610.03052
- Linux-kernel SRCU verified on more routine basis
  - Lance Roy: https://www.spinics.net/lists/kernel/msg2421833.html
- Conclusion: Promising, especially if SAT progress continues

Nidhugg (Very) Rough Schematic



https://link.springer.com/chapter/10.1007/978-3-662-46681-0_28
https://github.com/nidhugg/nidhugg

Nidhugg: Stateless Model Checker

- Good concurrency, nascent weak-memory functionality
  - Uses Clang/LLVM, emits LLVM-IR, then analyzes it
- Like CBMC, “Just enough specification”
  - Assertions in code act as specifications!
  - Can provide additional specifications in “verification driver” code
- And also substantial portion of Tree RCU verified
  - Kokologiannakis et al., NTUA: https://doi.org/10.1145/3092282.3092287
- Tentative conclusions comparing to CBMC:
  - Less capable than CBMC (CBMC handles data non-determinism)
  - More scalable than CBMC (Nidhugg analyzes more code faster)
  - But neither found a Linux-kernel bug I didn't already know about
  - Future work includes more detailed comparison
    - And hopefully finding bugs that I don't already know about!

https://github.com/nidhugg/nidhugg

Scorecard For Linux-Kernel C Code (Incomplete)

	Promela	PPCMEM	Herd	CBMC	Nidhugg
(1) Automated					
(2) Handle environment	(MM)		(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	2017

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

Scorecard For Linux-Kernel C Code

	Promela	PPCMEM	Herd	CBMC	Nidhugg	Test
(1) Automated						
(2) Handle environment	(MM)		(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	2017	1973

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So why do anything other than testing?

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So why do anything other than testing?

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

Other Possible Approaches

- By-hand formalizations and proofs
  - Stern: Semi-formal proof of URCU (2012 IEEE TPDS)
  - Gotsman: Separation-logic RCU semantics (2013 ESOP)
  - Tasserotti et al.: Formal proof of URCU linked list: (2015 PLDI)
  - These all constitute excellent work, but are not useful for regression testing
- seL4 tooling: Lacks support for fine-grained concurrency and RCU idioms
  - Might be applicable to small pieces of Linux-kernel RCU
  - Impressive work nevertheless!!!
- Apply Peter O'Hearn's Infer to the Linux kernel
- Dmitry Vyukov's kernel thread sanitizer (KTSAN)
- Ahmed et al.: Mutations for RCU validation
  - http://dx.doi.org/10.1109/ASE.2015.40
  - Found numerous holes, one of which was hiding a real bug
  - Upcoming work: Apply mutation to other code bases as well
  - **Conclusion**: Investments in testing still pay off

Challenges

- Find bug in rcu_preempt_offline_tasks()
  - Note: No practical impact because this function has been removed
  - http://paulmck.livejournal.com/37782.html
- Find bug in RCU_NO_HZ_FULL_SYSIDLE
  - http://paulmck.livejournal.com/38016.html
- Find bug in RCU linked-list use cases
  - http://paulmck.livejournal.com/39793.html
- Find lost-timer bug in the Linux kernel
  - Heavy rcutorture testing with CPU hotplug on four-socket system
  - Run rcutorture on TREE01 scenario, roughly 3-hour MTBF
  - Can you find this before we do? (We have recently found several)
- Take on Verification Challenge 6:
  - https://paulmck.livejournal.com/46993.html
- Find any other bug in popular open-source software

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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
  - Kleen: “Scaling Existing Lock-based Applications with Lock Elision”
    - http://queue.acm.org/detail.cfm?id=2579227
- Hardware lock elision: Hardware description
  - POWER ISA Version 2.07
    - http://www.power.org/documentation/power-isa-version-2-07/
  - Intel® 64 and IA-32 Architectures Software Developer Manuals
    - http://www.intel.com/content/www/us/en/processors/architectures-software-developer-manuals.html
  - Jacobi et al: “Transactional Memory Architecture and Implementation for IBM System z”
    - http://www.microsymposia.org/micro45/talks-posters/3-jacobi-presentation.pdf
- Hardware lock elision: Evaluations
  - http://pcl.intel-research.net/publications/SC13-TSX.pdf
  - http://kernel.org/pub/linux/kernel/people/paulmck/perfbook/perfbook.html Section 16.3
- Hardware lock elision: Need for weak atomicity
  - Herlihy et al: “Software Transactional Memory for Dynamic-Sized Data Structures”
    - http://research.sun.com/scalable/pubs/PODC03.pdf
  - Shavit et al: “Data structures in the multicore age”
    - http://doi.acm.org/10.1145/1897852.1897873
  - Haas et al: “How FIFO is your FIFO queue?”
    - http://dl.acm.org/citation.cfm?id=2414731
  - Gramoli et al: “Democratizing transactional programming”
    - http://doi.acm.org/10.1145/2541883.2541900

To Probe Deeper (4/5)

- RCU
  - Desnoyers et al.: “User-Level Implementations of Read-Copy Update”
    - http://www.rdrop.com/users/paulmck/RCU/urcu-main-accepted.2011.08.30a.pdf
    - http://www.computer.org/cms/Computer.org/dl/trans/td/2012/02/extras/ttd2012020375s.pdf
  - McKenney et al.: “RCU Usage In the Linux Kernel: One Decade Later”
    - http://rdrop.com/users/paulmck/techreports/survey.2012.09.17a.pdf
    - http://rdrop.com/users/paulmck/techreports/RCUUsage.2013.02.24a.pdf
  - McKenney: “Structured deferral: synchronization via procrastination”
    - http://doi.acm.org/10.1145/2483852.2483867
  - McKenney et al.: “User-space RCU” https://lwn.net/Articles/573424/
- Possible future additions
  - Boyd-Wickizer: “Optimizing Communications Bottlenecks in Multiprocessor Operating Systems Kernels”
    - http://pdos.csail.mit.edu/papers/sbw-phd-thesis.pdf
  - Clements et al: “The Scalable Commutativity Rule: Designing Scalable Software for Multicore Processors”
    - http://www.read.seas.harvard.edu/~kohler/pubs/clements13scalable.pdf
  - McKenney: “N4037: Non-Transactional Implementation of Atomic Tree Move”
    - http://www.rdrop.com/users/paulmck/scalability/paper/AtomicTreeMove.2014.05.26a.pdf
  - McKenney: “C++ Memory Model Meets High-Update-Rate Data Structures”
    - http://www2.rdrop.com/users/paulmck/RCU/C++Updates.2014.09.11a.pdf

To Probe Deeper (5/5)

- RCU theory and semantics, academic contributions (partial list)
  - Gamsa et al., “Tornado: Maximizing Locality and Concurrency in a Shared Memory Multiprocessor Operating System”
    - http://www.usenix.org/events/osdi99/full_papers/gamsa/gamsa.pdf
  - McKenney, “Exploiting Deferred Destruction: An Analysis of RCU Techniques”
    - http://www.rdrop.com/users/paulmck/RCU/RCUdissertation.2004.07.14e1.pdf
  - Hart, “Applying Lock-free Techniques to the Linux Kernel”
    - http://www.cs.toronto.edu/~tomhart/masters_thesis.html
  - Olsson et al., “TRASH: A dynamic LC-trie and hash data structure”
    - http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=4281239
  - Desnoyers, “Low-Impact Operating System Tracing”
    - http://www.lttng.org/pub/thesis/desnoyers-dissertation-2009-12.pdf
  - Dalton, “The Design and Implementation of Dynamic Information Flow Tracking ...”
    - http://csl.stanford.edu/~christos/publications/2009.michael_dalton.phd_thesis.pdf
  - Gotsman et al., “Verifying Highly Concurrent Algorithms with Grace (extended version)”
    - http://software.imdea.org/~gotsman/papers/recycling-esop13-ext.pdf
  - Liu et al., “Mindicators: A Scalable Approach to Quiescence”
    - http://dx.doi.org/10.1109/ICDCS.2013.39
  - Tu et al., “Speedy Transactions in Multicore In-memory Databases”
    - http://doi.acm.org/10.1145/2517349.2522713
  - Arbel et al., “Concurrent Updates with RCU: Search Tree as an Example”
    - http://www.cs.technion.ac.il/~mayaarl/podc047f.pdf

Questions?