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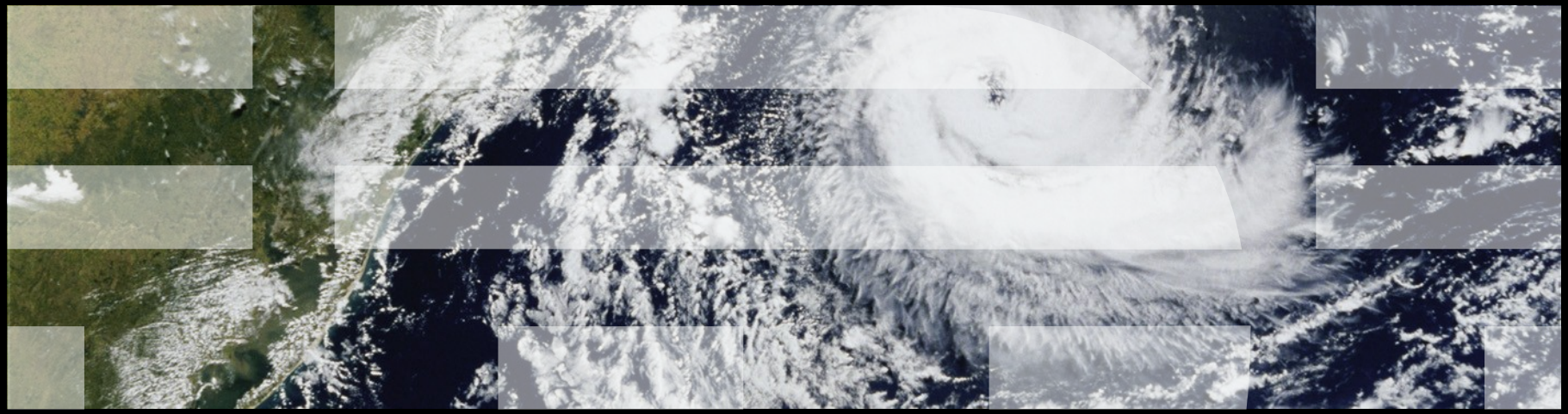
Enterprise End-User Summit 2013, New York, NY, USA May 14-15, 2013

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, tracing upgrades
- Christoph Lameter: Early adopter feedback
- Li Zhong: Power port
- Geoff Levand, Kevin Hilman: ARM port
- Peter Zijlstra: Scheduler-related review, comments, and work
- Paul E. McKenney: Read-copy update (RCU) work (fun with “Hotel California” interrupts!)
- Thomas Gleixner, Paul E. McKenney: “Godfathers”
- Ingo Molnar: Maintainer
- Other contributors:
  - Avi Kivity, Chris Metcalf, Geoff Levand, Gilad Ben Yossef, Hakan Akkan, Lai Jiangshan, Max Krasnyansky, Namhyung Kim, Paul Gortmaker, Paul Mackerras, Peter Zijlstra, Steven Rostedt, Zen Lin (and probably many more)

What Do Database, HPC, and RT Developers Want?

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

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But we need device drivers.

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And memory protection.

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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!!!”

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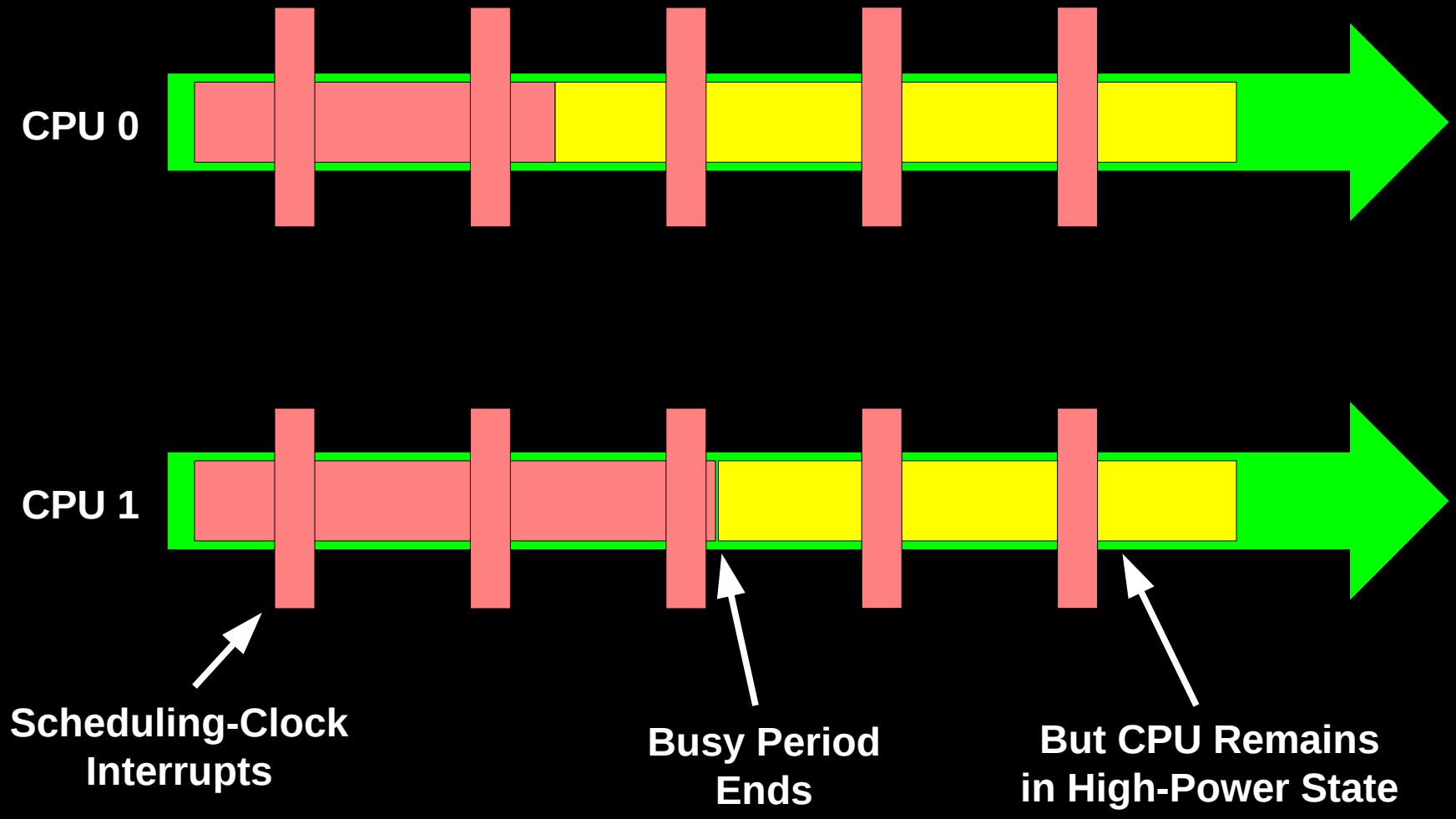
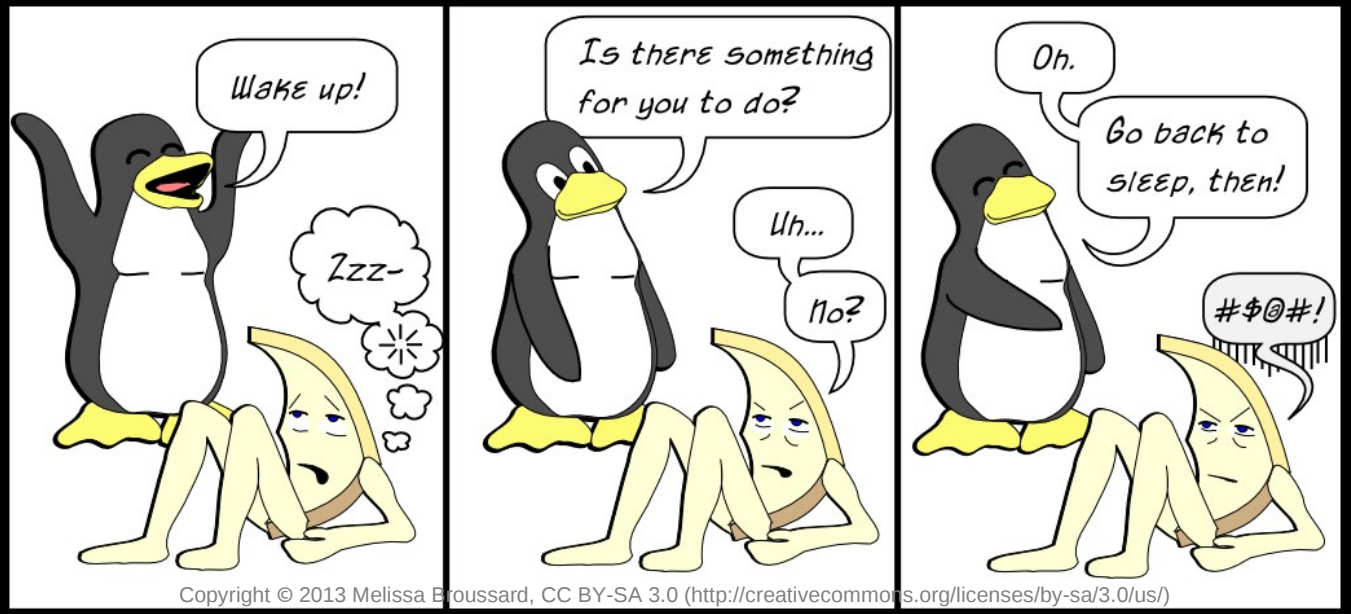
- For almost 20 years, my response was “Yeah, right, you really do want the whole kernel, just admit it already!!!”
- My first clue otherwise was Linux's dyntick-idle system
  - (Used in battery-powered systems for years prior to Linux's use.)

Before Linux's dyntick-idle System

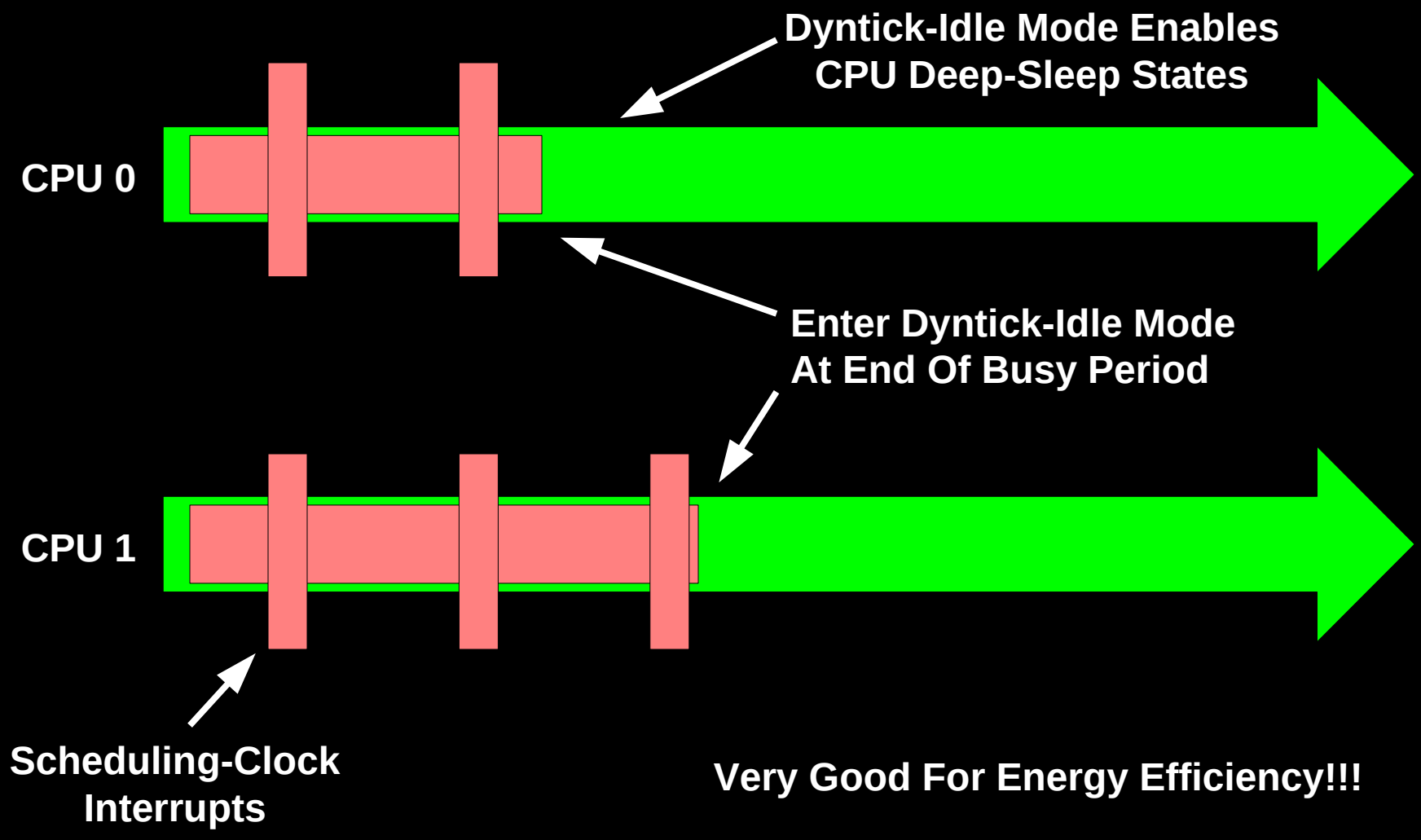


Scheduling-Clock Interrupts Really Optional???

- Scheduling-clock interrupt primary 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



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?

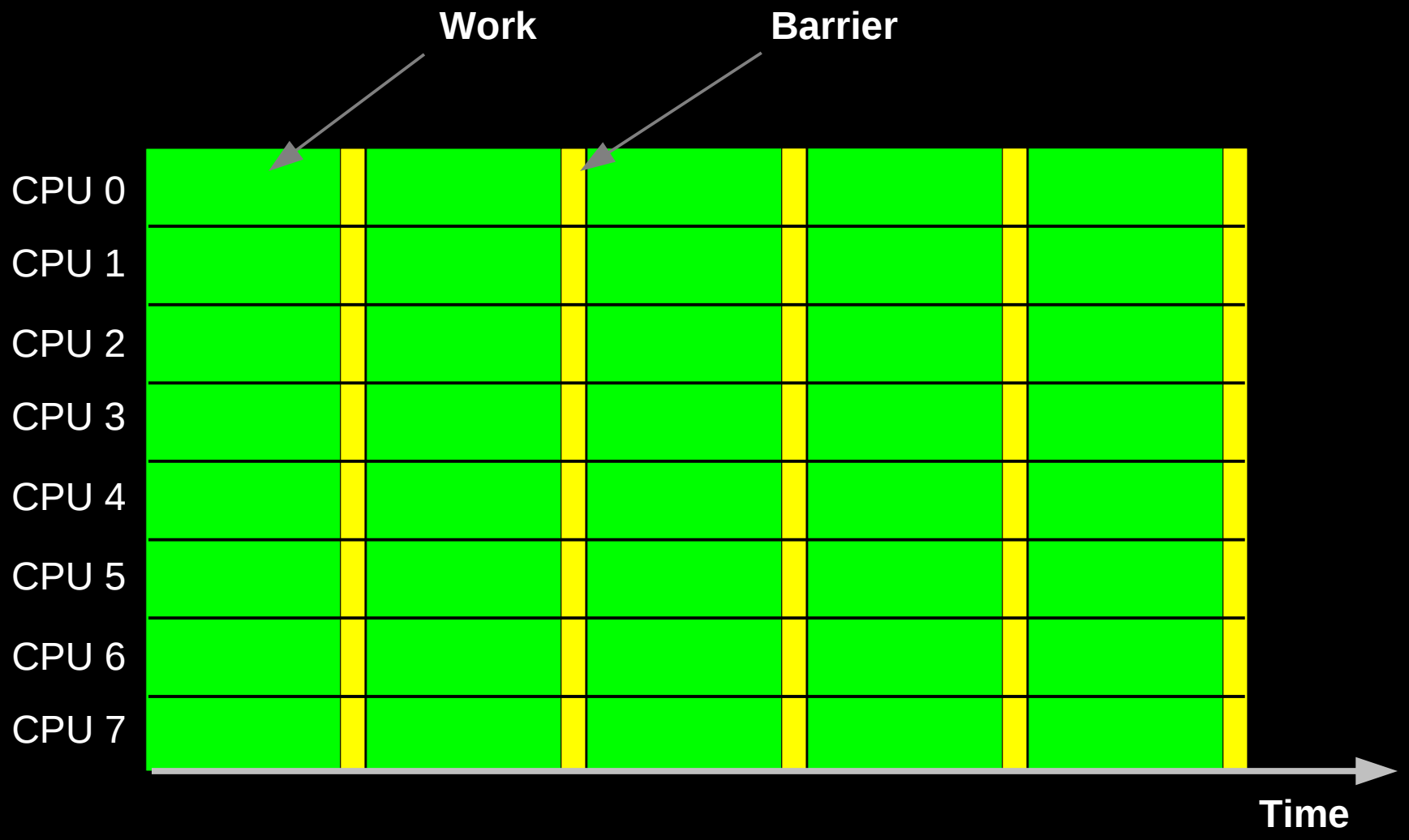
Is The Kernel Being In The Way Really A Problem?

- 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 happen to strongly believe in encouraging that sort of insanity!!!

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 happen to strongly believe in encouraging that sort of insanity!!!
- Some HPC workloads are sensitive to “OS jitter”
  - Especially iterative workloads with short iterations
  - And even more so on large systems booted with skew_tick=y

Iterative Workloads With Short Iterations: Ideal



Iterative Workloads With Short Iterations: OS Jitter

Now Try This With 800,000 CPUs In A Cluster...

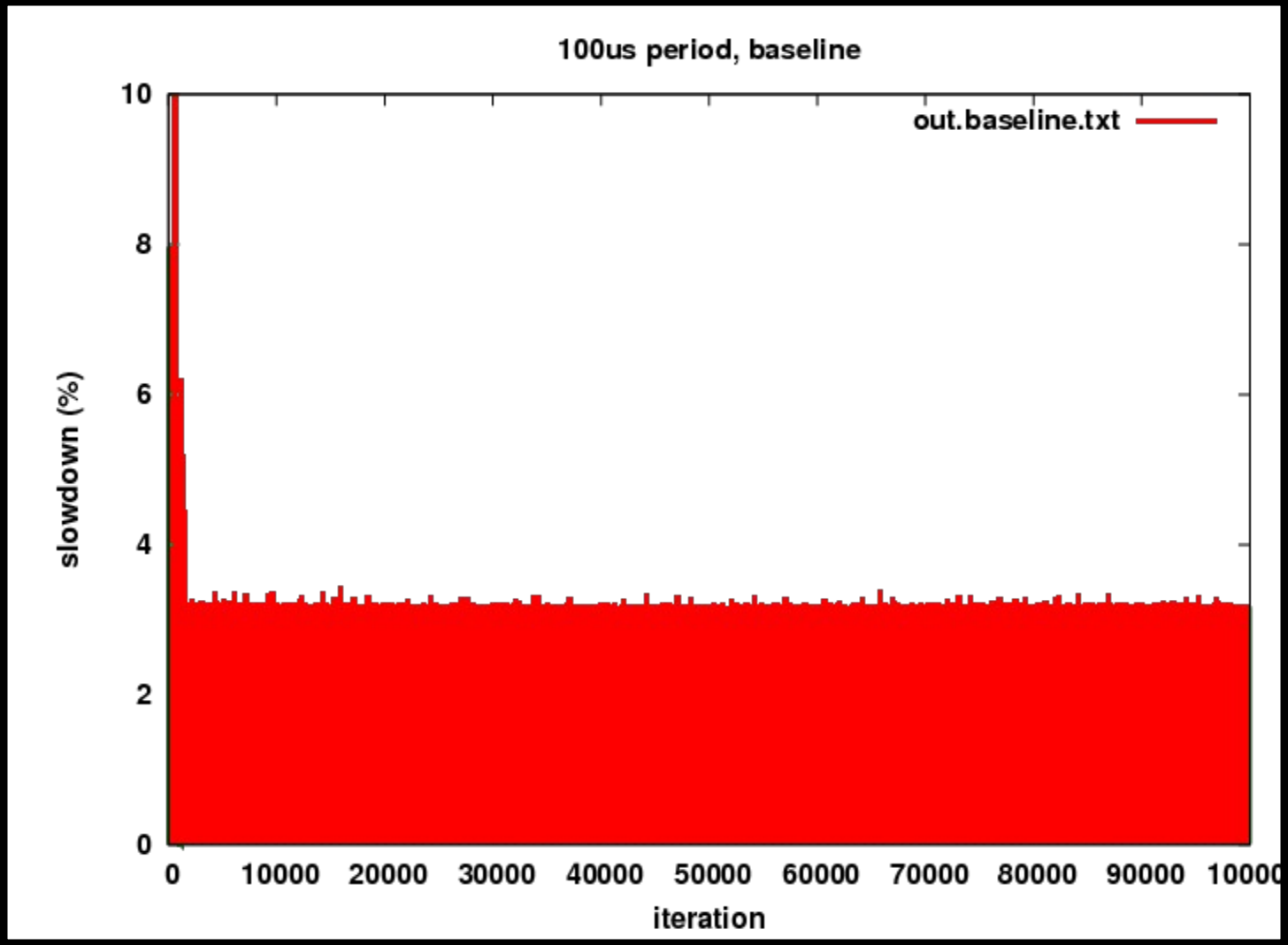
Yes, This Is A Real Problem For Some Workloads

Linux Kernel Is Now Out Of The Idle Loop's Way... So Can We Get It Out Of The Application's Way?

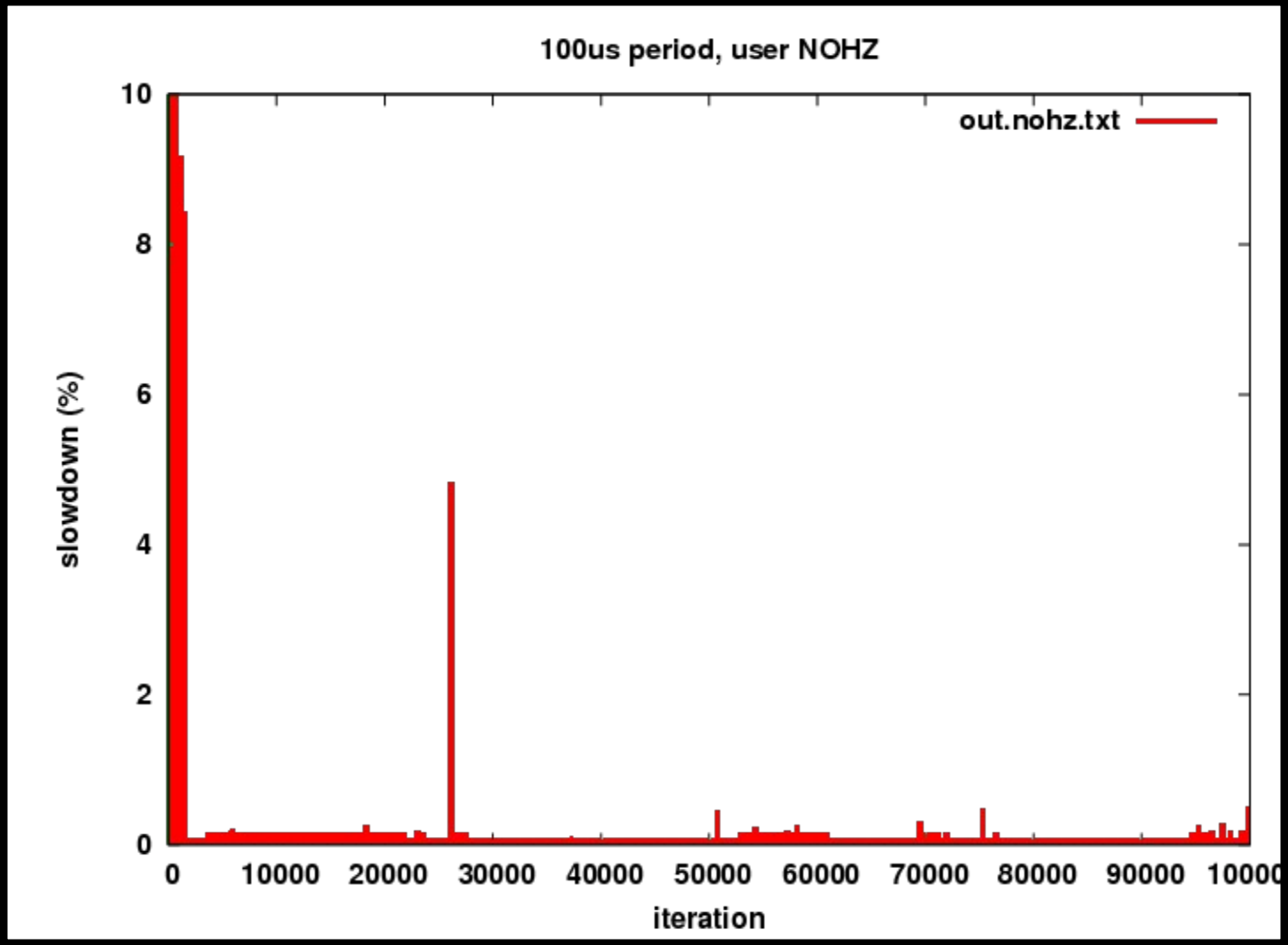
Josh Triplett's First Prototype, 2009

- 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)



Benchmark Results After (Anton Blanchard)



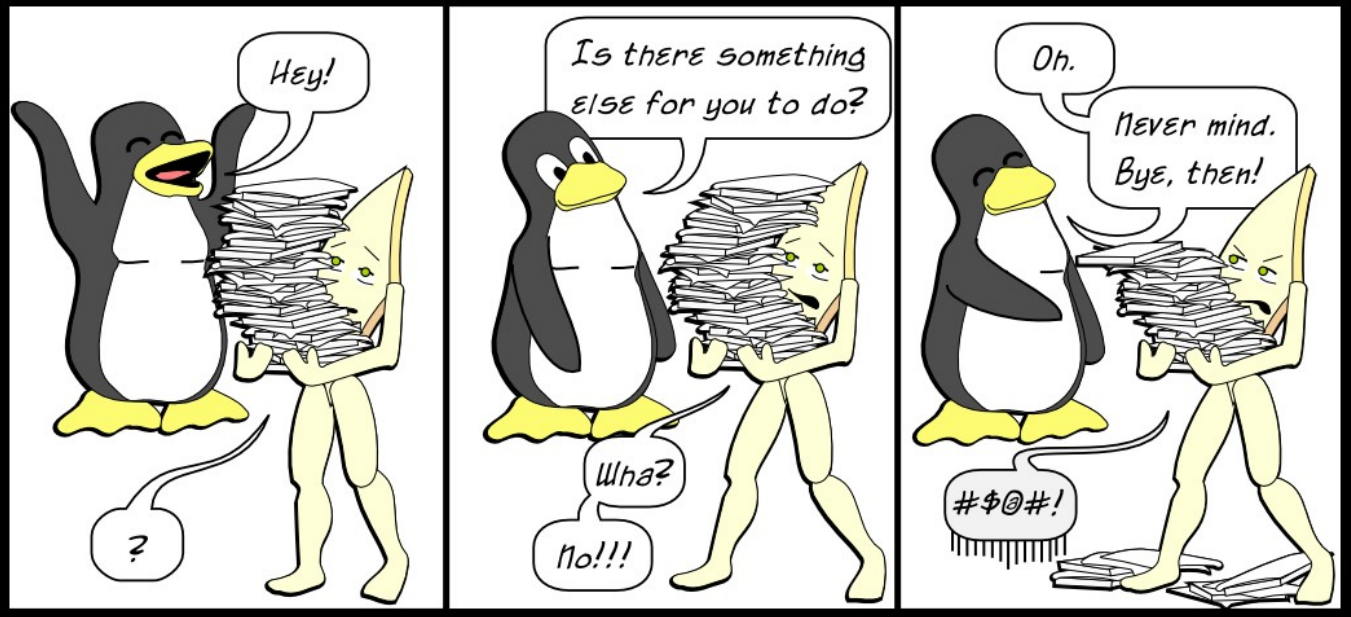
Well worth going after...

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)

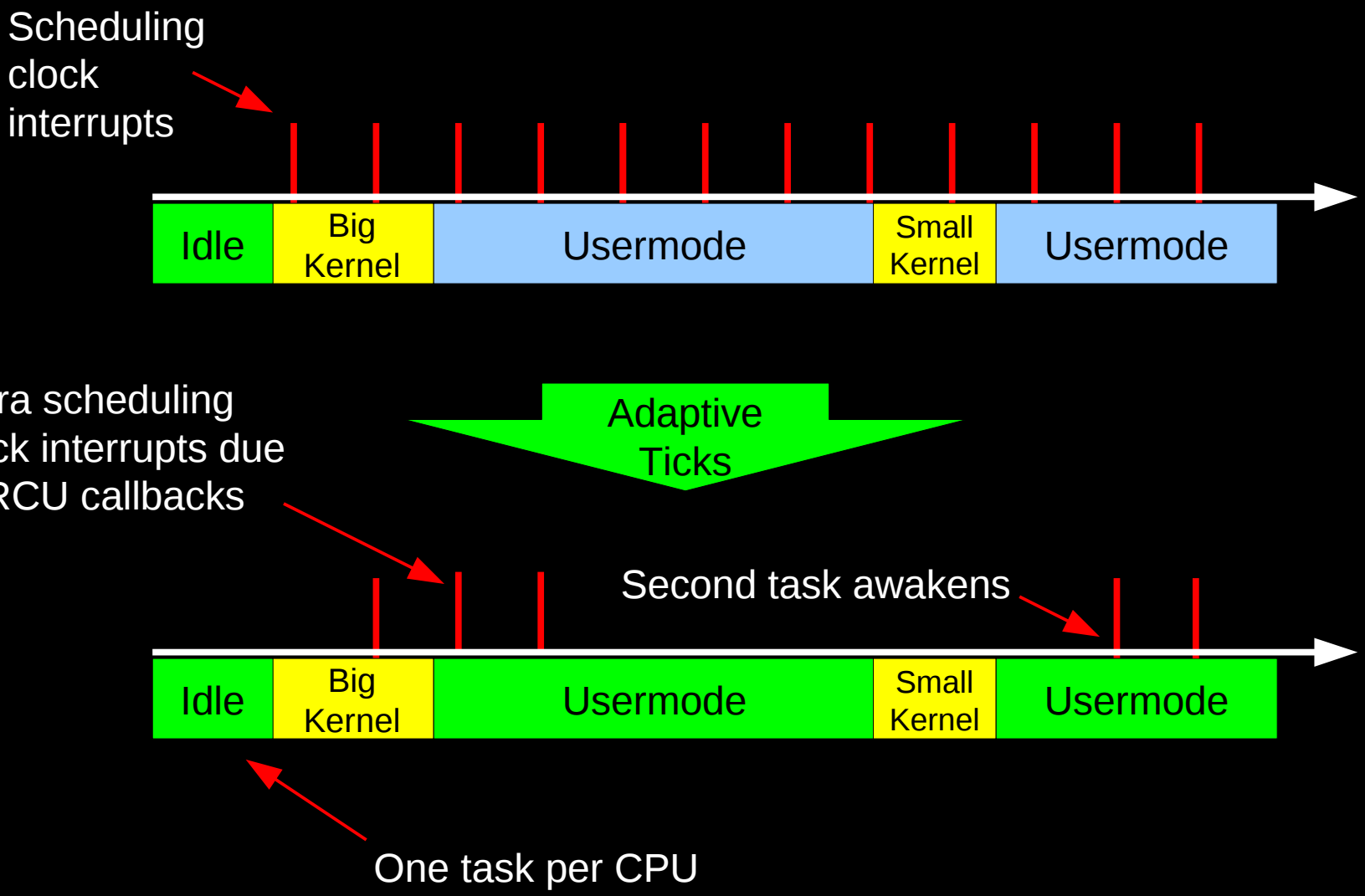
- User applications can monopolize CPU
  - But if there is only one runnable task, so what???
  - If new task awakens, interrupt the CPU, restart scheduling-clock interrrupts
  - In the meantime, we have an “adaptive ticks usermode” CPU
- No process accounting
  - Use delta-based accounting, based on 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-ticks usermode execution so that it ignores adaptive-ticks user-mode CPUs, similar to its handling of dyntick-ticks 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, with some teething pains:
  - CPU accounting bugs
  - Some configuration challenges
  - Bugs due to interactions with tracing
  - Many uses of perf disable adaptive ticks
  - Hard and soft lockup detectors can disable adaptive ticks
  - Unstable TSCs disable adaptive ticks
  - Fixes in the works... And probably more bugs as well! ;-)

How Well Does It Work?



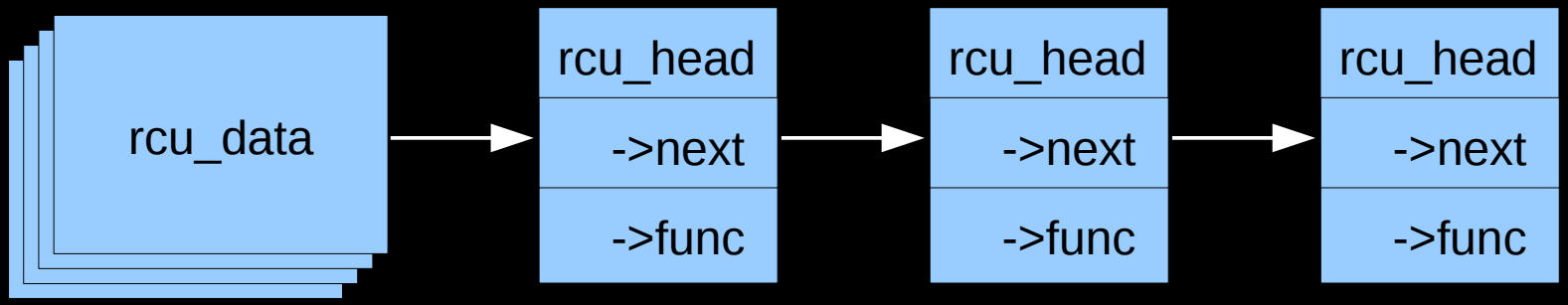
Other Than RCU, Looks Great!!!

- Need to fix RCU
- But first, what is RCU?

What Is RCU?

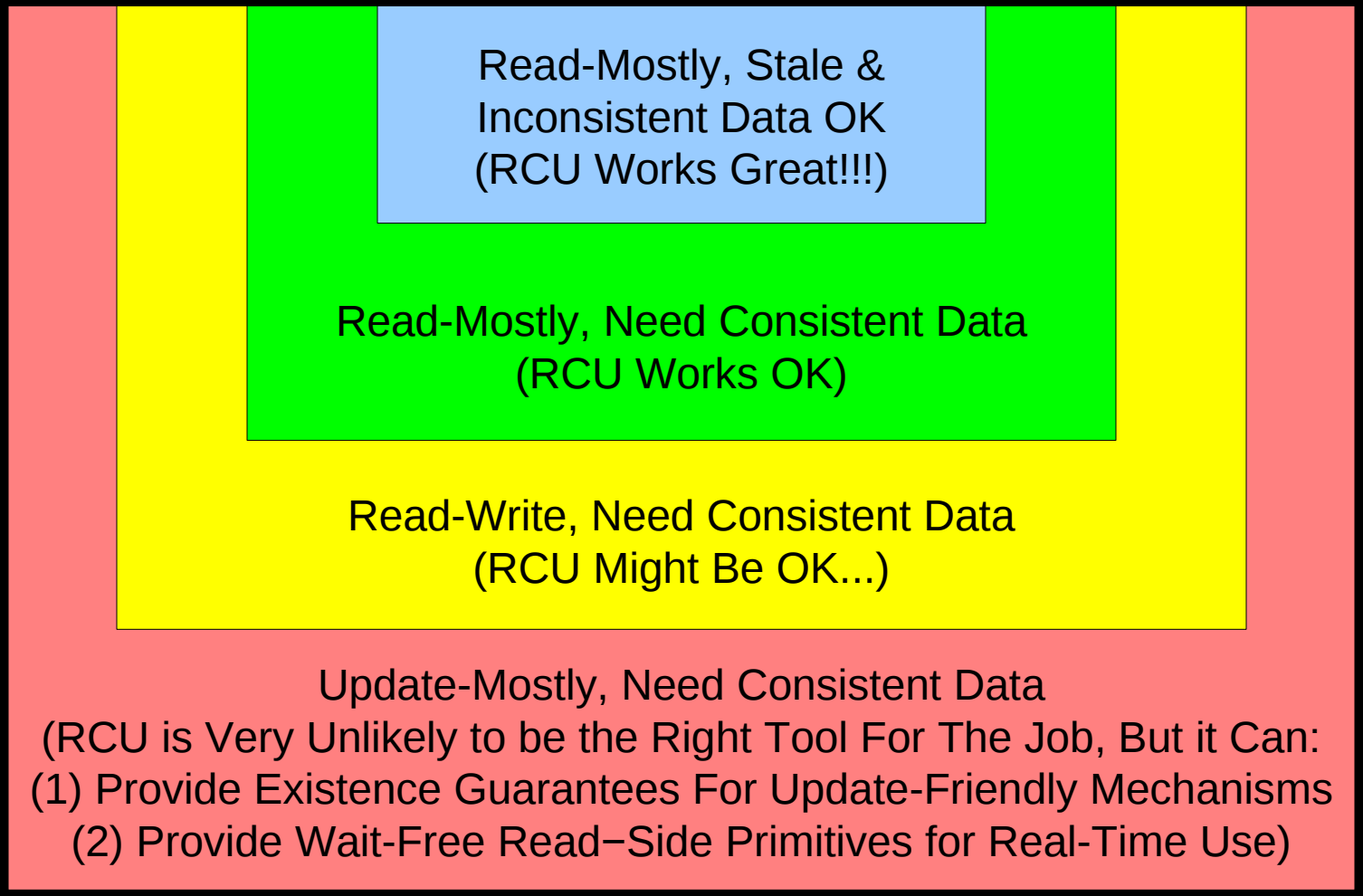
What Is RCU? (AKA Read-Copy Update)

- 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 (splat after 20 seconds) – but failing to defer long enough is fatal
  - RCU allows extremely fast & scalable read-side access to shared data



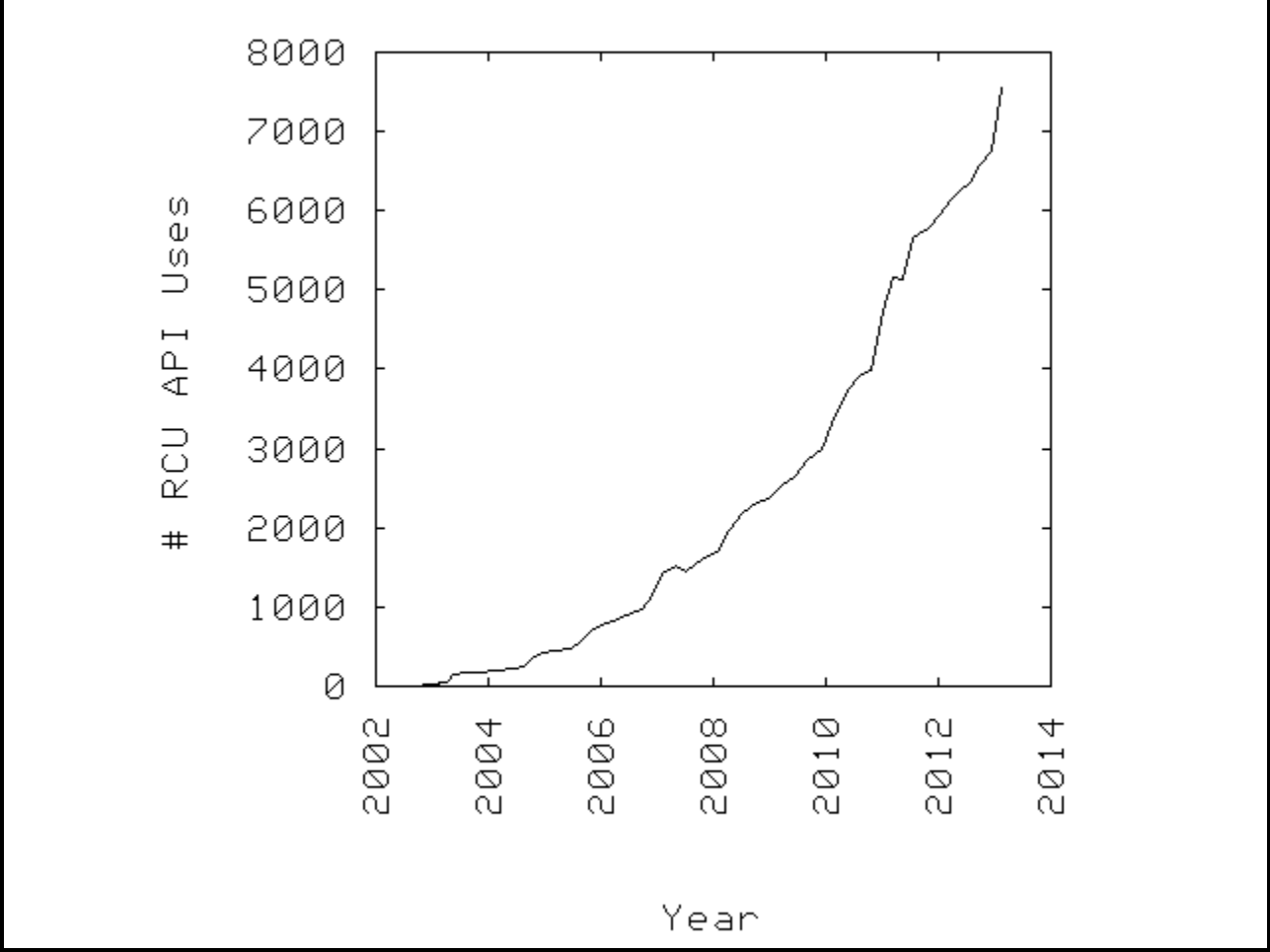
RCU:
Tapping The Awesome Power of Procrastination For Two Decades!!!

RCU Area of Applicability



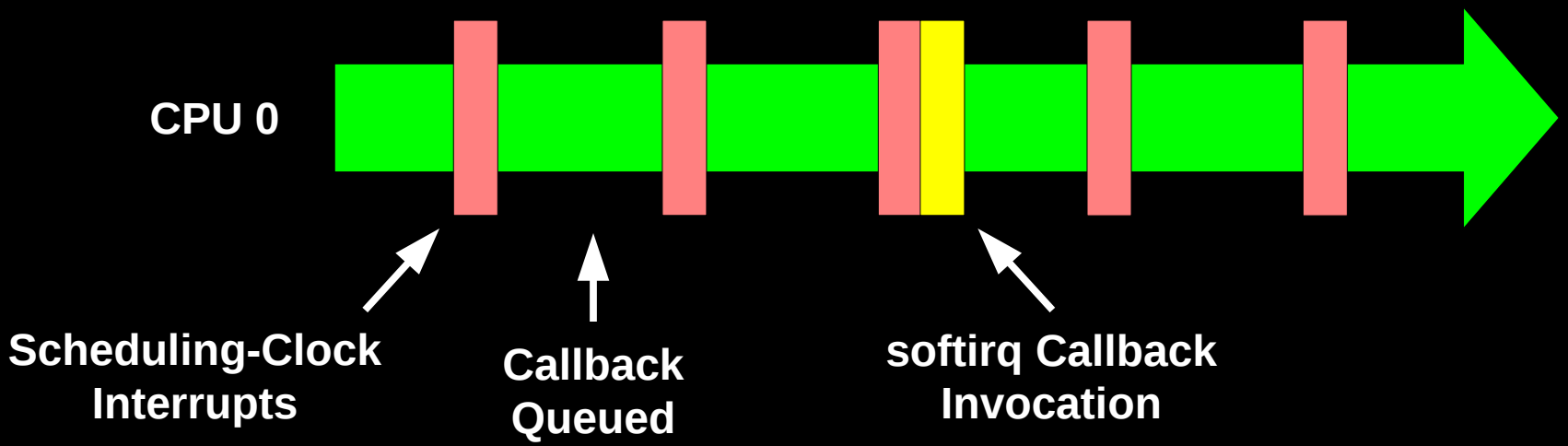
Use the right tool for the job!!!

Applicability To The Linux Kernel



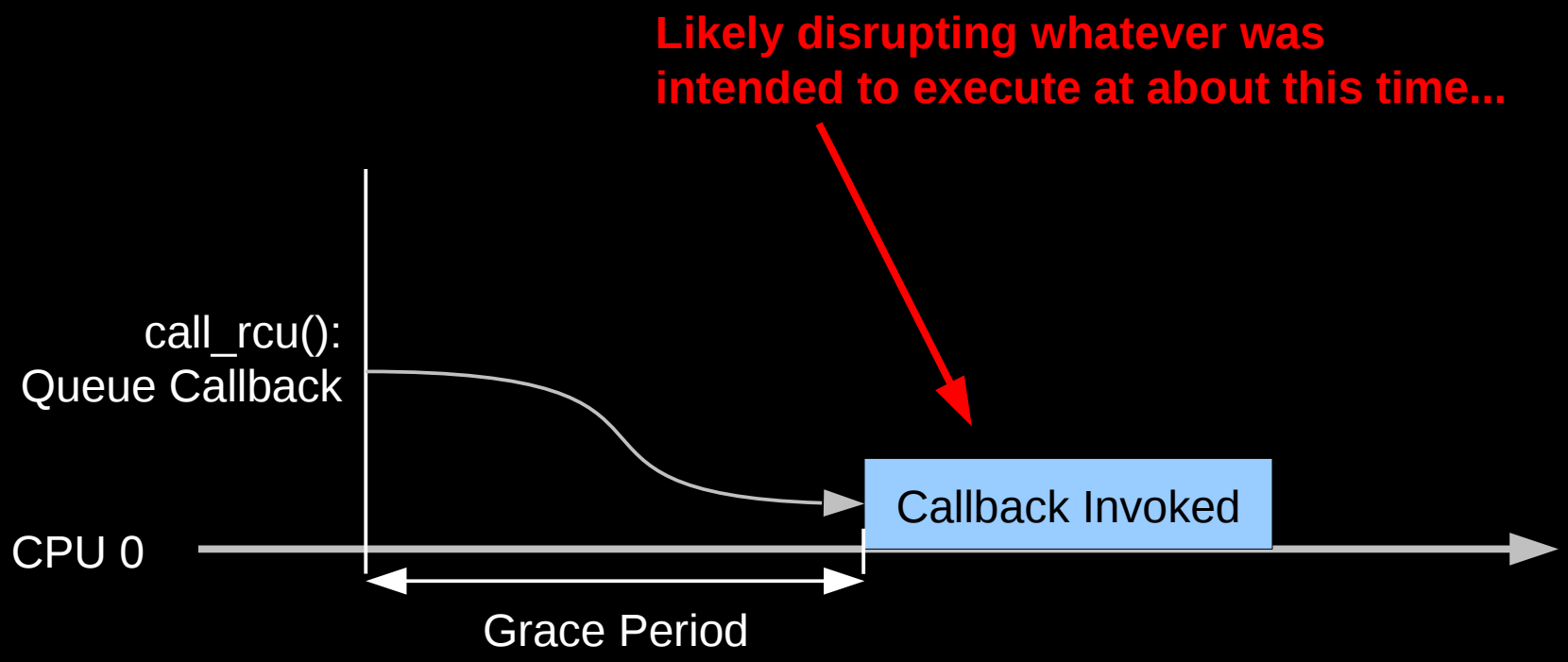
What Is RCU? (AKA Read-Copy Update)

- 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



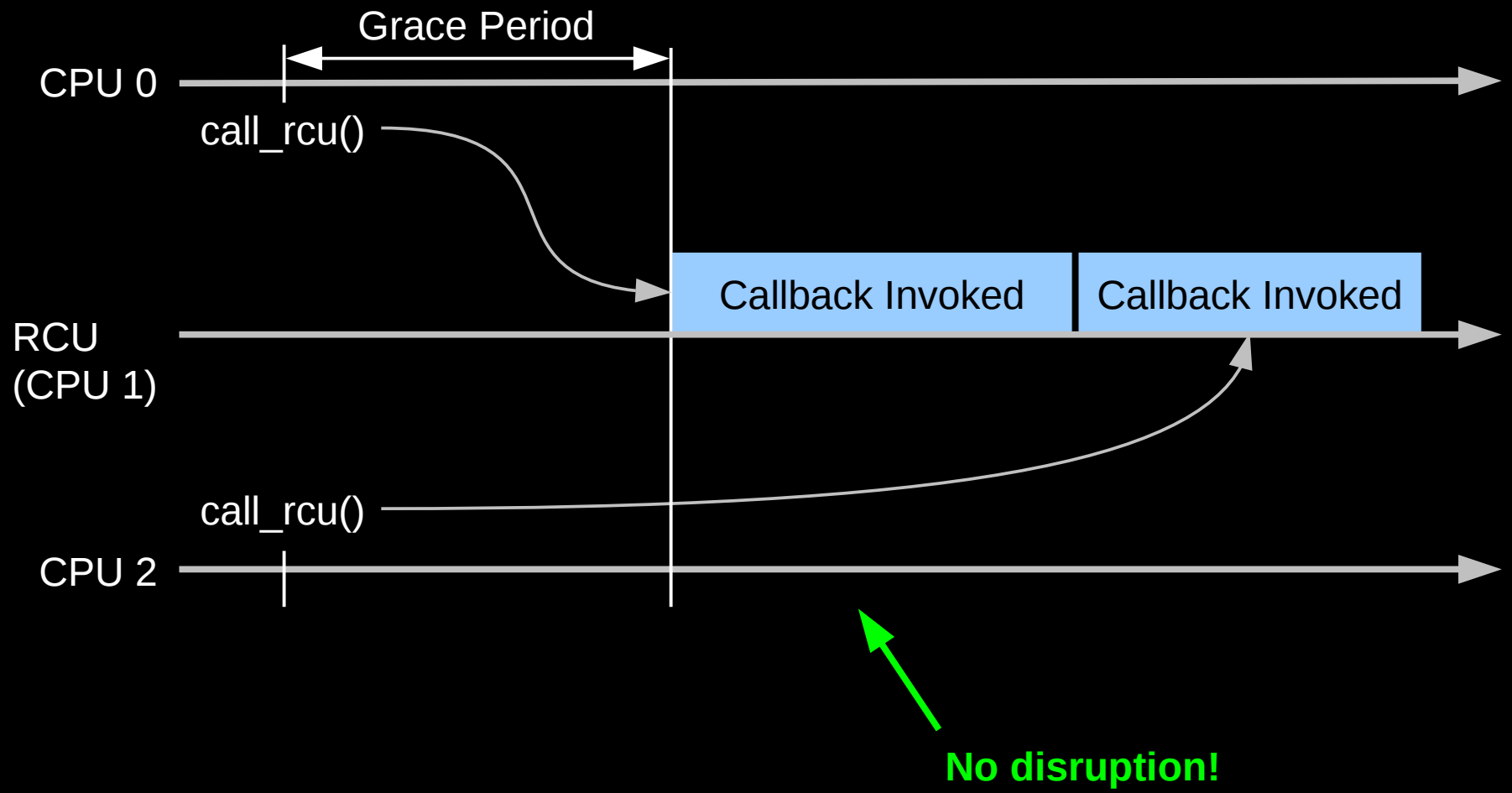
Procrastination's Dark Side

Procrastination's Dark Side: Eventually Must Do Work

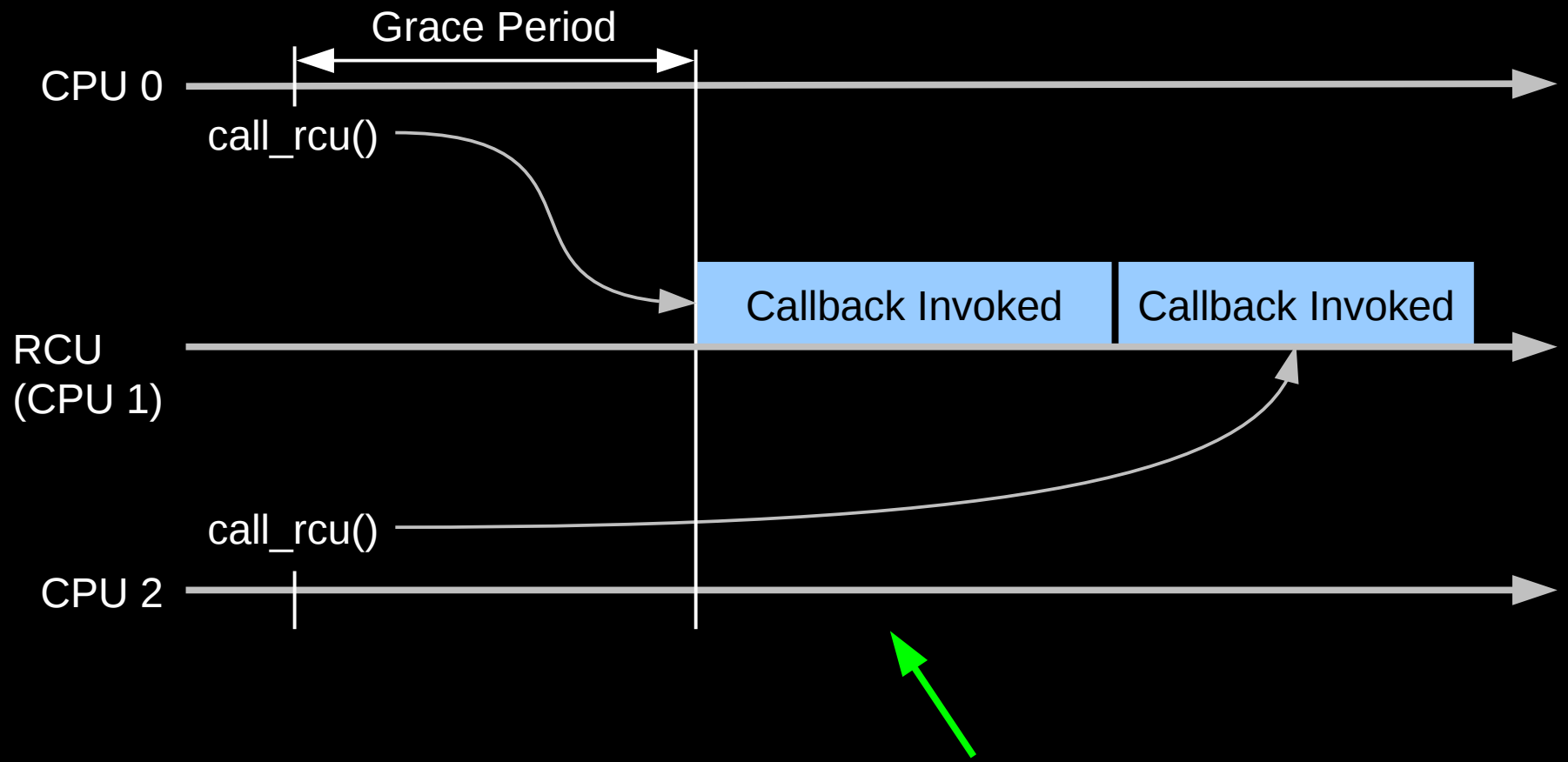


Why Not Offload RCU's Callbacks?

Offload RCU Callbacks: Houston/Korty Approach

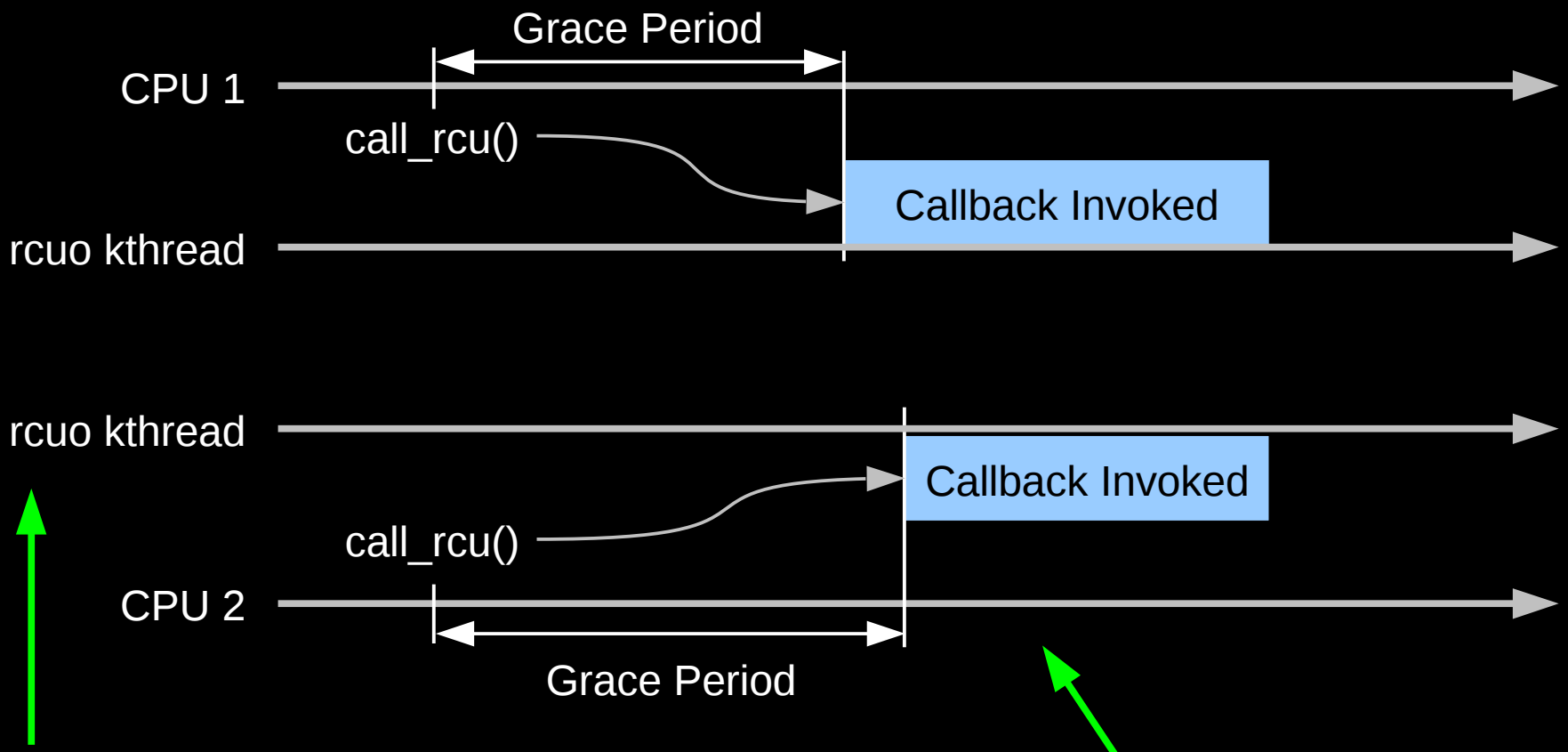


Offload RCU Callbacks: Houston/Korty Approach



No disruption!
(But also no scalability,
and Linux kernel must scale)

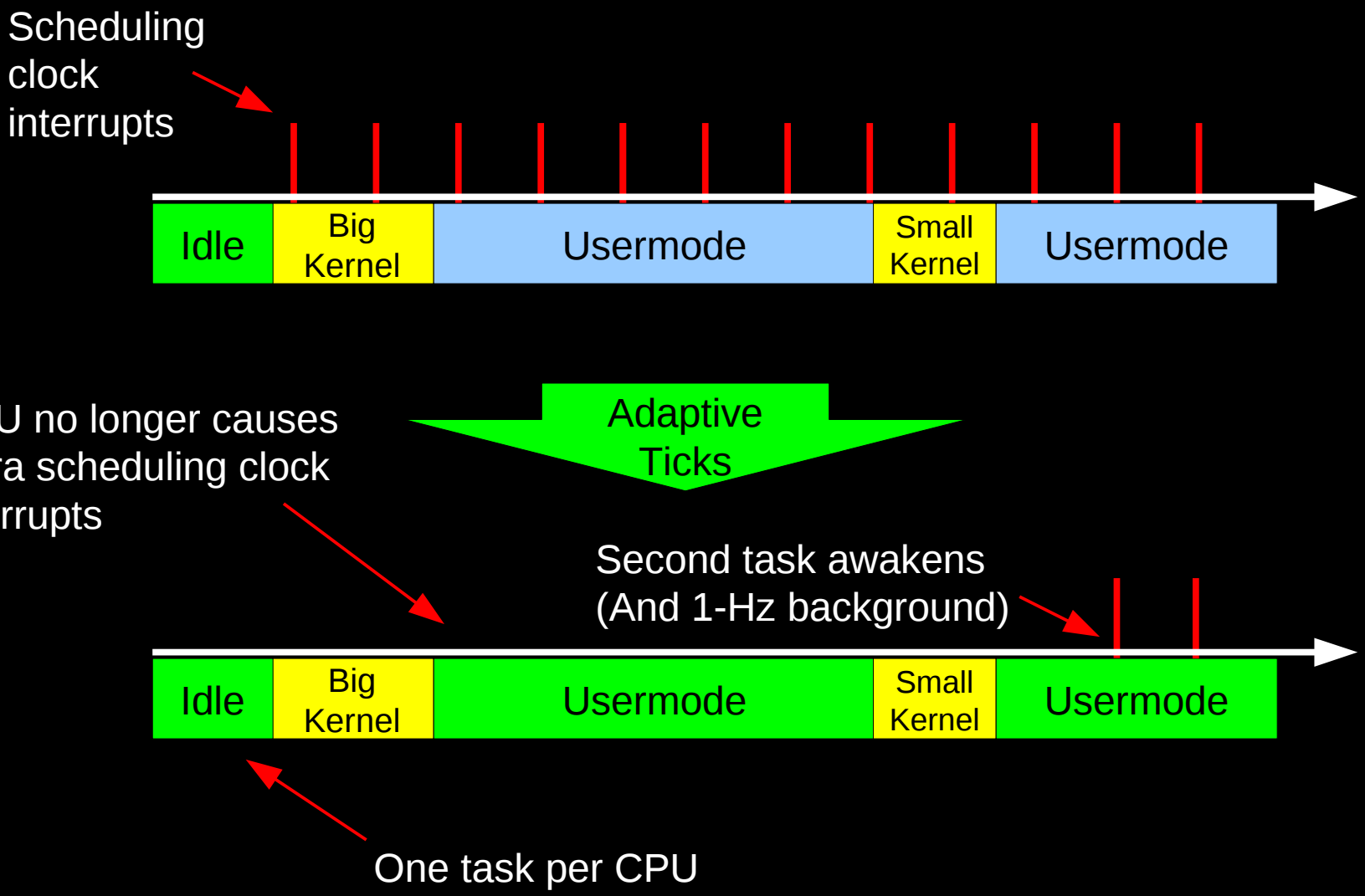
Scalable RCU Callback Offloading



Scheduler controls placement (or can place manually)

No disruption! Plus scalability!!!

Adaptive Ticks *And* Callback Offloading



Where To Run RCU Callbacks???

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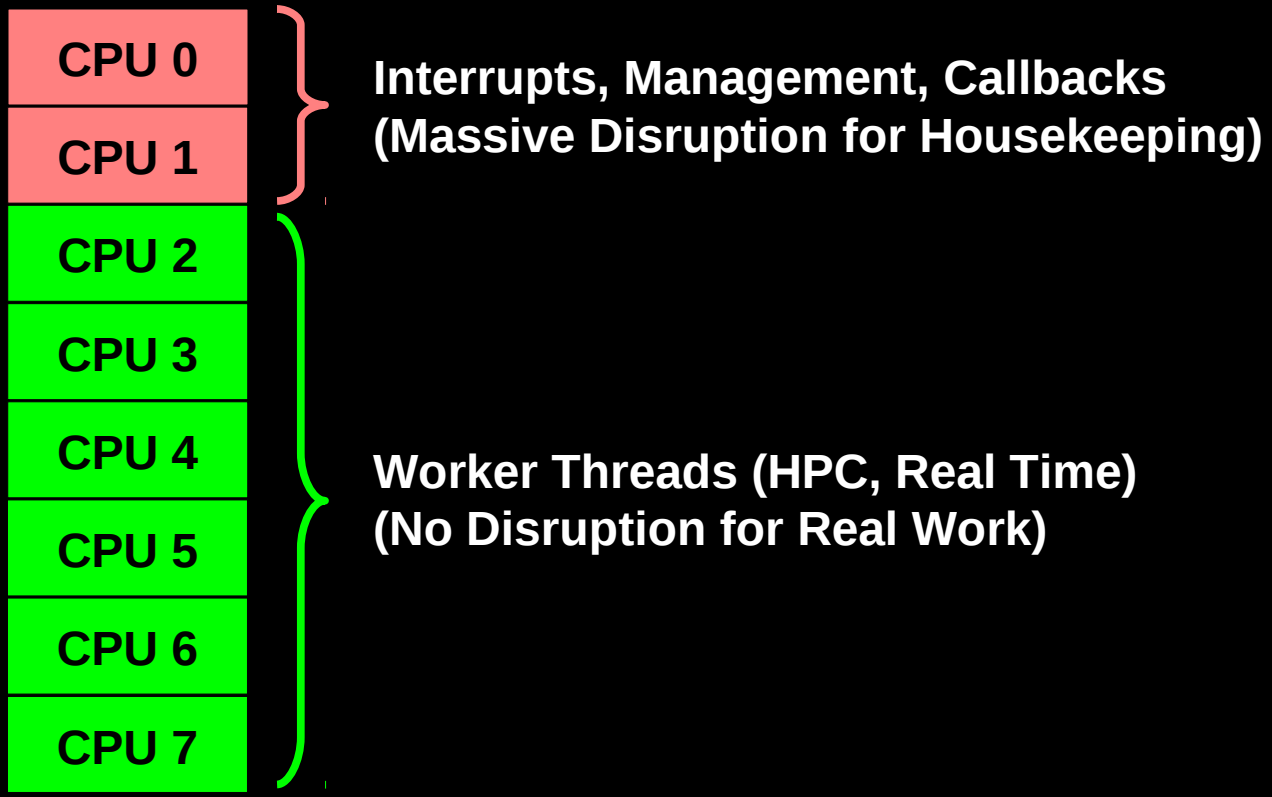


Exact Layout Depends on Workload

How Well Does It Work?

How Well Does It Work? Pretty good, but...

- Some shortcomings, as always:
  - Adaptive-ticks usermode slows user/kernel transitions slightly
    - Not a problem for computation-intensive workloads
  - One task per CPU for adaptive-ticks usermode execution
    - Also not a problem for many computation-intensive workloads
    - Could generalize: 1 SCHED_FIFO + N SCHED_OTHER, for example
  - Must reboot to reconfigure adaptive ticks and RCU callback offloading
  - Must configure interrupts and processes manually (see next slide)
  - Some remaining OS jitter sources (TLB, page faults, …)
    - Constrain workload to avoid these jitter sources
  - At least one CPU must keep scheduling-clock interrupt (timekeeping)
    - Even when all the CPUs are idle
  - RCU callback-offloading kthreads (rcuo) not priority boosted
    - Rely on configuration restrictions leaving idle time on housekeeping CPUs
    - Or run rcu0 kthreads at real-time priority (not for the faint of heart!)
  - 1-Hz “background” tick needed for load statistics and balancing
  - Work in progress: There are probably still a few bugs!

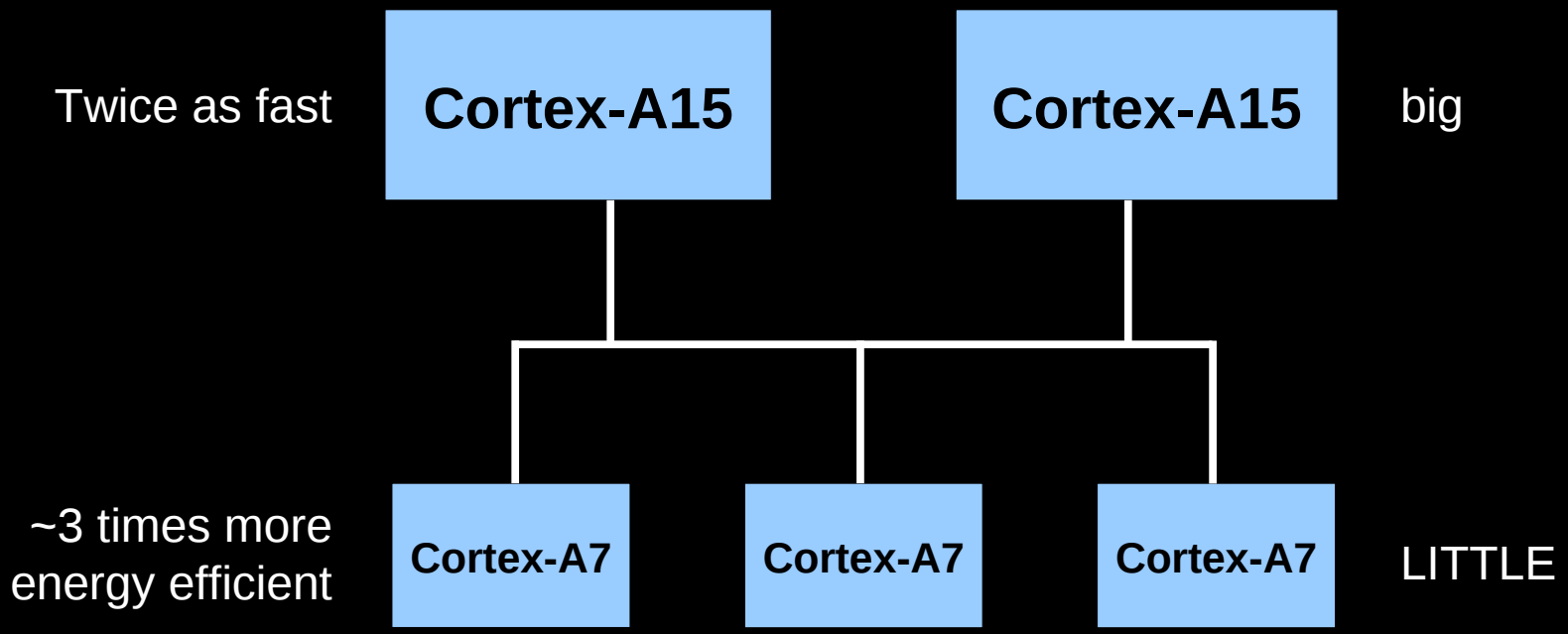
Removing Other Sources of Disturbance

- 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: Use huge pages!!!
- More information: Documentation/kernel-per-CPU-kthreads.txt (in -tip)

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???

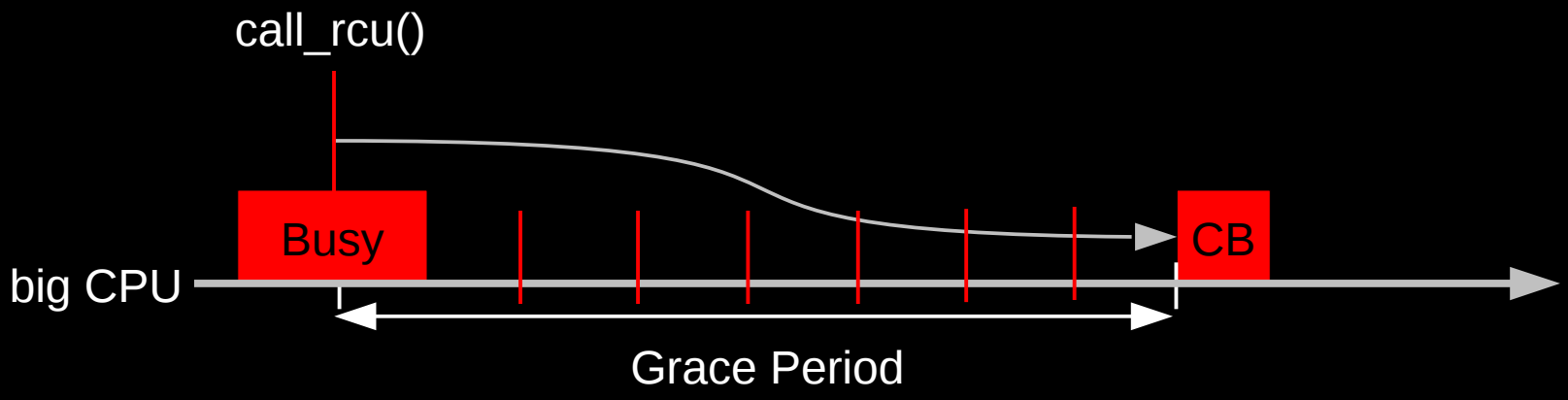
ARM big.LITTLE Architecture



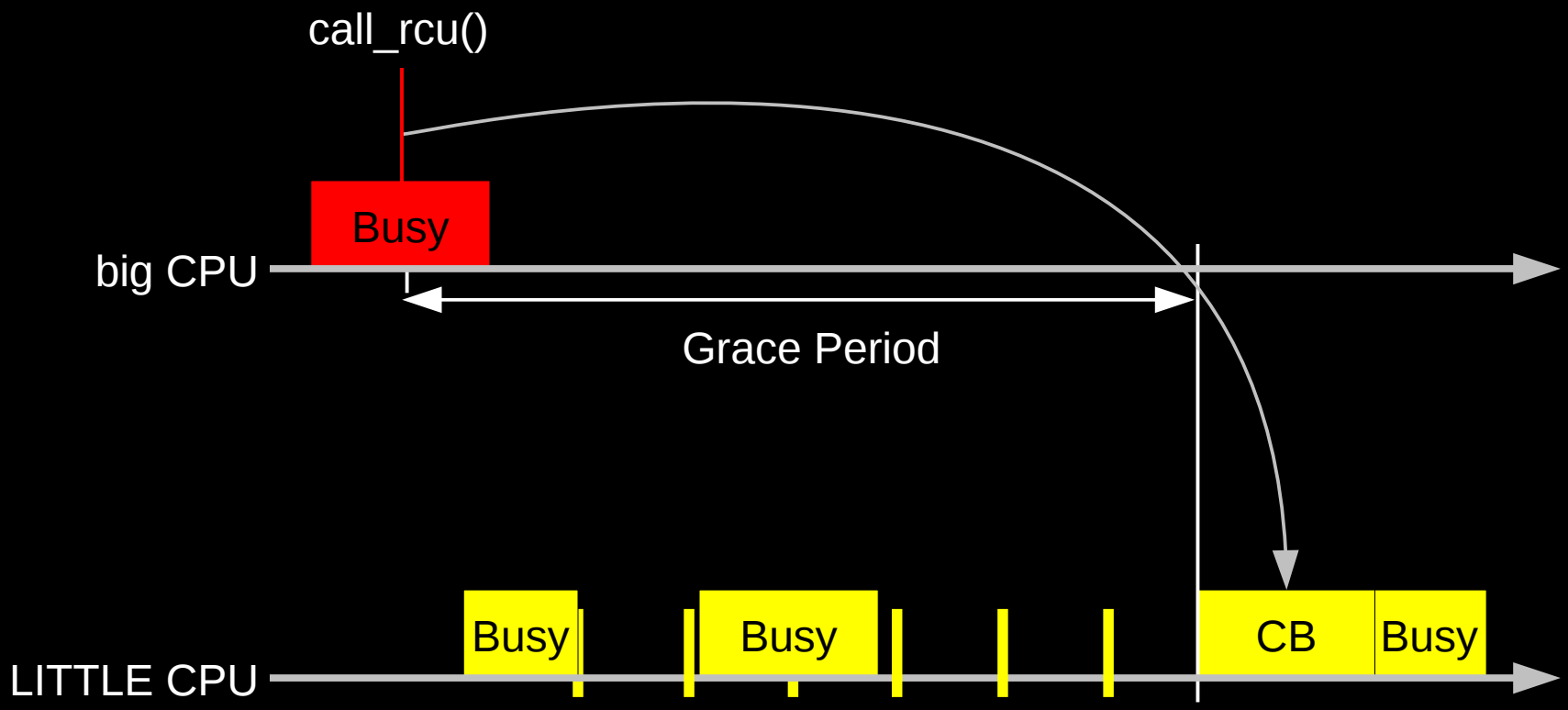
ARM big.LITTLE Architecture: Strategy

- 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

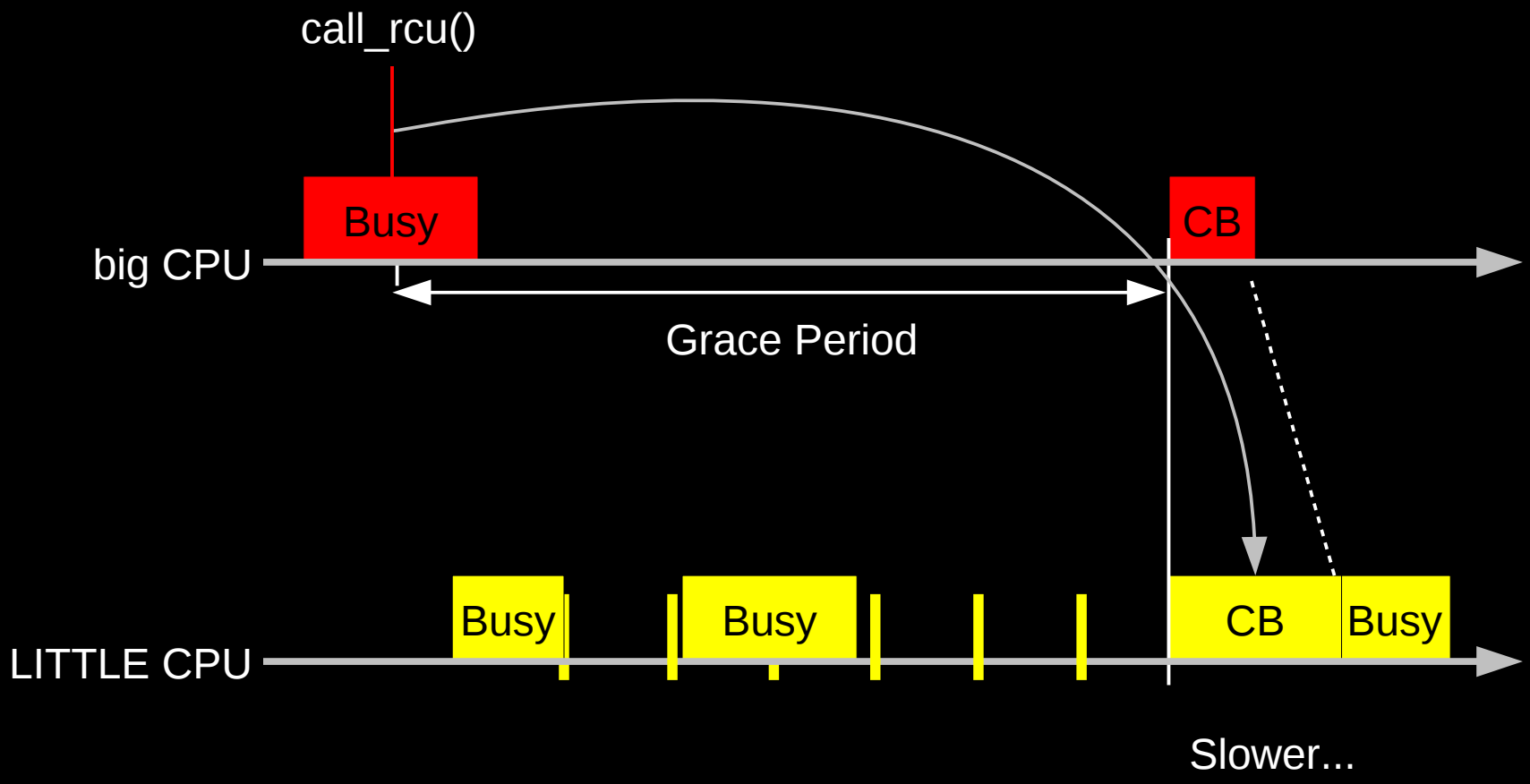
ARM big.LITTLE Without RCU Callback Offloading



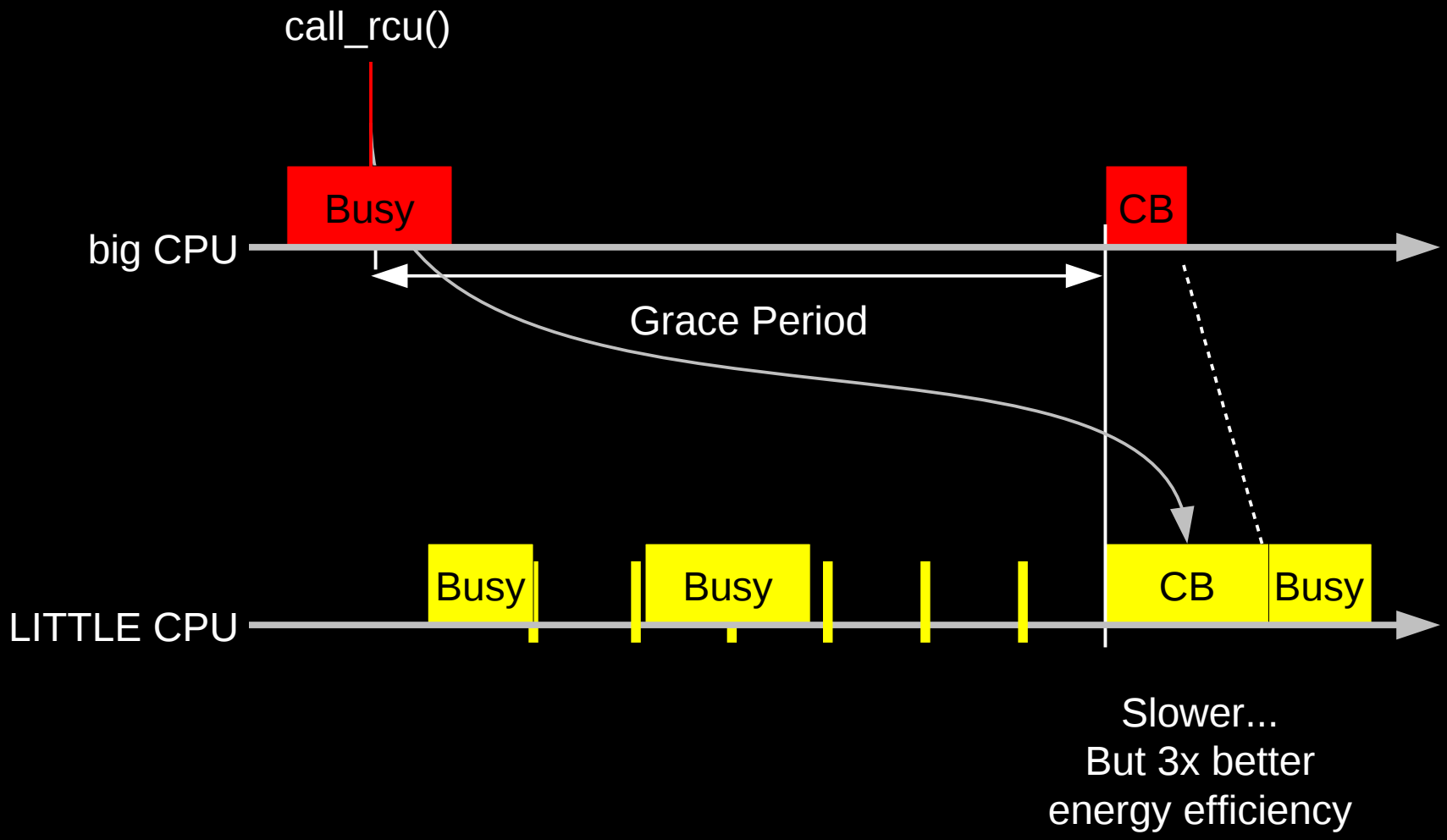
ARM big.LITTLE With RCU Callback Offloading



ARM big.LITTLE With RCU Callback Offloading



ARM big.LITTLE With RCU Callback Offloading



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%
- Poster presentation accepted into HOTPAR'13

To Probe More Deeply Into Adaptive Ticks

- Documentation/timers/NO_HZ.txt
- (Nearly) full tickless operation in 3.10
  - http://lwn.net/Articles/549580/
- “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)
  - http://www.rdrop.com/users/paulmck/realtime/paper/RTLWS2012occcRT.2012.10.19e.pdf
    - Slides 31-32
- “TODO”
  - https://github.com/fweisbec/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)
  - http://www.rdrop.com/users/paulmck/realtime/paper/RCUbattery.2013.01.30b.LCA.pdf
- "Relocating RCU callbacks" by Jon Corbet
  - http://lwn.net/Articles/522262/
- "What Is New In RCU for Real Time" (RTLWS 2012)
  - http://www.rdrop.com/users/paulmck/realtime/paper/RTLWS2012occcRT.2012.10.19e.pdf
    - Slides 21-on
- "Getting RCU Further Out of the Way" (Plumbers 2012)
  - http://www.rdrop.com/users/paulmck/realtime/paper/nocb.2012.08.31a.pdf
- "Cleaning Up Linux's CPU Hotplug For Real Time and Energy Management" (ECRTS 2012)
  - http://www.rdrop.com/users/paulmck/realtime/paper/hotplug-ecrts.2012.06.11a.pdf

Configuration Cheat Sheet (Subject to Change!)

- CONFIG_NO_HZ_FULL=y Kconfig: enable adaptive ticks
  - Implies dyntick-idle mode (specify separately via CONFIG_NO_HZ_IDLE=y)
  - Specify which CPUs at compile time: CONFIG_NO_HZ_FULL_ALL=y
    - But boot CPU is excluded, used as timekeeping CPU
  - "full_nohz=" boot parameter: Specify adaptive-tick CPUs, overriding build-time Kconfig
    - "full_nohz=1,3-7" says CPUs 1, 3, 4, 5, 6, and 7 are adaptive-tick
    - Omitting "full_nohz=": No CPUs are adaptive-tick unless CONFIG_NO_HZ_FULL_ALL=y
    - Boot CPU cannot be adaptive-ticks, it will be used as timekeeping CPU regardless
  - PMQOS to reduce idle-to-nonidle latency
    - X86 can also use "idle=mwait" and "idle=poll" boot parameters, but note that these can cause thermal problems and degrade energy efficiency, especially "idle=poll"
- CONFIG_RCU_NOCB_CPU=y Kconfig: enable RCU offload
  - Specify which CPUs to offload at build time:
    - RCU_NOCB_CPU_NONE=y Kconfig: No offloaded CPUs (specify at boot time)
    - RCU_NOCB_CPU_ZERO=y Kconfig: Offload CPU 0 (intended for randconfig testing)
    - RCU_NOCB_CPU_ALL=y Kconfig: Offload all CPUs
  - "rcu_nocbs=" boot parameter: Specify additional offloaded CPUs
- How-to info: Documentation/timers/NO_HZ.txt
- Available in 3.10

Summary

- General-purpose OS or bare-metal performance?
  - Why not both?
  - Work in progress gets us very close for CPU-bound workloads:
    - Adaptive ticks userspace execution (early version in mainline)
    - RCU callback offloading (version two in mainline)
    - Interrupt, process, daemon, and kthread affinity
    - Timer offloading
  - Some restrictions:
    - Need to reserve CPU(s) for housekeeping; 1-Hz residual tick
    - Adaptive-ticks and RCU-callback-offloaded CPUs specified at boot time
    - One task per CPU for adaptive-ticks usermode execution
    - Global TLB-flush IPIs, cache misses, and TLB misses are still with us
  - Serendipity: Energy-efficiency benefits as well!

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    - Global TLB-flush IPIs, cache misses, and TLB misses are still with us
  - Serendipity: Energy-efficiency benefits as well!
- Extending Linux's reach farther into extreme computing!!!

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