Bare-Metal Multicore Performance in a General-Purpose Operating System
Group Effort: Acknowledgments

- Josh Triplett: First prototype (LPC 2009)
- Frederic Weisbecker: Core kernel work and x86 port
- Steven Rostedt: Lots of code review and comments
- Li Zhong: Power port
- Geoff Levand, Kevin Hilman: ARM port
- Paul E. McKenney: Read-copy update (RCU) work
- Thomas Gleixner, Paul E. McKenney: “Godfathers”
What Do Database, HPC, and RT Developers Want?
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Get The #@#$##*!!! Kernel Out Of Our #@#$##*!!! Way!!!
Get The #$@#$*!!! Kernel Out Of Our #$@#$*!!! Way!!!

But we need device drivers.
What Do Database, HPC, and RT Developers Want?

Get The #@#$#*!!! Kernel Out Of Our #@#$#*!!! Way!!!

But we need device drivers.
And file systems.
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But we need device drivers.
And file systems.
And memory protection.
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Get The #@#$#*!!! Kernel Out Of Our #@#$#*!!! Way!!!

But we need device drivers.
And file systems.
And memory protection.
And...
So What Are Us Poor Kernel Developers To Do???
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- For almost 20 years, my response was “Yeah, right, you really do want the whole kernel, just admit it already!!!”
So What Are Us Poor Kernel Developers To Do???

- For almost 20 years, my response was “Yeah, right, you really do want the whole kernel, just admit it already!!!”
- My first clue to a third way was Linux's dyntick-idle system – (Used in battery-powered systems for years prior to Linux's use.)
Before Linux's dyntick-idle System

CPU 0

Scheduling-Clock Interrupts

Busy Period Ends

But CPU Remains in High-Power State

CPU 1
Scheduling-Clock Interrupts Really Optional???

- Scheduling-clock interrupt purpose:
  - Check for other work from time to time
  - Prevent a given process from monopolizing the CPU

- But if the CPU is idle, there is nothing for it to do anyway!!!
Linux's dyntick-idle System

- Dyntick-Idle Mode Enables CPU Deep-Sleep States
- Enter Dyntick-Idle Mode At End Of Busy Period
- Very Good For Energy Efficiency!!!
Linux Kernel Is Now Out Of The Idle Loop's Way...
Linux Kernel Is Now Out Of The Idle Loop's Way...
So Can We Get It Out Of The Application's Way?
Is The Kernel Being In The Way Really A Problem?
For aggressive real-time workloads, scheduling clock tick does add measurable latency
– Some insane people really are getting sub-20-microsecond real-time interrupt latencies out of the Linux kernel...
– And I strongly believe in encouraging that sort of insanity!!!
For aggressive real-time workloads, scheduling clock tick does add measurable latency
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Some HPC workloads are sensitive to “OS jitter”
   - Especially iterative workloads with short iterations
Iterative Workloads With Short Iterations: Ideal
Iterative Workloads With Short Iterations: OS Jitter

OS Jitter Multiplied!!!
Now Try This With 800,000 CPUs In A Cluster...

OS Jitter Multiplied!!!
Yes, This Is A Real Problem For Some Workloads
Linux Kernel Is Now Out Of The Idle Loop's Way...
So Can We Get It Out Of The Application's Way?
Josh Triplett's First Prototype, 2009

- Always turn off scheduling-clock interrupt for user code
- Good demonstration of feasibility and benefit
  - 2009 Linux Plumbers Conference presentation
  - http://linuxplumbersconf.org/ocw/proposals/103
  - See next two slides for performance comparison
Benchmark Results Before (Anton Blanchard)
Well worth going after...
But There Were A Few Small Drawbacks...

- No process accounting
- User applications can monopolize CPU
- RCU grace periods go forever, running system out of memory
  - More on this later
Can We Do Something About The Drawbacks? (Discussion at 2010 Linux Plumbers Conference)

- User applications can monopolize CPU
  - But if there is only one runnable task, so what???
So Another Look At The Drawbacks... (Discussion at 2010 Linux Plumbers Conference)

- User applications can monopolize CPU
  - But if there is only one runnable task, so what???
  - If new task awakens, interrupt the CPU, restart scheduling-clock interrupts
  - In the meantime, we have an “adaptive idle usermode” CPU

- No process accounting
  - Use delta-based accounting, based on when process started running
  - One CPU retains scheduling-clock interrupts for timekeeping purposes

- RCU grace periods go forever, running system out of memory
  - Inform RCU of adaptive-idle usermode execution so that it ignores adaptive-idle user-mode CPUs, similar to its handling of dyntick-idle CPUs

- Frederic Weisbecker took on this task (for x86-64)
  - Geoff Levand and Kevin Hilman: Port to ARM
  - Li Zhong: Port to PowerPC
  - I was able to provide a bit of help with RCU
How Well Does It Work?
How Well Does It Work?

- Preliminary results look good
How Well Does It Work?

Scheduling clock interrupts

Extra scheduling clock interrupts due to RCU callbacks

Adaptive Ticks

Second task awakens

One task per CPU
Other Than RCU, Looks Great!!!

- Need to fix RCU
- But first, what is RCU?
What Is RCU?
What Is RCU? (AKA Read-Copy Update)

- For an overview, see 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
  - Deferring the work a bit longer than needed is OK, deferring too long is bad – but failing to defer long enough is fatal
  - Allow extremely fast and scalable read-side access to shared data
RCU: Tapping The Awesome Power of Procrastination For Two Decades!!!
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!!!*
Applicability To The Linux Kernel

![Graph showing the growth of RCU API uses from 2002 to 2014](image-url)
What Is RCU? (AKA Read-Copy Update)

- 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.
Procrastination's Dark Side
Procrastination's Dark Side: Eventually Must Do Work

Likely disrupting whatever was intended to execute at about this time...

call_rcu(): Queue Callback

CPU 0

Grace Period

Callback Invoked
Why Not Offload RCU's Callbacks?
Offload RCU Callbacks: Houston/Korty Approach

CPU 0

RCU (CPU 1)

CPU 2

Grace Period

call_rcu()

Callback Invoked

Callback Invoked

No disruption!
Offload RCU Callbacks: Houston/Korty Approach

CPU 0

call_rcu()

RCU (CPU 1)

call_rcu()

CPU 2

Grace Period

Callback Invoked | Callback Invoked

No disruption! (But also no scalability, and Linux kernel must scale)
Scalable RCU Callback Offloading

Scheduler controls placement (or can place manually)

No disruption!
Adaptive Ticks And Callback Offloading

Scheduling clock interrupts

RCU no longer causes extra scheduling clock interrupts

Second task awakens

One task per CPU
Where To Run RCU Callbacks???
Where To Run RCU Callbacks???

- **Interrupts, Management, Callbacks**
  - Massive Disruption for Housekeeping

- **Worker Threads (HPC, Real Time)**
  - No Disruption for Real Work

Exact Layout Depends on Workload
How Well Does It Work?
How Well Does It Work?

- Preliminary data looks good: also helps save energy
  - See later slides

- Some shortcomings, as always:
  - Adaptive-idle usermode slows user/kernel transitions slightly
    - Not a problem for computation-intensive workloads
  - One task per CPU for adaptive-idle usermode execution
    - Also not a problem for many computation-intensive workloads
  - Must reboot to reconfigure adaptive idle and RCU callback offloading
  - Must configure interrupts and processes manually (see next slide)
  - CPU 0 cannot be offloaded (future work)
  - At least one CPU must keep scheduling-clock interrupt (timekeeping)
  - Scalability likely limited to a few hundred CPUs (future work)
  - RCU callback-offloading kthreads (rcuo) not priority boosted
    - Rely on configuration restrictions leaving idle time on housekeeping CPUs
  - Work in progress: There are probably still a few bugs!
Removing Other Sources of Disturbance

- **Interrupts: /proc/irq/*/**
  - One directory for each IRQ
  - `smp_affinity` file for hexadecimal specification (0x03)
  - `smp_affinity_list` for decimal CPU-list specification (0-1)
  - Verify via /proc/interrupts
  - Documentation/IRQ-affinity.txt in Linux kernel source for more info

- **Timers: CPU hotplug remove then reinsert**

- **Processes, daemons, and kthreads:**
  - Per-task affinity (taskset command, sched_setaffinity() syscall)
  - cgroups or cpusets (Documentation/cgroups/*.txt)

- **Global TLB-flush operations**
  - Can be caused by kernel module unloading
    - So don't unload kernel modules on production systems!

- **Cache and TLB misses are still with us**
RCU Callback Offloading: Energy Efficiency

- Preliminary data courtesy of Dietmar Eggemann and Robin Randhawa of ARM on early-silicon big.LITTLE system
- But what is big.LITTLE???
ARM big.LITTLE Architecture

Twice as fast

Cortex-A15

~3 times more energy efficient

Cortex-A7

big

Cortex-A15

LITTLE

Cortex-A7

Cortex-A7
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
ARM big.LITTLE Without RCU Callback Offloading

- big CPU
- Busy
- Grace Period
- LITTLE CPU
- Busy
- Busy
- Busy

call_rcu()
ARM big.LITTLE With RCU Callback Offloading

call_rcu()

Grace Period

Big CPU

Busiest

LITTLE CPU

Busy

Busy

CB

Busy
ARM big.LITTLE With RCU Callback Offloading

call_rcu()

big CPU

Busy

Grace Period

CB

LITTLE CPU

Busy

Busy

Busy

Busy

CB

Busy
ARM big.LITTLE With RCU Callback Offloading

call_rcu()

big CPU

Busy

Grace Period

CB

LITTLE CPU

Busy

Busy

Busy

Busy

CB

Busy

But 3x better energy efficiency
ARM big.LITTLE With no-CBs CPUs: Preliminary Results (Randhawa and Eggemann, ARM)

- Reference System: No offloading
- Test System: big CPUs offloaded, kthreads on LITTLE CPUs
- Approximate power savings:
  - cyclictest: 10%
  - andebench8: 2%
  - audio: 10%
  - bbench_with_audio: 5%
To Probe More Deeply Into Adaptive Idle

- “The 2012 realtime minisummit” (LWN, CPU isolation discussion)
  - http://lwn.net/Articles/520704/

- “Interruption timer périodique” (Kernel Recipes, in French)
  - https://kernel-recipes.org/?page_id=410

- “What Is New In RCU for Real Time” (RTLWS 2012)
    - Slides 31-32

- “TODO”
  - https://github.com/fveisbec/linux-dynticks/wiki/TODO

- “NoHZ tasks” (LWN)
  - http://lwn.net/Articles/420544/
To Probe More Deeply Into RCU Callback Offloading

- “Making RCU Respect Your Device's Battery Lifetime: On-The-Job Energy-Efficiency Training For RCU Maintainers” (LCA 2013)

- “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)
Summary

- General-purpose OS or bare-metal performance?
  - Why not both?
  - Work in progress gets us very close for CPU-bound workloads:
    - Adaptive idle userspace execution (work in progress)
    - RCU callback offloading (early version in mainline)
    - Interrupt, process, daemon, and kthread affinity
    - Timer offloading
  - Some restrictions:
    - Need to reserve CPU(s) for housekeeping
    - Adaptive-idle and RCU-callback-offloaded CPUs specified at boot time
    - One task per CPU for adaptive-idle usermode execution
    - Cache and TLB misses are still with us
  - Serendipity: Energy-efficiency benefits as well!
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Extending Linux's reach farther into extreme computing!!!
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