Making RCU Respect Your Device's Battery Lifetime

On-The-Job Energy-Efficiency Training For RCU Maintainers
Overview

- What is RCU?
- “The Good Old Days”
- Overview of RCU's many variants of energy efficiency
- Current state of RCU energy efficiency
- Future directions
What is RCU?

- For an overview, see [http://lwn.net/Articles/262464/](http://lwn.net/Articles/262464/)

- For the purposes of this presentation, think of RCU as something that defers work, with one work item per callback
  - Each callback has a function pointer and an argument
  - Callbacks are queued on per-CPU lists, invoked after grace period
    - Invocation can result in OS jitter and real-time latency
    - Deferring the work a bit longer than needed is OK, deferring too long is bad – but failing to defer long enough is fatal
What is RCU?

- RCU uses a state machine driven out of the scheduling-clock interrupt to determine when it is safe to invoke callbacks.
- Actual callback invocation is done from softirq.
RCU Area of Applicability

- **Read-Mostly, Stale & Inconsistent Data OK**
  (RCU Works Great!!!)

- **Read-Mostly, Need Consistent Data**
  (RCU Works OK)

- **Read-Write, Need Consistent Data**
  (RCU Might Be OK...)

- **Update-Mostly, Need Consistent Data**
  (RCU is Really Unlikely to be the Right Tool For The Job,
  But SLAB_DESTROY_BY_RCU Is A Possibility)

Use the right tool for the job!!!
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For More Information on RCU...

- Documentation/RCU in the Linux® kernel source code
- “User-Level Implementations of Read-Copy Update” (Mathieu Desnoyers et al.)
  - http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.159
- “The RCU API, 2010 Edition”
  - http://lwn.net/Articles/418853/
- “What is RCU” LWN series
  - http://lwn.net/Articles/262464/ (What is RCU, Fundamentally?)
  - http://lwn.net/Articles/263130/ (What is RCU's Usage?)
  - http://lwn.net/Articles/264090/ (What is RCU's API?)
- “Introducing technology into the Linux kernel: a case study”
  - http://doi.acm.org/10.1145/1400097.1400099
- “Meet the Lockers” (Neil Brown)
  - http://lwn.net/Articles/453685/
- “Read-Copy Update” (2001 OLS paper, still used in a number of college courses)
- Plus more at: http://www.rdrop.com/users/paulmck/RCU
RCU:
Tapping The Awesome Power of Procrastination
For Two Decades!!!
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“The Good Old Days”
Not Much “Good Old Days” Code Left in RCU

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Not Much “Good Old Days” Code Left in RCU

Why did I wait so long to conserve energy???
Why Did I Wait Until 2011 to Conserve Energy?

- The fact is that I didn't wait that long!!!

- But RCU's energy-efficiency code is unusual in that it has been rewritten a great many times
  - RCU has been concerned about energy efficiency for about ten years
  - Not much energy-efficiency code in RCU in the 1990s: Why?

- Other minor changes:
  - Expedited grace periods
  - Additions to rcutorture
  - Additional list-traversal primitives
  - Upgrading real-time response
  - Plus the usual list of fixes, improvements, and adaptations
“The Good Really Old Days”

- RCU used by DYNIX/ptx: Heavy database servers
- Used for a number of applications:
  - Fraud detection in large financial systems
  - Inventory monitoring/control for large retail firms
  - Rental car tracking/billing
  - Manufacturing coordination/control
    - Including manufacturing of airliners
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Airliner Manufacturing Plants Had Lots of These:

Author: William M. Plate Jr. (Public Domain)
Airliner Manufacturing Plants Had Lots of These

At About 40KW Each

Author: William M. Plate Jr.  (Public Domain)
And if You Think That *Welders* Are Power-Hungry...
If You Are Running a Bunch of Welders or Turbines...

- Not only are you not going to care much about RCU's contribution to power consumption...
If You Are Running a Bunch of Welders or Turbines...

- Not only are you not going to care much about RCU's contribution to power consumption...
- You are not going to care much about the whole server's contribution to power consumption!
- But of course things look very different for small battery-powered devices...
RCU's Many Energy-Efficiency Implementations
Initial RCU Did Have One Energy-Efficiency Feature

- Initial DYNIX/ptx RCU had light-weight read-side primitives
  - “Free” is a very good price!!!

- This meant that the system returned to idle more quickly than it would with heavier-weight synchronization primitives
  - But 1990s systems consumed more power idle than when running!
  - This was because the idle loop fit into cache, thus allowing the CPU to execute useless instructions at a very high rate

- But today's CPUs have many energy-efficiency features
  - And have very low idle power, especially for long-duration idle periods

- So why does RCU need to worry about energy efficiency???
  - After all, it is just a synchronization primitive!!!
RCU Driven From Scheduling Clock Interrupt

What RCU Did (2003)

Scheduling-Clock Interrupts

RCU's Use of Scheduling-Clock Interrupts Wastes Power and Prevents Deep CPU Sleep States

What Is Required

No Scheduling-Clock Interrupts, CPU Enters Deep Sleep
RCU Driven From Scheduling Clock Interrupt

What RCU Did (2003)

Scheduling-Clock Interrupts

RCU's Use of Scheduling-Clock Interrupts Wastes Power and Prevents Deep CPU Sleep States

What Is Required

No Scheduling-Clock Interrupts, CPU Enters Deep Sleep

Which is why RCU has a dyntick-idle subsystem!
RCU and Dyntick Idle (AKA CONFIG_NO_HZ=y)

- List of implementations:
  - 2004: Dyntick-idle bit vector
    - Manfred Spraul locates theoretical bug
RCU and Dyntick Idle (AKA CONFIG_NO_HZ=y)

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  - But after it had been in-tree for *four years*
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- 2008: -rt version (with Steven Rostedt)
  - Very complex: http://lwn.net/Articles/279077/
- 2009: Separate out NMI accounting
  - Greatly simplified: No proof of correctness required ;-)

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RCU and Dyntick Idle as of Early 2010

Dyntick-Idle Mode Enables CPU Deep-Sleep States

Enter Dyntick-Idle Mode

Scheduling-Clock Interrupts

Need to Process RCU Callbacks Before Entering Dyntick-Idle Mode

RCU Grace Period Ends
So RCU is Perfectly Energy Efficient, Right?
So RCU is Perfectly Energy Efficient, Right?

- Well, I thought that RCU was very energy efficient
- Then in early 2010 I got a call from someone working on a battery-powered multicore system
- And he was very upset with RCU

- Why?
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RCU Energy Inefficiency

No RCU Read-Side Critical Sections!

Enter Dyntick-Idle Mode

CPU 0

Scheduling-Clock Interrupts

RCU Callbacks Prevent Dyntick-Idle Mode Entry

CPU is Draining the Battery For No Good Reason!!!
RCU and Dyntick Idle (AKA CONFIG_NO_HZ=y)

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  - 2004: Dyntick-idle bit vector
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  - 2010: CONFIG_RCU_FAST_NO_HZ for small systems
    - Force last CPU into dyntick-idle mode
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CONFIG_RCU_FAST_NO_HZ

No RCU Read-Side Critical Sections!

Enter Dyntick-Idle Mode

CPU 0

Scheduling-Clock Interrupts

All Other CPUs Idle, Grace Period Ends Immediately

CPU 1

RCU Callbacks Invoked Immediately

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So RCU is Perfectly Energy Efficient, Right?
So RCU is Perfectly Energy Efficient, Right?

- This time, I was wiser:
  - I suspected CONFIG_FAST_NO_HZ needed on large systems

- And someone mentioned this to me in late 2011

- But some things never change: He was very upset with RCU

- Why?
Might Never Have All But One CPU Dyntick-Idled!!!

The more CPUs you have, the worse this effect gets
RCU and Dyntick Idle (AKA CONFIG_NO_HZ=y)

List of implementations:
- 2004: Dyntick-idle bit vector
  - Manfred Spraul locates theoretical bug
  - A few months before the mainframe guys encounter it
  - But after it has been in-tree for four years
- 2008: -rt version (with Steven Rostedt)
  - Very complex: http://lwn.net/Articles/279077/
- 2009: Separate out NMI accounting
  - Greatly simplified: No proof of correctness required
- 2010: CONFIG_RCU_FAST_NO_HZ for small systems
  - Force last CPU into dyntick-idle mode
- 2012: CONFIG_RCU_FAST_NO_HZ for large systems
  - Force CPUs with callbacks into dyntick-idle, but wake them up later
  - (See 2012 ELC presentation)
Large-System CONFIG_RCU_FAST_NO_HZ: Before
Large-System CONFIG_RCU_FAST_NO_HZ: After

Extra work at idle entry might (or might not) save work later
Large-System CONFIG_RCU_FAST_NO_HZ: Results

- Performance work showed equivocal results
- Often a great reduction in wakeups, but not always as large of energy savings as desired
- Repeated attempts to drain callbacks on idle entry do not seem to be as helpful as desired
- Can CONFIG_RCU_FAST_NO_HZ reduce scheduling-clock ticks with less idle-entry RCU-callback work?
  - To find out, let's look at RCU grace-period and callback handling
  - Grace period: The period of time that RCU defers work
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Grace-Period Handling In The Good Really Old Days

Scheduling-clock interrupt

<table>
<thead>
<tr>
<th>GP #</th>
<th>CPU 0</th>
<th>CPU 1</th>
<th>CPU 2</th>
<th>CPU 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

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RCU Callback Handling In The Good Really Old Days

CPU 0

->nxtlist
->nxttail[]

RCU_DONE_TAIL
RCU_WAIT_TAIL
RCU_NEXT_READY_TAIL
RCU_NEXT_TAIL

A --> B --> C --> D --> E
RCU Callback Handling In The Good Really Old Days

Advance callbacks

CPU 0

->nxtlist

->nxttail[]

RCU_DONE_TAIL
RCU_WAIT_TAIL
RCU_NEXT_READY_TAIL
RCU_NEXT_TAIL

A → B → C → D → E

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RCU Callback Handling In The Good Really Old Days

CPU 0

Invoke callbacks

->nxtlist

->nxttail[]

RCU_DONE_TAIL

RCU_WAIT_TAIL

RCU_NEXT_READY_TAIL

RCU_NEXT_TAIL
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RCU Callback Handling In The Good Really Old Days

New callbacks arrive

CPU 0

0

1

->nxtlist

->nxttail[]

RCU_DONE_TAIL

RCU_WAIT_TAIL

RCU_NEXT_READY_TAIL

RCU_NEXT_TAIL
Grace-Period Handling And TREE_RCU

- Problem: Lock contention
- Solution: Apply hierarchy in the form of TREE_RCU
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Grace-Period Handling And TREE_RCU: 4096 CPUs

```
struct rcu_state

struct rcu_node

struct rcu_node

struct rcu_data
CPU 15

struct rcu_data
CPU 4095

struct rcu_data
CPU 0

struct rcu_data
CPU 4080

Level 0: 1 rcu_node
Level 1: 4 rcu_nodes
Level 2: 256 rcu_nodes
Total: 261 rcu_nodes
```
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Grace-Period Handling And TREE_RCU: 4 CPUs

CPU 2 & 3 awareness of race-period start delayed
Grace-Period Handling, TREE_RCU, and dyntick-idle

Callbacks registered here ... ... are guaranteed done here
Grace-Period Handling, TREE_RCU, and dyntick-idle

Callbacks registered here ...

... are guaranteed done here

But CPU 3 is asleep and unaware!
Dealing With dyntick-idle Grace-Period Latency

- Don't allow CPUs with callbacks to go dyntick-idle
  - Which would unfortunately put us back where we started

- Try to force RCU state machine to drain callbacks
  - Already tried that, consumes too much CPU for too little benefit

- Impose time limit on dyntick-idle sojourns with callbacks
  - About 6 seconds if all lazy and about 4 jiffies if at least one non-lazy
  - Seems to work reasonably well: times can be adjusted at runtime
  - But still greatly degrades grace-period latency for dyntick-idle CPUs

- Mark callbacks with corresponding grace-period number
Grace-Period Handling, TREE_RCU, and dyntick-idle

Callbacks registered here are marked with grace period 2

And will be recognized as ready when CPU 3 awakens
But What If No Other CPU Needs Grace Period?

Callbacks registered and marked here, but grace period 2 never starts!!!
Dealing With dyntick-idle Grace-Period Latency

- Don't allow CPUs with callbacks to go dyntick-idle
  - Which would unfortunately put us back where we started

- Try to force RCU state machine to drain callbacks
  - Already tried that, consumes too much CPU for too little benefit

- Impose time limit on dyntick-idle sojourns with callbacks
  - About 6 seconds if all lazy and about 4 jiffies if at least one non-lazy
  - Seems to work reasonably well: times can be adjusted at runtime
  - But still degrades grace-period latency for dyntick-idle CPUs, so...

- Mark callbacks with corresponding grace-period number
  - But cannot start later grace periods, so...

- Register corresponding grace period with RCU core
Grace-Period Handling, TREE_RCU, and dyntick-idle

Callbacks registered here are marked with grace period 2

And RCU knows to start grace period 2
Grace-Period Handling, TREE_RCU, and dyntick-idle

Callbacks registered here are marked with grace period 2
And RCU knows to start grace period 2
And that grace period 3 is not needed
Preliminary Energy Efficiency Results

- Data courtesy of Dietmar Eggemann and Robin Randhawa of ARM on early-silicon big.LITTLE system
- Early results equivocal, but RCU_FAST_NO_HZ might not be helping much on big.LITTLE
  - Looking into kthread throttling and tuning
  - Also double-checking experiment setup
- Alternative approach: no-CBs CPUs!
- But what is big.LITTLE???
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ARM big.LITTLE Architecture

Cortex-A15

Twice as fast

Cortex-A15

big

~3 times more energy efficient

Cortex-A7

Cortex-A7

Cortex-A7

LITTLE
ARM big.LITTLE Architecture: Strategy

- Run on the LITTLE by default
- Run on big if heavy processing power is required
- In other words, if feasible, run on LITTLE for efficiency, but run on big if necessary to preserve user experience
  - This suggests that RCU callbacks should run on LITTLE CPUs
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ARM big.LITTLE Without no-CBs CPUs

![Diagram showing the relationship between big and LITTLE CPUs with grace period and busy states](image-url)

- **Big CPU**
  - Busy
  - Grace Period
  - CB

- **LITTLE CPU**
  - Busy
  - Busy
  - Busy
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ARM big.LITTLE With no-CBs CPUs

big CPU

Busy

Grace Period

LITTLE CPU

Busy

Busy

CB

Busy
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ARM big.LITTLE With no-CBs CPUs: No Free Lunch

Diagram showing the concepts of big CPU and LITTLE CPU, busy states, and the grace period.
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ARM big.LITTLE With no-CBs CPUs: Preliminary Results

- Reference System: RCU_NOCB_CPU=n
- Test System: RCU_NOCB_CPU=y, big CPUs offloaded, kthreads confined to LITTLE CPUs
- Approximate power savings:
  - cyclictest: 10%
  - andebench8: 2%
  - audio: 10%
  - bbench_with_audio: 5%
- Next steps:
  - Get no-CBs CPUs to production quality
  - More adjustment to RCU_FAST_NO_HZ
Offloadable RCU Callbacks: Limitations and Futures

- Probably several remaining bugs in no-CBs CPUs
  - Not yet production quality

- Must reboot to reconfigure no-CBs CPUs
  - Should be just fine for many uses
  - Hopefully also OK for HPC and real-time workloads

- No energy-efficiency code: lazy & non-lazy CBs? Non-lazy!
  - But non-lazy Cbs are common case, so deferring interpretation of laziness.

- No-CBs CPUs' kthreads not subject to priority boosting
  - Probably not a near-term problem

- Setting all no-CBs CPUs' kthreads to RT prio w/out pinning them: bad!
  - At least on large systems: Probably OK near-term, maybe long term as well

- Note: I do not expect no-CBs path to completely replace current CB path
To Probe More Deeply Into no-CBs CPUs...

- “Relocating RCU callbacks” by Jon Corbet
  - http://lwn.net/Articles/522262/

- “What Is New In RCU for Real Time (RTLWS 2012)”
  - Slides 21-on

- “Getting RCU Further Out of the Way (Plumbers 2012)”

- “Cleaning Up Linux’s CPU Hotplug For Real Time and Energy Management” (ECRTS 2012)
Lessons Learned and Relearned
Lessons Learned, Old and New

- Workload matters!!!
  - Different workloads have different requirements
  - A given workload's requirements change over time
    - More important, one's understanding of requirements changes over time!
  - Supporting a single workload is easier than supporting many of them
Lessons Learned, Old and New

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- Energy-efficient and performance benchmarkers
  - You would never believe what either group will do for 5%...
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- The guys who request an enhancement are rarely the guys who are willing to test your patches

- The importance of the community
A Brief History of RCU Issues

- ~1993: SMP scalability (30 CPUs) for RDBMS workloads
- 1996: NUMA (64 CPUs) for RDBMS workloads
- 2002: SMP scalability (~30 CPUs) for general workloads
- 2004: SMP scalability (~512 CPUs) for HPC workloads
  - And some concern about energy efficiency
- 2005: Real-time response (~4 CPUs)
- 2008: SMP scalability (>1024 CPUs) for HPC workloads
  - 100s of CPUs for more general workloads
- 2009: Real-time response (~30 CPUs) for general workloads
- 2010: Energy efficiency (~2 CPUs), real-time response when CPU-bound
- 2011: Energy efficiency (lots of CPUs)
- 2012: RCU causes 200-microsecond latency spikes...
And So I Owe The Linux Community Many Thanks

- Because of the many RCU-related challenges from the Linux community, some of my most important work and collaborations have been in the past ten years.
And So I Owe The Linux Community Many Thanks

- Because of the many RCU-related challenges from the Linux community, some of my most important work and collaborations have been in the past ten years
- Not many people my age can truthfully say that
- Here is hoping for ten more years!!! ;-)

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