Real-Time Response on Multicore Systems:

*It is Bigger Than I Thought*
History of Real Time (AKA Preemptible) RCU

- December 2004: realized that I needed to fix RCU...
- March 2005: first hint that solution was possible
  - I proposed flawed approach, Esben Neilsen proposed flawed but serviceable approach
- May 2005: first design fixing flaws in Esben's approach
- June 2005: first patch submitted to LKML
- August 2005: patch accepted in -rt
- November 2006: priority boosting patch
- Early 2007: priority boosting accepted into -rt
- September 2007: preemptible RCU w/o atomics
- January 2008: preemptible RCU in mainline
- December 2009: scalable preemptible RCU in mainline
- July 2011: RCU priority boosting in mainline
The -rt Patchset Was Used in Production Early On

- **2006: aggressive real-time on 64-bit systems**
  - Real-time Linux kernel (x86_64, 4-8 processors, deadlines down to 70 microseconds, measured latencies less than 40 microseconds)
    - I only did RCU. Ingo Molnar, Sven Dietrich, K. R. Foley, Thomas Gleixner, Gene Heskett, Bill Huey, Esben Nielsen, Nick Piggin, Lee Revell, Steven Rostedt, Michal Schmidt, Daniel Walker, and Karsten Wiese did the real work, as did many others joining the project later on.
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But some were not inclined to believe SMP -rt worked, so…
The Writeup

You show me a hard real-time system, and I will show you a hammer that will cause it to miss its deadlines.
The Limits of Hard Real Time in the Hard Real World

You can make your system more robust, but I can get a bigger hammer.
But Do Hardware Failures Count?

Rest assured, sir, that should there be a failure, it will not be due to software!
“SMP and Embedded Real Time”

**Five Real-Time Myths:**
- Embedded systems are always uniprocessor systems
- Parallel programming is mind crushingly difficult
- Real time must be either hard or soft
- Parallel real-time programming is impossibly difficult
- There is no connection between real-time and enterprise systems

**Despite the cute cartoons, this message was not well-received in all quarters...**
Nevertheless, I Believe That “SMP and Embedded Real Time” Has Stood the Test of Time
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Except For One Really Big Error...
Big Error in “SMP and Embedded Real Time”

February 8, 2012
– Dimitri Sivanic reports 200+ microsecond latency spikes from RCU
– My initial response, based on lots of experience otherwise:
  • “You must be joking!!!”
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  • “You mean it took only 200 microseconds?”
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My big error: I was thinking in terms of 4-8 CPUs, maybe eventually as many as 16-32 CPUs
– More than two orders of magnitude too small!!!
Real-Time Response on Multicore Systems: It is Bigger Than I Thought

RCU Initialization

```
struct rcu_state
    struct rcu_node
        struct rcu_node
        struct rcu_node
        struct rcu_node
        struct rcu_node

Level 0: 1 rcu_node
Level 1: 4 rcu_nodes
Level 2: 256 rcu_nodes
Total: 261 rcu_nodes
```

- `struct rcu_state`
- `struct rcu_node`
- `struct rcu_data CPU 0`
- `struct rcu_data CPU 15`
- `struct rcu_data CPU 4080`
- `struct rcu_data CPU 4095`
But Who Cares About Such Huge Systems?
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- Their users do!  :-)
- And you need to care about them as well
But Who Cares About Such Huge Systems?

- Their users do! :-)
- And you need to care about them as well
- Systems are still getting larger
  - I do remember 8-CPU systems being called “huge” only ten years ago
  - Today, laptops with 8 CPUs are readily available
  - And CONFIG_SMP=n is now inadequate for many smartphones
  - And the guys with huge systems provide valuable testing services
- Some Linux distributions build with NR_CPUS=4096
  - Something about only wanting to provide a single binary...
  - RCU must adjust, for example, increasing CONFIG_RCU_FANOUT
RCU Initialization, CONFIG_RCU_FANOUT=64

- Level 0: 1 rcu_node
- Level 2: 64 rcu_nodes
- Total: 65 rcu_nodes

Decreases latency from 200+ to 60-70 microseconds. “Barely acceptable” to users. But...
CONFIG_RCU_FANOUT=64 Consequences

Scalability vs. Energy Efficiency: Round 1
CONFIG_RCU_FANOUT=64 Consequences

- Huge systems want 64 CPUs per leaf rcu_node structure
- Smaller energy-efficient systems want scheduling-clock interrupts delivered to each socket simultaneously
  - Reduces the number of per-socket power transitions under light load
- If all 64 CPUs attempt to acquire their leaf rcu_node structure's lock concurrently: Massive lock contention
Issues With Scheduler-Clock Synchronization

- Synchronized: energy efficiency great, lock contention bad
- Unsynchronized: lock contention great, energy efficiency horrible

Six-CPU package with single power domain
CONFIG_RCU_FANOUT=64 Consequences

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  - Reduces the number of per-socket power transitions under light load
- If all 64 CPUs attempt to acquire their leaf rcu_node structure's lock concurrently: Massive lock contention
- Solution: Mike Galbraith added a boot parameter controlling scheduling-clock-interrupt skew
  - Later, Frederic Weisbecker's patch should help, but still have the possibility of all CPUs taking scheduling-clock interrupts
- Longer term: schedule events for energy and scalability
Unintended Consequences

- RCU polls CPUs to learn which are in dyntick-idle mode
  - force_quiescent_state() samples per-CPU counter

- Only one force_quiescent_state() at a time per RCU flavor
  - Mediated by trylock

- When 4096 CPUs trylock the same lock simultaneously, the results are not pretty: massive memory contention

- Immediate solution (Dimitri Sivanic):
  - Better mapping of rcu_state fields onto cachelines
  - Longer delay between force_quiescent_state() invocations, but...
Longer Polling Delay Consequences

Scalability vs. Grace-Period Latency: Round 1
Increased Polling Interval Consequences

- Increasing the polling interval increases the expected grace-period latency
- And people are already complaining about the grace periods taking too long!
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- Short-term solution: Control polling interval via boot parameter/sysfs; people can choose what works for them
Increased Polling Interval Consequences

- Increasing the polling interval increases the expected grace-period latency
- And people are already complaining about the grace periods taking too long!
- Short-term solution: Control polling interval via boot parameter/sysfs; people can choose what works for them
- Longer-term solution: Move grace period startup, polling, and cleanup to kthread, eliminating force_quiescent_state()'s lock
  - But this does not come for free...
  - And there are force_quiescent_state() calls from RCU_FAST_NO_HZ
Grace-Period kthread Issues

- Increases binding between RCU and the scheduler
- Single lock mediates kthread wait_event()/wake_up()
  - But preemption points reduce PREEMPT=n latency
  - So there is at least some potential benefit from taking this path
Grace-Period kthread Issues and Potential Benefits

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- Estimate of latency reduction:
  - Reducing rcu_node structures from 261 to 65 resulted in latency reduction from roughly 200 to 70 microseconds
  - Reducing rcu_node structures to one per preemption opportunity might reduce latency to about 30 microseconds (linear extrapolation)
  - But why not just run the test?
Grace-Period kthread Issues and Potential Benefits

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  - But why not just run the test?
    - Because time on a 4096-CPU system is hard to come by
    - Fortunately, I have a very long history of relevant experience...
Coping With 4096-CPU System Scarcity
About That Single Global Lock...
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  - So if already running or being awakened, no action required

- This situation can be handled by a variation on a tournament lock (Graunke & Thakkar 1990)
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- Grace-period operations are global events
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- This situation can be handled by a variation on a tournament lock (Graunke & Thakkar 1990)
  - A variation that does not share the poor performance noted by Graunke and Thakkar
Conditional Tournament Lock

- `struct rcu_state`
  - `struct rcu_node`
  - `struct rcu_node`
  - `struct rcu_node`

**Checked at each level**

**spin_trylock() at each level, release at next level**

**gp_flags**
Conditional Tournament Lock Code

```c
rnp = per_cpu_ptr(rsp->rda, raw_smp_processor_id())->mynode;
for (; rnp != NULL; rnp = rnp->parent) {
  ret = (ACCESS_ONCE(rsp->gp_flags) & RCU_GP_FLAG_FQS) ||
         !raw_spin_trylock(&rnp->fqslock);
  if (rnp_old != NULL)
    raw_spin_unlock(&rnp_old->fqslock);
  if (ret) {
    rsp->n_force_qs_lh++;
    return;
  }
  rnp_old = rnp;
}
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7   if (ret) {
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9      return;
10    }
11   rnp_old = rnp;
12 }
```

Effectiveness TBD
Other Possible Issues
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- The synchronize_*_expedited() primitives loop over all CPUs
  - Parallelize? Optimize for dyntick-idle state?

- The rcu_barrier() primitives loop over all CPUs
  - Parallelize? Avoid running on other CPUs?

- Should force_quiescent_state() use state in non-leaf rcu_nodes?
  - This actually degrades worst-case behavior

- Lots of force_quiescent_state() use from RCU_FAST_NO_HZ
  - Use callback numbering to (hopefully) get rid of this

- Grace-period initialization/cleanup hits all rcu_node structures
  - Parallelize?

- NR_CPUS=4096 on small systems (RCU handles at boot)

- And, perhaps most important...
Possible Issue With RCU in a kthread

Scheduler vs. RCU???
Possible Issue With RCU in a kthread

Scheduler vs. RCU???

When these two fight, they both lose!
Possible Issue With RCU in a kthread

Scheduler vs. RCU???

When these two fight, they both lose!
Much better if they both win!!!
The Linux Scheduler and RCU

- RCU uses the scheduler and the scheduler uses RCU
  - Plenty of opportunity for both RCU and the scheduler to lose big time!
  - See for example: http://lwn.net/Articles/453002/
  - Or this more-recent deadlock: https://lkml.org/lkml/2012/7/2/163
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- But driving RCU's grace periods from a kthread should be OK
  - As long as the scheduler doesn't wait for a grace period on any of its
    wake-up or context-switch fast paths: Either directly or indirectly
  - And as long as the scheduler doesn't exit an RCU read-side critical
    section while holding a runqueue or pi lock if that RCU read-side
    critical section had any chance of being preempted

- Driving RCU's grace periods kthread simplifies RCU:
  - dyntick-idle: No more stalls due to sleeping CPUs
  - force_quiescent_state(): no more races with grace-period completion
Conclusions
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  - The real opportunities for new work involve combinations of them

- Some need for 10s-of-microseconds latency on 4096 CPUs
  - Translates to mainstream need on tens or hundreds of CPUs
    - Supporting this is not impossible
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  – But even more work required for open-source applications

▫ The major large-system challenges are at the design level
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- Sometimes taking on crazy requirements simplifies things!!!
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