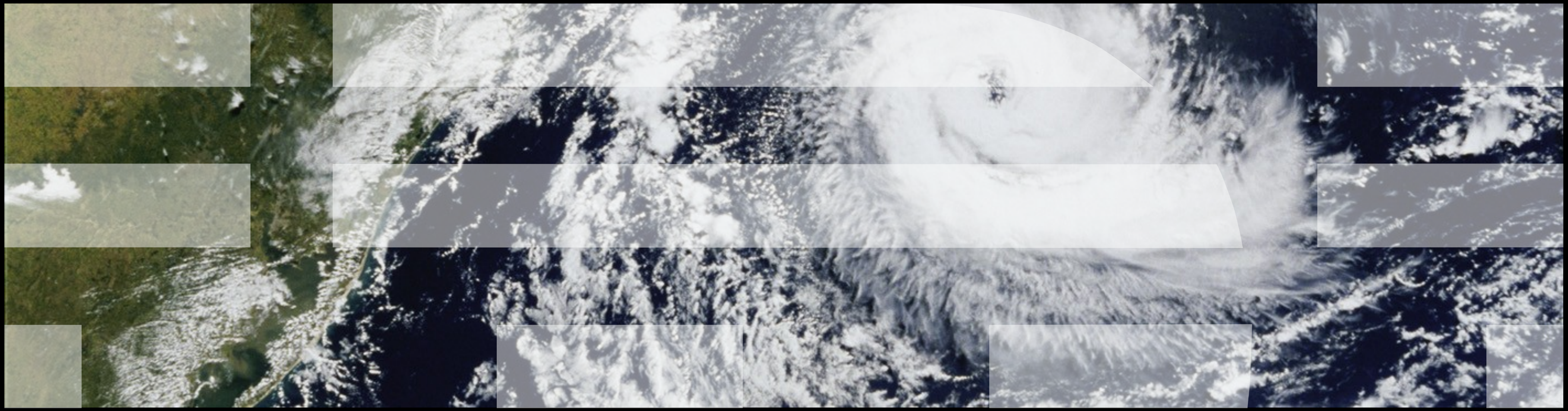
Paul E. McKenney, IBM Distinguished Engineer, Linux Technology Center
Member, IBM Academy of Technology
Linux Plumbers Conference LKMM Overview, September 15, 2017

Linux-Kernel Memory Ordering Workshop

Joint work with Jade Alglave, Luc Maranget, Andrea Parri, and Alan Stern



Changes Since LWN Article

- simpler model: two rounds of simplification vs. strong model
  - Fewer instances of mutually assured recursion
  - Simpler model omits 2+2W, release sequences, and addrpo
    - Will add them back in if compelling use cases arise
  - Simplified cumulativity (weakened B-cumulativity)
  - More complex strong model retained as linux-kernel-hardware.cat because it more closely delineates hardware guarantees
    - Updated from LWN strong model: simplify & handle recent HW changes
- Added a full set of atomic RMW operations
- Added an early implementation of locking
  - spin_trylock(s) equivalent to cmpxchg_acquire(s, 0, 1) emulation
  - spin_unlock(s) equivalent to smp_store_release(s, 0) emulation
  - Large performance advantages over emulation!

Example Simplification: “happens-before” Relation

- LWN strong-kernel.cat hb:

```
let rec B-cum-propbase = (B-cum-hb ; hb* ) |
                (rfe? ; AB-cum-hb ; hb* )
    and propbase = propbase0 | B-cum-propbase
    and short-obs = ((ncoe|fre) ; propbase+ ; rfe) & int
    and obs = short-obs |
                ((hb* ; (ncoe|fre) ; propbase* ; B-cum-propbase ; rfe) & int)
    and hb = hb0 | (obs ; rfe-ppo)
```

- Current linux-kernel-hardware.cat hb:

```
let rec prop = (overwrite & ext)? ; cumul-fence ; hb*
    and hb = ppo | rfe | (((hb* ; prop) \ id) & int)
```

- Current linux-kernel.cat hb:

```
let hb = ppo | rfe | ((prop \ id) & int)
```

Purpose of the Linux Kernel Memory Model

- Hoped-for benefits of a Linux-kernel memory model
  - Memory-ordering education tool (includes RCU)
  - Core-concurrent-code design aid: Automate memory-barriers.txt
  - Ease porting to new hardware and new toolchains
  - Basis for additional concurrency code-analysis tooling
    - For example, CBMC and Nidhugg (CBMC now part of rcutorture)
- Likely drawbacks of a Linux-kernel memory model
  - Extremely limited size: Handful of processes with handful of code
    - Analyze concurrency core of algorithm
    - Maybe someday automatically identifying this core
    - Perhaps even automatically stitch together multiple analyses (dream on!)
  - Limited types of operations (no function call, structures, call_rcu(), …)
    - Can emulate some of these
    - We expect that tools will become more capable over time
    - (More on this on a later slide)

Current Status and Demo

- Release-candidate memory model:
  - https://github.com/aparri/memory-model
  - Two rounds of simplification since the LWN article's strong model!
- Lots and lots of litmus tests:
  - https://github.com/paulmckrcu/litmus
- Demo: How to run model and capabilities
- Plan: Add memory model to Linux kernel
  - In new tools/memory-model directory

RCU Full Litmus Test: Trigger on Weak CPUs?

```
C auto/C-RW-G+RW-Rr+RW-Ra
{
}

P0(int *x0, int *x1)
{
  r1 = READ_ONCE(*x0);
  synchronize_rcu();
  WRITE_ONCE(*x1, 1);
}

P1(int *x1, int *x2)
{
  rcu_read_lock();
  r1 = READ_ONCE(*x1);
  smp_store_release(x2, 1);
  rcu_read_unlock();
}

P2(int *x2, int *x0)
{
  rcu_read_lock();
  r1 = smp_load_acquire(x2);
  WRITE_ONCE(*x0, 1);
  rcu_read_unlock();
}

exists
(0:r1=1 /\ 1:r1=1 /\ 2:r1=1)
```

https://github.com/paulmckrcu/litmus/blob/master/auto/C-RW-G%2BRW-Rr%2BRW-Ra.litmus

Same RCU Litmus Test: Trigger on Weak CPUs?

```
P0(int *x0, int *x1)
{
  r1 = READ_ONCE(*x0);
  synchronize_rcu();
  WRITE_ONCE(*x1, 1);
}
```

```
P1(int *x1, int *x2)
{
  rcu_read_lock();
  r1 = READ_ONCE(*x1);
  smp_store_release(x2, 1);
  rcu_read_unlock();
}
```

```
P2(int *x2, int *x0)
{
  rcu_read_lock();
  r1 = smp_load_acquire(x2);
  WRITE_ONCE(*x0, 1);
  rcu_read_unlock();
}
```

```
exists (0:r1=1 /\ 1:r1=1 /\ 2:r1=1)
```

https://github.com/paulmckrcu/litmus/blob/master/auto/C-RW-G%2BRW-Rr%2BRW-Ra.litmus

Current Model Capabilities ...

- READ_ONCE() and WRITE_ONCE()
- smp_store_release() and smp_load_acquire()
- rcu_assign_pointer(), rcu_dereference() and lockless_dereference()
- rcu_read_lock(), rcu_read_unlock(), and synchronize_rcu()
  - Also synchronize_rcu_expedited(), but same as synchronize_rcu()
- smp_mb(), smp_rmb(), smp_wmb(), smp_read_barrier_depends(), smp_mb__before_atomic(), and smp_mb__after_atomic()
- xchg(), xchg_relaxed(), xchg_release(), xchg_acquire(), cmpxchg(), cmpxchg_relaxed(), cmpxchg_release(), and cmpxchg_acquire()
  - Plus a great many atomic_*() functions, see linux-kernel.def for list
- spin_lock(), spin_unlock(), and spin_trylock()

… And Limitations

- Compiler optimizations not modeled
- No arithmetic
- Single access size, no partially overlapping accesses
- No arrays or structs (but can do trivial linked lists)
- No dynamic memory allocation
- No interrupts, exceptions, I/O, or self-modifying code
- No functions
- No asynchronous RCU grace periods, but can emulate them:
  - Separate thread with release-acquire, grace period, and then callback code
- Locking is new and lightly tested
  - Compare suspicious results to emulations with xchg() and report any bugs!

How to Run Models

- Download herd tool as part of diy toolset
  - http://diy.inria.fr/sources/index.html
- Build as described in INSTALL.txt
  - Need ocaml v4.01.0 or better: http://caml.inria.fr/download.en.html
    - “make world.opt” – Or install from your distro (easier and faster!)
    - Recent ocaml needs opam, see diy's README
- Memory model (https://github.com/aparri/memory-model):
  - linux.def: Support pseudo-C code
  - linux-kernel.cfg: Specify Linux-kernel model
  - linux-kernel.bell: “Bell” file defining events and relationships
  - linux-kernel.cat: “Cat” file defining actual memory model
  - linux-kernel-hardware.cat: Complex model more closely describing HW
- Various litmus tests (https://github.com/paulmckrcu/litmus):
  - herd7 -conf linux-kernel.cfg C-RW-R+RW-Gr+RW-Ra.litmus
  - herd7 -conf linux-kernel.cfg C-RW-R+RW-G+RW-R.litmus

Repeat of Earlier Litmus Test: Trigger on Weak CPUs?

```
P0(int *x0, int *x1)
{
  r1 = READ_ONCE(*x0);
  synchronize_rcu();
  WRITE_ONCE(*x1, 1);
}
```

```
P1(int *x1, int *x2)
{
  rcu_read_lock();
  r1 = READ_ONCE(*x1);
  smp_store_release(x2, 1);
  rcu_read_unlock();
}
```

```
P2(int *x2, int *x0)
{
  rcu_read_lock();
  r1 = smp_load_acquire(x2);
  WRITE_ONCE(*x0, 1);
  rcu_read_unlock();
}
```

```
exists (0:r1=1 /\ 1:r1=1 /\ 2:r1=1)
```

https://github.com/paulmckrcu/litmus/blob/master/auto/C-RW-G%2BRW-Rr%2BRW-Ra.litmus

Running Litmus Test on Earlier Slide

```
$ herd7 -conf strong.cfg litmus/auto/C-RW-G+RW-Rr+RW-Ra.litmus
Test auto/C-RW-G+RW-Rr+RW-Ra Allowed
States 7
0:r1=0; 1:r1=0; 2:r1=0;
0:r1=0; 1:r1=0; 2:r1=1;
0:r1=0; 1:r1=1; 2:r1=0;
0:r1=0; 1:r1=1; 2:r1=1;
0:r1=1; 1:r1=0; 2:r1=0;
0:r1=1; 1:r1=0; 2:r1=1;
0:r1=1; 1:r1=1; 2:r1=0;
No
Witnesses
Positive: 0 Negative: 7
Condition exists (0:r1=1 /\ 1:r1=1 /\ 2:r1=1)
Observation auto/C-RW-G+RW-Rr+RW-Ra Never 0 7
Hash=0cb6fa9aabafe5e4e28d1332afa966e3
```

Cannot happen

But Wait! There Are Prizes!!!

- First person to find a bug in the memory model
  - For example, a litmus test allowed by hardware with mainline Linux support, where that litmus test is prohibited by the memory model
  - Prize: Libre Computer Potato kickstarter board
- First person using memory model to find a bug in the kernel
  - For example, a missing smp_mb()
  - Consolation category: Missing comment in arch code relying on arch-specific behavior
  - Prize: Libre Computer Potato kickstarter board
- Best litmus test (counter-intuitive, biggest kernel example, ...)
  - Prize: Libre Computer Potato kickstarter board
- And a surprise consolation prize!!!

Another RCU Litmus Test: Trigger on Weak CPUs?

```
P0(int *x0, int *x1)
{
  r1 = READ_ONCE(*x0);
  synchronize_rcu();
  WRITE_ONCE(*x1, 1);
}
```

```
P1(int *x1, int *x2)
{
  rcu_read_lock();
  r1 = READ_ONCE(*x1);
  WRITE_ONCE(*x2, 1);
  rcu_read_unlock();
}
```

```
P2(int *x2, int *x0)
{
  rcu_read_lock();
  r1 = READ_ONCE(*x2);
  WRITE_ONCE(*x0, 1);
  rcu_read_unlock();
}
```

exists (0:r1=1 /\ 1:r1=1 /\ 2:r1=1)

https://github.com/paulmckrcu/litmus/blob/master/auto/C-RW-G%2BRW-R%2BRW-R.litmus

A Hierarchy of Litmus Tests: Rough Rules of Thumb

- Only one thread or only one variable: No ordering needed!
- Dependencies and rf relations everywhere
  - No additional ordering required
- If all rf relations, can replace dependencies with acquire
  - Some architecture might someday also require release, so careful!
- If only one relation is non-rf, can use release-acquire
  - Dependencies/rmb/wmb/READ_ONCE() ***sometimes*** replace acquire
  - But be safe – actually run the model to find out exactly what works!!!
- If two or more relations are non-rf, strong barriers needed
  - ***At least*** one between each non-rf relation
  - But be safe – actually run the model to find out exactly what works!!!

But for full enlightenment, see memory model itself
  - https://github.com/aparri/memory-model

A Hierarchy of Memory Ordering: Rough Overheads

- Read-write dependencies:
  - Free everywhere
- Read-read address dependencies:
  - Free other than on DEC Alpha
- Release/acquire chains and read-read control dependencies:
  - Lightweight: Compiler barrier on x86 and mainframe, special instructions on ARM, lightweight isync or lwsync barriers on PowerPC
- Restore sequential consistency:
  - Full memory barriers
    - Expensive pretty much everywhere
    - But usually affect performance more than scalability

Litmus Test Exercises (1/4)

- All rf relations and dependencies
  - C-LB+ldref-o+o-ctrl-o+o-dep-o.litmus
- All rf relations but one dependency removed
  - C-LB+ldref-o+o-o+o-dep-o.litmus
- Message passing with read-to-read address dependency
  - C-MP+o-assign+o-dep-o.litmus
- Message passing with lockless_dereference()
  - C-MP+o-assign+ldref-o.litmus
- All rf relations, acquire load instead of one dependency
  - C-LB+ldref-o+acq-o+o-dep-o.litmus

Litmus Test Exercises (2/4)

- All rf relations, but all dependencies replaced by acquires
  - C-LB+acq-o+acq-o+acq-o.litmus
- One co relation, the rest remain rf relations
  - C-WWC+o+acq-o+acq-o.litmus
- One co, rest remain rf, but with release-acquire
  - C-WWC+o+o-rel+acq-o.litmus
- One co, one fr, and only one remaining rf relation
  - C-Z6.0+o-rel+acq-o+o-mb-o.litmus
- One co, one fr, one rf, and full memory barriers
  - C-Z6.0+o-mb-o+acq-o+o-mb-o.litmus

Litmus Test Exercises (3/4)

- One co, one fr, one rf, and all but one full memory barriers
  - C-3.SB+o-o+o-mb-o+o-mb-o.litmus
- One co, one fr, one rf, and all full memory barriers
  - C-3.SB+o-mb-o+o-mb-o+o-mb-o.litmus
- IRIW, but with release-acquire
  - C-IRIW+rel+rel+acq-o+acq-o.litmus
- Independent reads of independent writes (IRIW), full barriers
  - C-IRIW+o+o+o-mb-o+o-mb-o.litmus

Litmus Test Exercises (4/4): Kernel vs. Hardware

- Only co: 2+2W
  - C-2+2W+o-r+o-r.litmus
  - C-2+2W+o-wmb-o+o-wmb-o.litmus
    - herd7 -conf linux-kernel.cfg <file>.litmus
    - herd7 -conf linux-kernel.cfg -cat linux-kernel-hardware.cat <file>.litmus
- Weaker B-cumulativity
  - https://www.kernel.org/pub/linux/kernel/people/paulmck/LWNLinuxMM/C-wmb-is-B-cumulative.litmus
- No release sequences (also a difference from C11)
  - C-Mprelseq+o-r+rmwinc+a-o.litmus, C-relseq.litmus, C-relseq-not-B-cumulative.litmus
- Additional exercises in the Examples.html file:
  - https://www.kernel.org/pub/linux/kernel/people/paulmck/LWNLinuxMM/Examples.html

Quick Guide to Linux Kernel Memory Model

"rcu-path": Constraints on ordering based on RCU read-side critical sections and grace periods

"pb": Propagates-before, or constraints based on order of stores reaching memory (including effects of barriers)

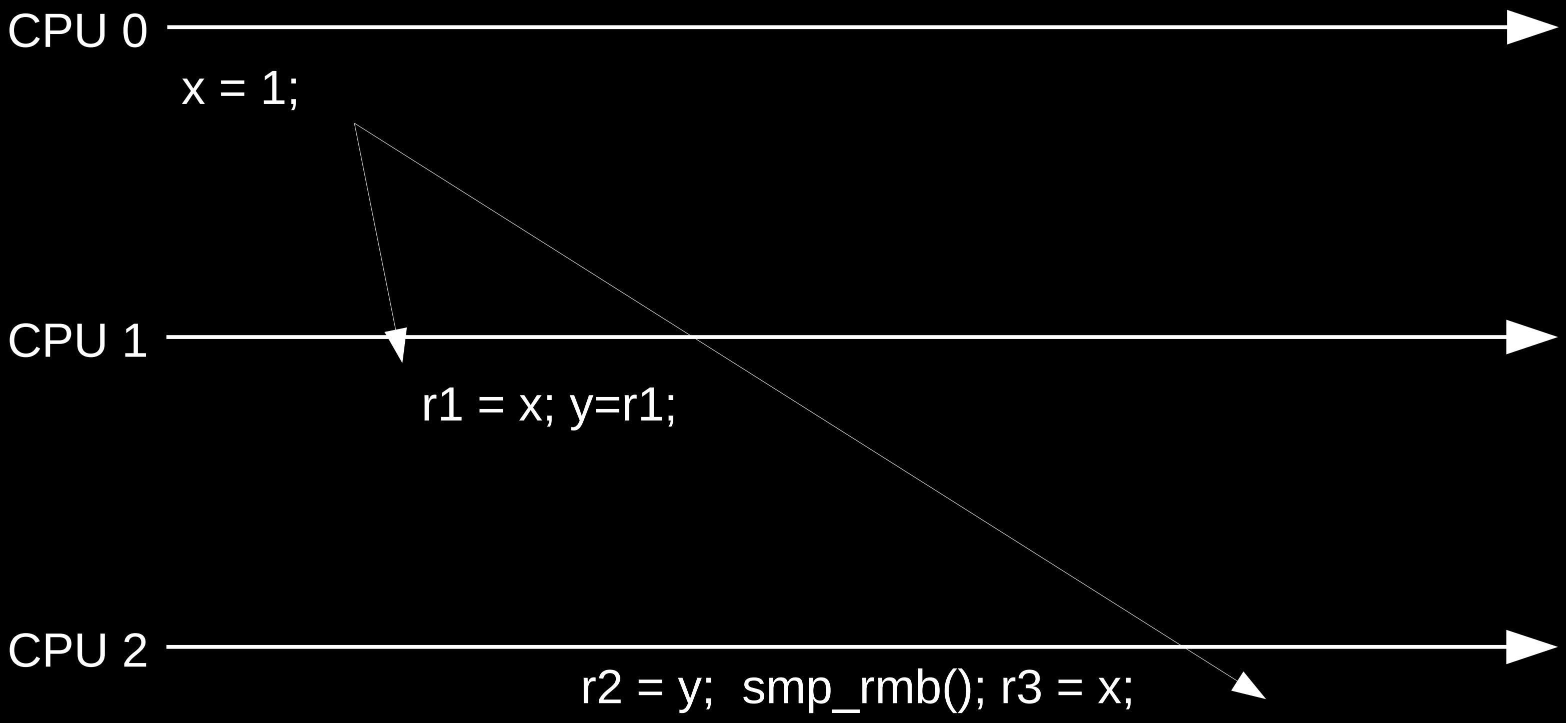
"hb": Happens-before, or constraints based on temporal ordering

"ppo": Preserved program order, or intra-thread constraints on instruction execution

"coherence": SC Per-Variable

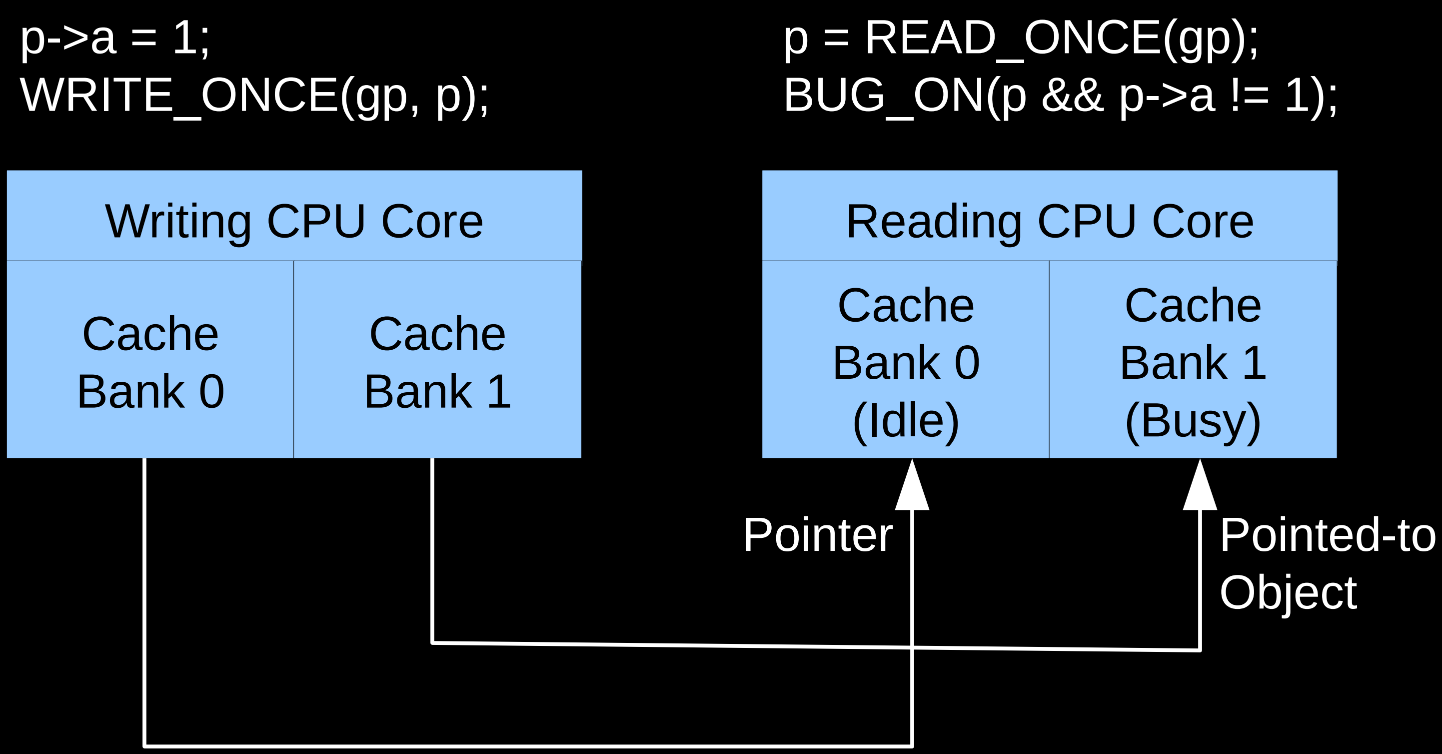
"RMW": Atomic Operations

“Non-Multicopy Atomic”: Writes Unsynchronized



Can have r1==1 && r2==1 && r3==0
What would prohibit this outcome?
(C-WRC-o+o-data-o+o-rmb-o.litmus)

Lack of Ordering For Read-Read Dependencies



Can you write one litmus test demonstrating this and another prohibiting this?

Legal Statement

- This work represents the view of the authors and does not necessarily represent the view of their employers.
- IBM and IBM (logo) are trademarks or registered trademarks of International Business Machines Corporation in the United States and/or other countries.
- Linux is a registered trademark of Linus Torvalds.
- Other company, product, and service names may be trademarks or service marks of others.

Questions?