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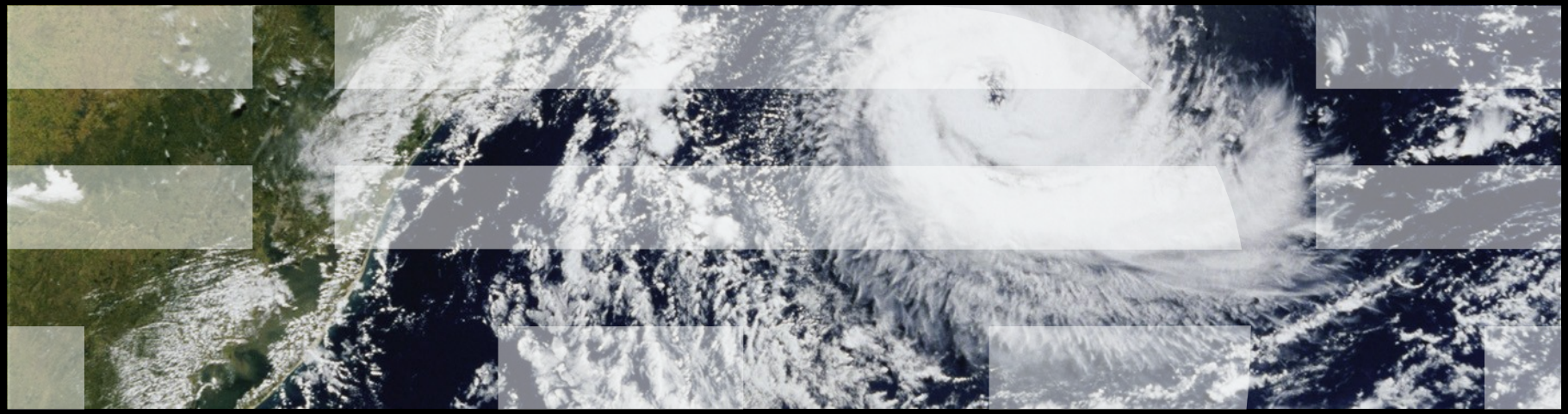
Member, IBM Academy of Technology
linux.conf.au Kernel Miniconf, January 22, 2018

Decoding Those Inscrutable RCU CPU Stall Warnings

“They are for your own good! Honest!!!”

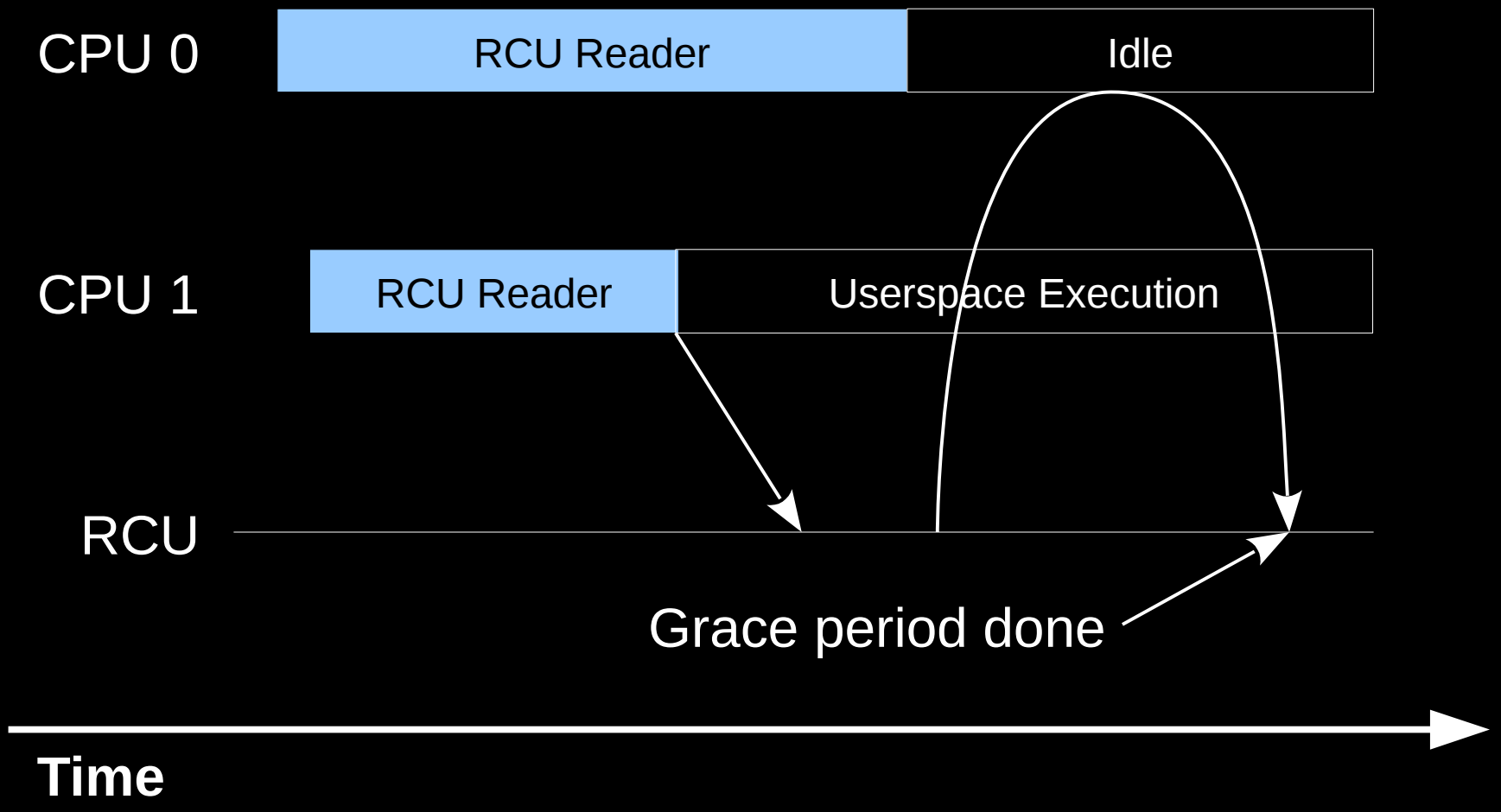


Overview

- Why does RCU emit CPU stall warnings?
- Decoding CPU stall warnings
- What causes CPU stalls?
- Obligatory war stories
- Summary

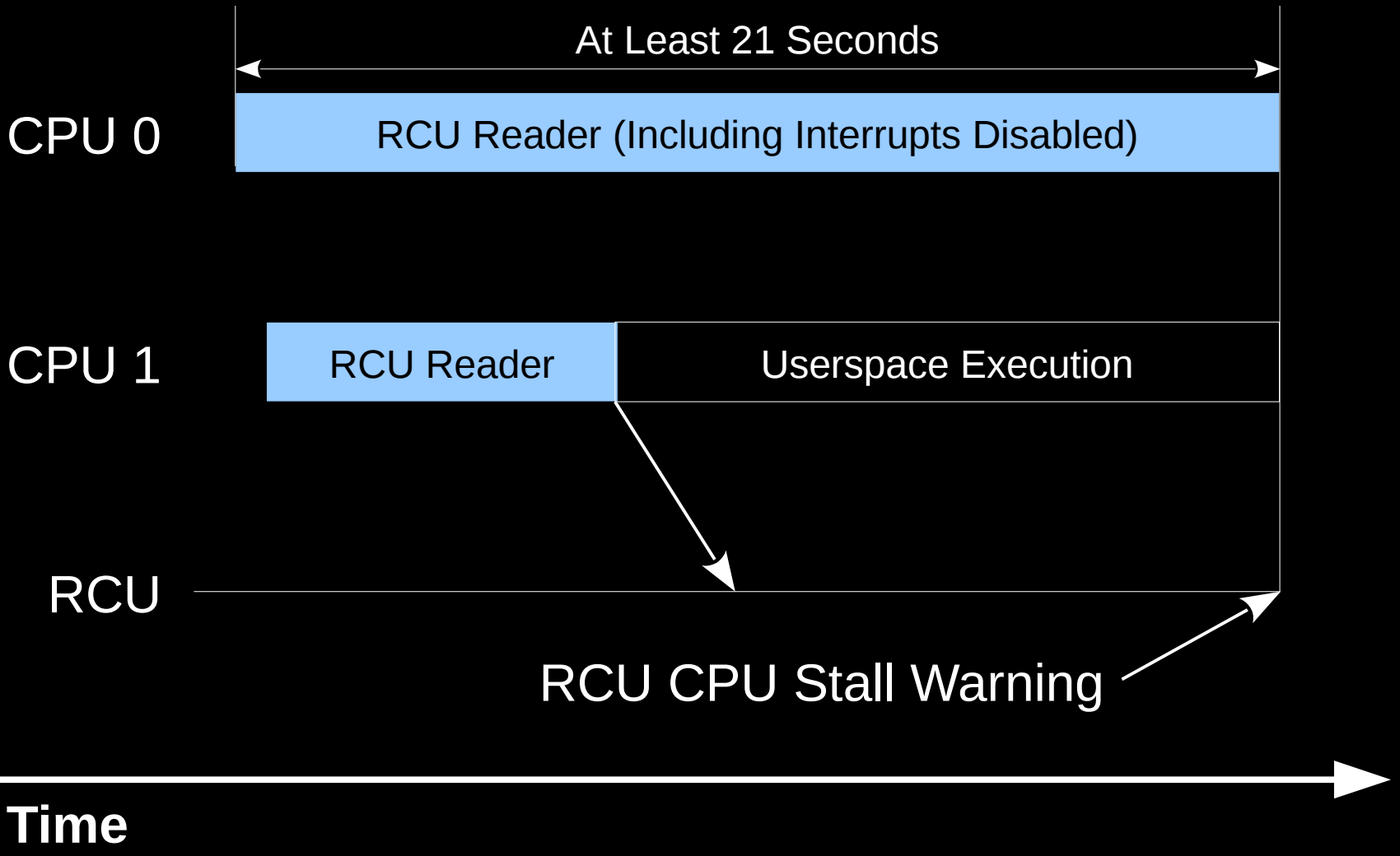
Why Does RCU Emit CPU Stall Warnings?

RCU Mostly Doesn't Emit CPU Stall Warnings!!!



More complexity for CONFIG_PREEMPT=y kernels

When Does RCU Emit CPU Stall Warnings?
When a CPU or Task Appears to be in Deep Trouble!!!



An RCU CPU Stall Warning Normally Indicates Trouble Outside of RCU

But What if I Don't Want CPU Stall Warnings???

But What if I Don't Want CPU Stall Warnings???

- Boot with rcupdate.rcu_cpu_stall_suppress=1
- Boot with rcupdate.rcu_cpu_stall_timeout=NN (in seconds)
  - Or build with CONFIG_RCU_CPU_STALL_TIMEOUT=NN
  - 3 <= N <= 300, in seconds
- Why would you want to suppress CPU stall warnings?
  - Slow embedded system tested on faster development system
    - Increase timeout on slow embedded system (or decrease during test)
  - Throughput-based rip-and-replace cloud-computing environment
  - Embedded production environment where console output is ignored
    - Suppress warnings entirely
- But if response time matters, you care about CPU stalls
  - Especially during development and testing

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  - Embedded production environment where console output is ignored
    - Suppress warnings entirely
- But if response time matters, you care about CPU stalls
  - Especially during development and testing

But you might be suppressing real errors!!!

Decoding CPU Stall Warnings

Example RCU CPU Stall Warning Splat (First Format)

```
INFO: rcu_sched detected stalls on CPUs/tasks:
        0-...0: (1 GPs behind) idle=bf2/140000000000000/0 softirq=554/555 fqs=6754
        (detected by 1, t=21003 jiffies, g=-154, c=-155, q=120339)
Sending NMI from CPU 1 to CPUs 0:
NMI backtrace for cpu 0
CPU: 0 PID: 773 Comm: rcu_torture_sta Not tainted 4.13.0-rc2+ #1
Hardware name: QEMU Standard PC (i440FX + PIIX, 1996), BIOS Bochs 01/01/2011
task: ffff93f7ddd172c0 task.stack: ffff95a3417f4000
RIP: 0010:get_seconds+0xc/0x10
RSP: 0000:ffff95a3417f7ef0 EFLAGS: 00000097
RAX: 0000000059a853e2 RBX: 0000000059a853e6 RCX: ffffffff8bc45d98
RDX: 0000000000000001 RSI: 0000000000000092 RDI: ffffffff8cf7f34c
RBP: ffff95a3417f7f00 R08: 00000000fffffffe R09: 000000000000060e
R10: 0000000000000005 R11: 000000000000000a R12: ffff93f7ddfae100
R13: ffff95a3400d7cf0 R14: 0000000000000000 R15: ffff93f7ddd172c0
FS:  0000000000000000(0000) GS:ffff93f7dfc00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 0000000080050033
CR2: 0000000000000000 CR3: 0000000019a0a000 CR4: 00000000000006f0
Call Trace:
 ? rcu_torture_stall+0xcb/0x140
 kthread+0x104/0x140
 ? rcu_torture_stats+0x70/0x70
 ? kthread_park+0x60/0x60
 ret_from_fork+0x22/0x30
```

Identifying an RCU CPU Stall Warning (First Format)

```
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task: ffff93f7ddd172c0 task.stack: ffff95a3417f4000
RIP: 0010:get_seconds+0xc/0x10
RSP: 0000:ffff95a3417f7ef0 EFLAGS: 00000007
RAX:
RDX:
RBP: ffff95a3417f7f00 R08: 00000000fffffffe R09: 000000000000060e
R10: 0000000000000005 R11: 000000000000000a R12: ffff93f7ddfae100
R13: ffff95a3400d7cf0 R14: 0000000000000000 R15: ffff93f7ddd172c0
FS:  0000000000000000(0000) GS:ffff93f7dfc00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 0000000080050033
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```
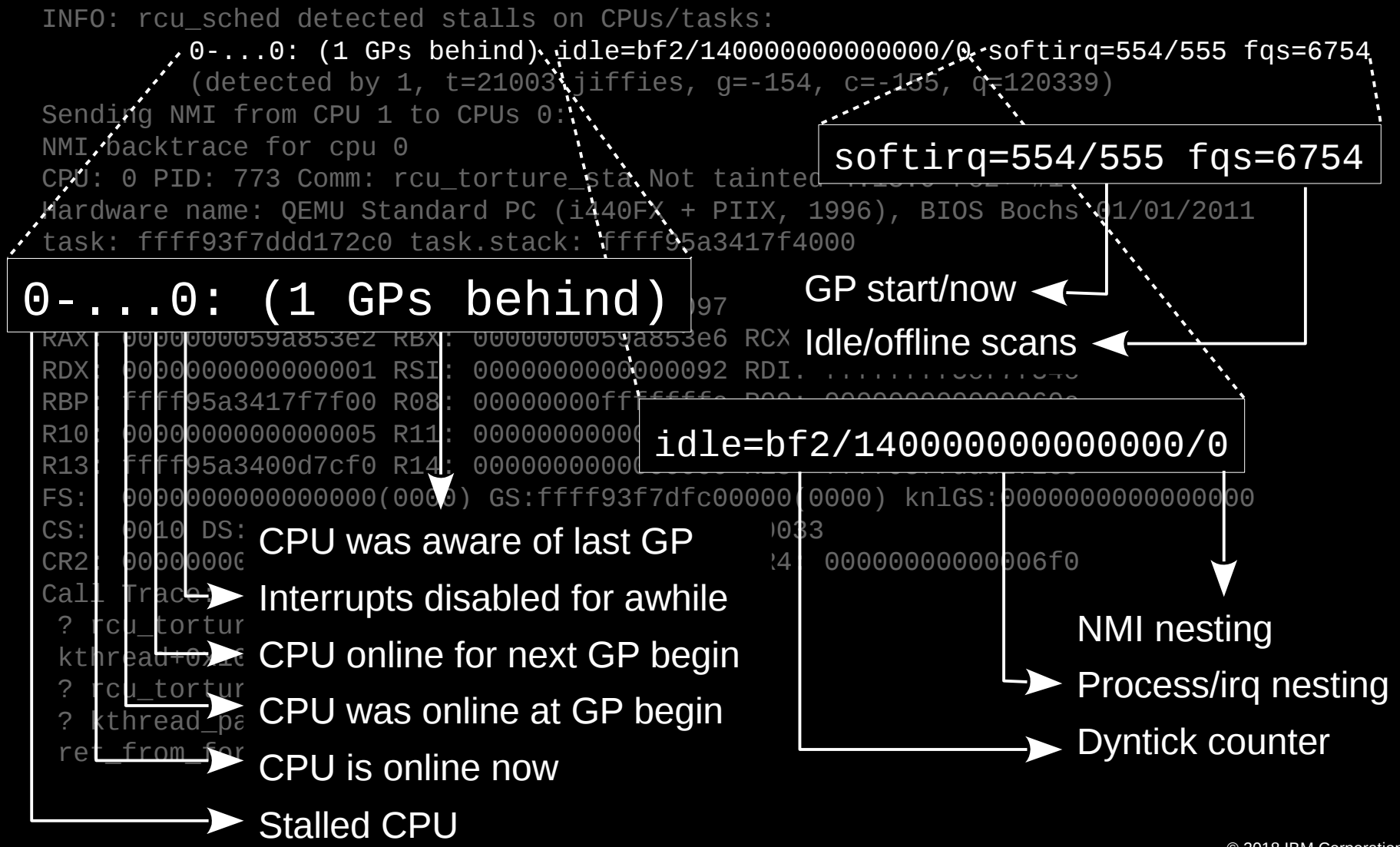
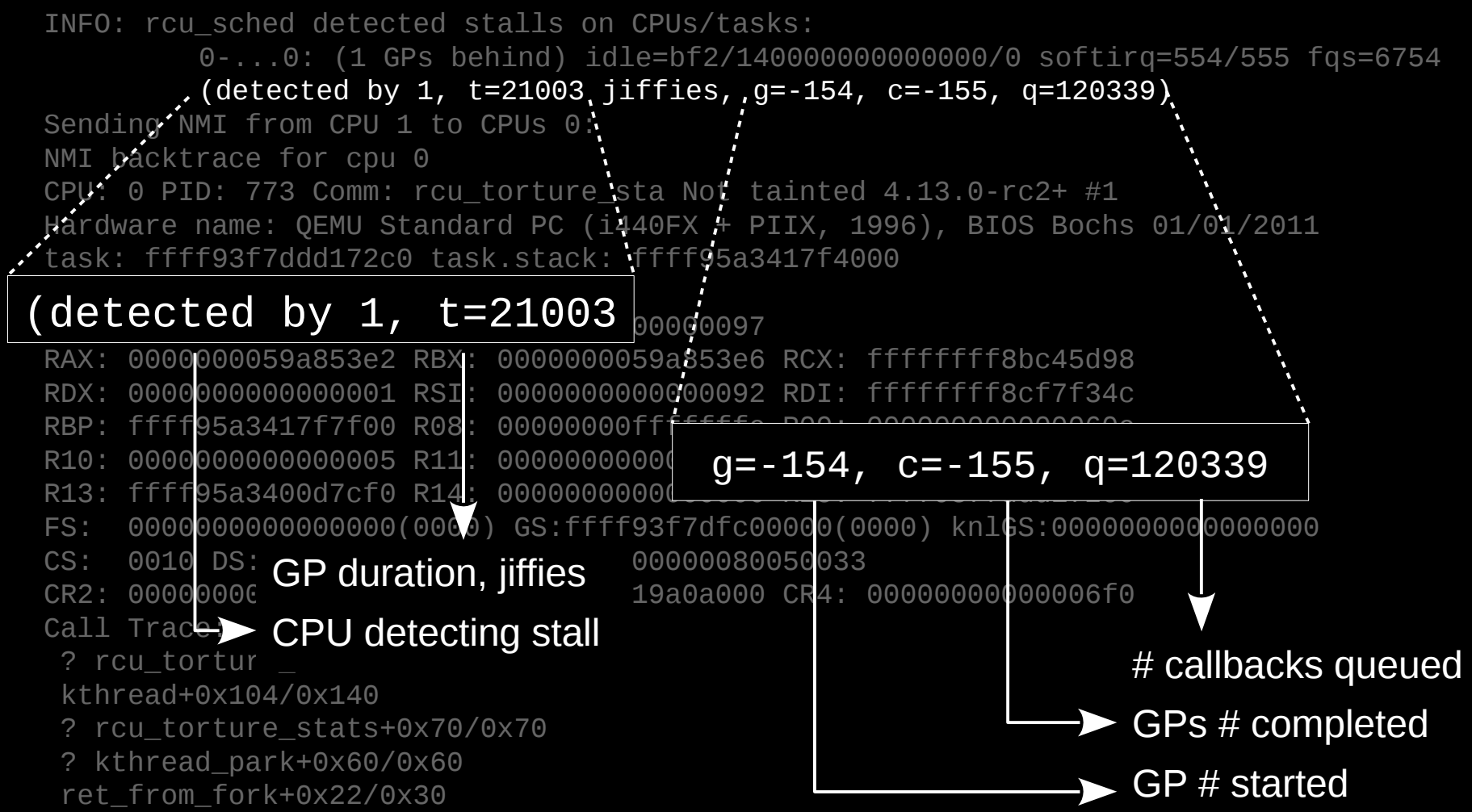

rcu_sched detected stalls on CPUs/tasks

Which CPU is Stalled? (First Format)



Which CPU Detected the Stall? (First Format)



NMI Backtrace Start

```
INFO: rcu_sched detected stalls on CPUs/tasks:
        0-...0: (1 GPs behind) idle=bf2/140000000000000/0 softirq=554/555 fqs=6754
        (detected by 1, t=21003 jiffies, g=-154, c=-155, q=120339)
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task: ffff93f7ddd172c0 task.stack: ffff95a3417f4000
RIP: 0010:get_seconds+0xc/0x10
RSP: 0000:ffff95a3417f7ef0 EFLAGS: 00000097
RAX: 0000000059a853e2 RBX: 0000000059a853e6 RCX: ffffffff8bc45d98
RDX: 0000000000000001 RSI: 0000000000000092 RDI: ffffffff8cf7f34c
RBP: ffff95a3417f7f00 R08: 00000000fffffffe R09: 000000000000060e
R10: 0000000000000005 R11: 000000000000000a R12: ffff93f7ddfae100
R13: ffff95a3400d7cf0 R14: 0000000000000000 R15: ffff93f7ddd172c0
FS:  0000000000000000(0000) GS:ffff93f7dfc00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 0000000080050033
CR2: 0000000000000000 CR3: 0000000019a0a000 CR4: 00000000000006f0
Call Trace:
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 kthread+0x104/0x140
 ? rcu_torture_stats+0x70/0x70
 ? kthread_park+0x60/0x60
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```

NMI Backtrace Stack

```
INFO: rcu_sched detected stalls on CPUs/tasks:
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task: ffff93f7ddd172c0 task.stack: ffff95a3417f4000
RIP: 0010:get_seconds+0xc/0x10
RSP: 0000:fff                                    0097
RAX: 00000000                                   53e6 RCX: ffffffff8bc45d98
RDX: 0000000000000001 RSI: 0000000000000092 RDI: ffffffff8cf7f34c
RBP: ffff95a3417f7f00 R08: 00000000fffffffe R09: 000000000000060e
R10: 0000000000000005 R11: 000000000000000a R12: ffff93f7ddfae100
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 ? kthread_park+0x60/0x60
 ret_from_fork+0x22/0x30
```

rcu_torture_stall

Example RCU CPU Stall Warning Splat (2nd Format)

```
INFO: rcu_sched self-detected stall on CPU
          0-....: (20937 ticks this GP) idle=b5e/140000000000001/0 softirq=258/258 fqs=5176
           (t=21000 jiffies g=-159 c=-160 q=98)
NMI backtrace for cpu 0
CPU: 0 PID: 713 Comm: rcu_torture_sta Not tainted 4.13.0-rc2+ #1
Hardware name: QEMU Standard PC (i440FX + PIIX, 1996), BIOS Bochs 01/01/2011
Call Trace:
 <IRQ>
 dump_stack+0x4d/0x6e
 nmi_cpu_backtrace+0xc5/0xd0
...
 smp_apic_timer_interrupt+0x33/0x50
 apic_timer_interrupt+0x86/0x90
RIP: 0010:get_seconds+0x0/0x10
RSP: 0000:ffffa446813ebef0 EFLAGS: 00000297 ORIG_RAX: ffffffffffffff10
RAX: 00000000599827f5 RBX: 00000000599827f9 RCX: ffffffff84a45cd8
RDX: 0000000000000001 RSI: 0000000000000092 RDI: ffffffff85d7320c
RBP: ffffa446813ebf00 R08: 0000000fffffffe R09: 00000000000005fd
R10: 0000000000000005 R11: 000000000000000a R12: ffff8810de08f0c0
R13: ffffa446800d3cf0 R14: 0000000000000000 R15: ffff8810de0ea580
 </IRQ>
 ? rcu_torture_stall+0xcb/0x140
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 ? rcu_torture_stats+0x70/0x70
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Hardware name: QEMU Standard PC (i440FX + PIIX, 1996), BIOS Bochs 01/01/2011
Call Trace:
 <IRQ>
 dump_stack+0x4d/0x6e
 nmi_cpu_backtrace+0xc5/0xd0
...
 smp_ap
 apic_t
RIP: 0010:get_seconds+0x0/0x10
RSP: 0000:ffffa446813ebef0 EFLAGS: 00000297 ORIG_RAX: ffffffffffffff10
RAX: 00000000599827f5 RBX: 00000000599827f9 RCX: ffffffff84a45cd8
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```

rcu_sched self-detected stall on CPU

Which CPU is Stalled? (2nd Format)

```
INFO: rcu_sched self-detected stall on CPU
         0-....: (20937 ticks this GP) idle=b5e/140000000000001/0 softirq=258/258 fqs=5176
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NMI backtrace for cpu 0
CPU: 0 PID: 713 Comm: rcu_torture_sta Not tainted 4.13.0-rc2+ #1
Hardware name: QEMU Standard PC (i440FX + PIIX, 1996), BIOS Bochs 01/01/2011
Call Trace:
 <IRQ>
 dump_stack+0x4d/0x6e
 smp_apic_timer_interrupt+0x370/0x50
 apic_timer_interrupt+0x86/0x90
RIP: 0010:get_seconds+0x0/0x10
RSP: 0000:ffffa446813ebef0 EFLAGS: 00000297 ORIG_RAX: ffffffffffffff10
RAX: 0000000599827f5 RBX: 0000000599827f9 RCX: ffffffff84a45cd8
RDX: 0000000000000001 RSI: 0000000000000092 RDI: ffffffff85d7320c
RBP: ffffa446813ebf00 R08: 0000000ffffffff0 R09: 00000000000005fd
R10: 0000000000000 R11: ff8810de08f0c0
R13: ffffa44680[0] R14: ff8810de0ea580
 </IRQ>
 ? rcu_torture_s
 kthread+0x10[0]/0
 ? rcu_torture_s
 ? kthread_park+
 ret_from_fork+0
```

0-....: (20937 ticks this GP)

- CPU was aware of last GP
- Interrupts enabled
- CPU online for next GP begin
- CPU was online at GP begin
- CPU is online now
- Stalled CPU

NMI Backtrace Start Plus Interrupt Stack (2nd Format)

```
INFO: rcu_sched self-detected stall on CPU
         O-….: (20937 ticks this GP) idle=b5e/140000000000001/0 softirq=258/258 fqs=5176
          (t=21000 jiffies g=-159 c=-160 q=98)
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CPU: 0 PID: 713 Comm: rcu_torture_sta Not tainted 4.13.0-rc2+ #1
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Call Trace:
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 ? kthread_park+0x60/0x60
 ret_from_fork+0x22/0x30
```
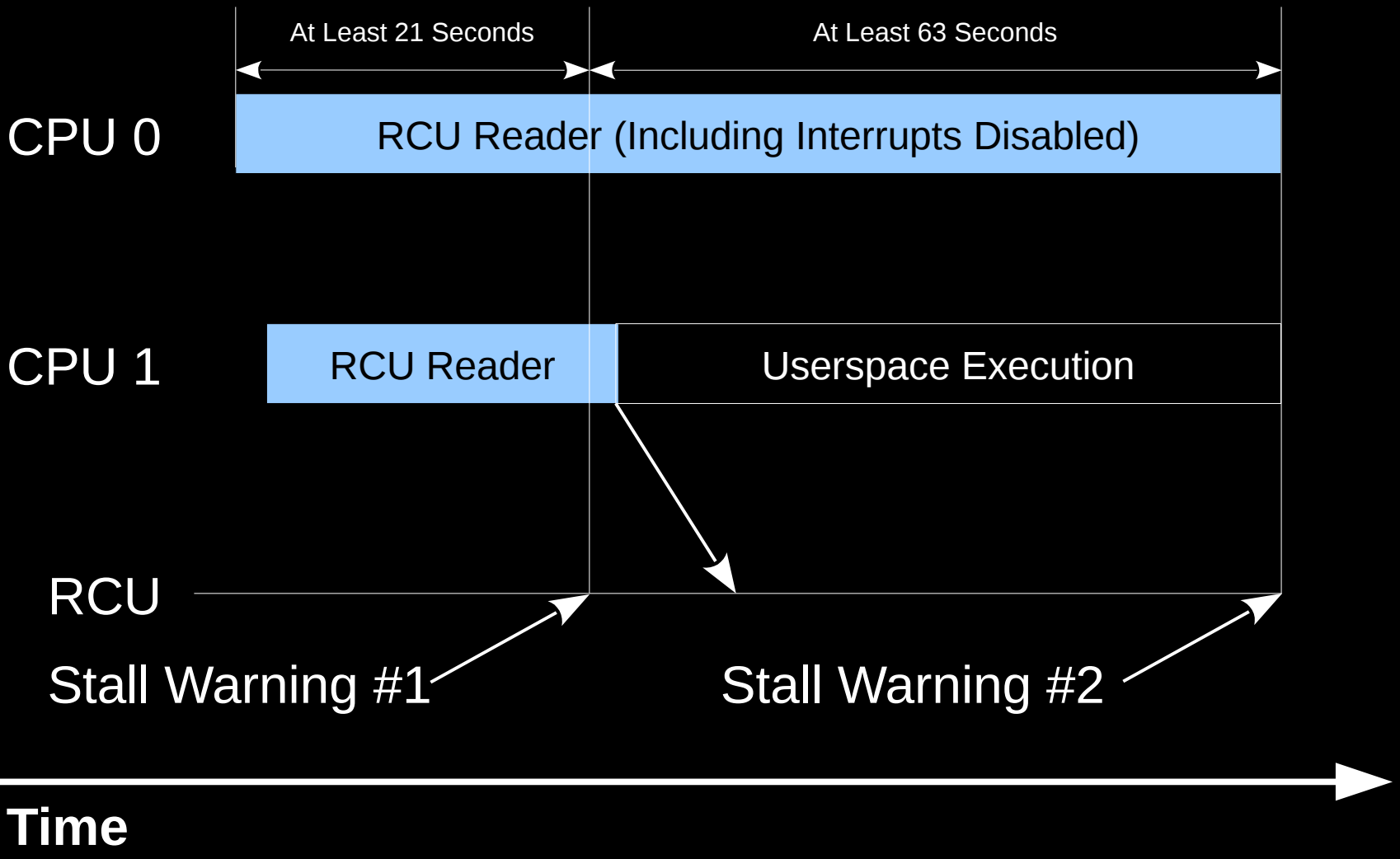

rcu_torture_stall

Ignore interrupt frame

Repeated Stall Warnings: Compare Stack Traces!



What Causes CPU Stalls?

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```
rcu_read_lock();
for (;;)
        do_something;
rcu_read_unlock();
```

- How to fix this?

What Causes CPU Stalls?

```
rcu_read_lock();
for (;;)
        do_something;
rcu_read_unlock();
```

- How to fix this?
  - Break out of RCU read-side critical section occasionally
    - Preferably every few milliseconds
  - Ensure that your loops are finite

What Causes CPU Stalls?

```
local_irq_disable();
for (;;)
        do_something;
local_irq_enable();
```

- How to fix this?

What Causes CPU Stalls?

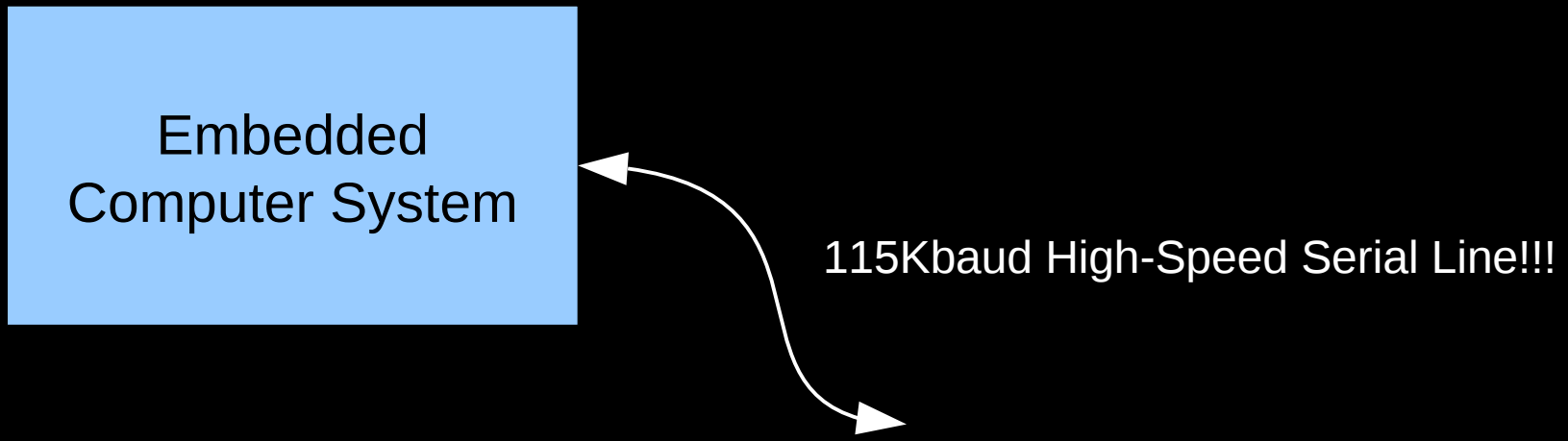
```
local_irq_disable();
for (;;)
        do_something;
local_irq_enable();
```

- How to fix this?
  - Break out of interrupt-disable regions occasionally
    - Increase break-out frequency until tglx stops throwing frozen sharks
  - Ensure that your loops are finite
    - Decrease loop length until tglx stops throwing frozen sharks

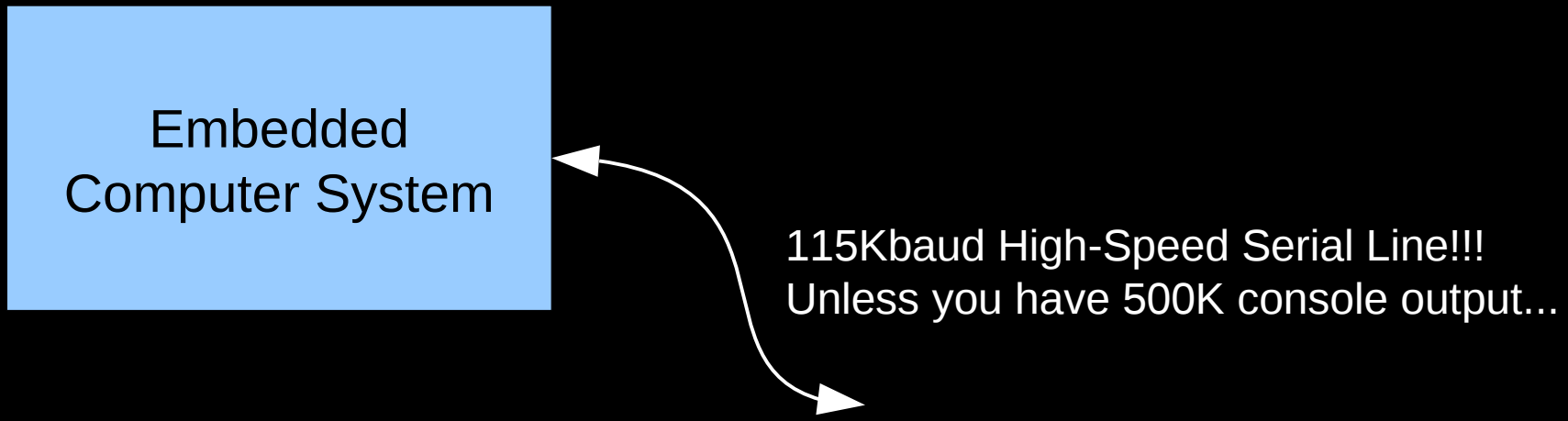
Variations on Long-Reader and IRQ-Disable Themes

- Looping with preemption disabled
  - You should expect incoming frozen sharks in this case as well
- Looping with bottom-half execution disabled
  - Ditto
- Long-running interrupt within RCU reader
- PREEMPT=n: Looping without invoking schedule() or cond_resched_rcu_qs()
- PREEMPT=y: Indefinitely preempting an RCU reader
  - Can also try RCU_BOOST=y
- In virtualized environments, vCPU preemption
  - (Working on it, see Aravinda Prasad et al. 2017 USENIX paper)

What Causes CPU Stalls?

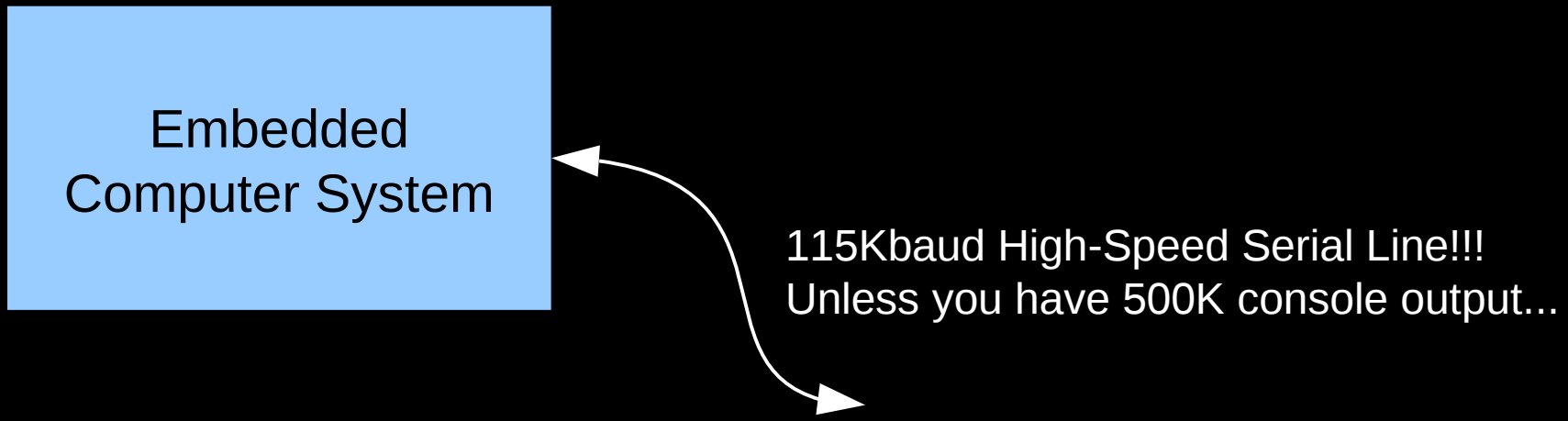


What Causes CPU Stalls?



What do you do about this?

What Causes CPU Stalls?



What do you do about this?
Tejun Heo's patch eliminates NMI-watchdog knockon failures:
https://patchwork.kernel.org/patch/10153045/

What Causes CPU Stalls?

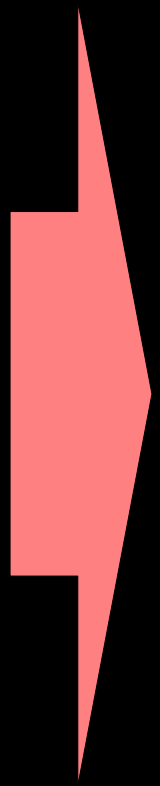
- Develop on fast system that just barely avoids CPU stalls
  - Then deploy on slow system
- Interrupt overload
- Turning on super-high-overhead debugging
  - https://marc.info/?l=linux-kernel&m=150176048506696
  - So adjust/disable the CPU stall timeout in this case!!!
- Prevent RCU_SOFTIRQ from running
  - For example, CPU-bound high-priority real-time process
- Completely shut off CPU's scheduler-clock interrupt
- Hardware failure
  - In one case, a fail-stop CPU!
  - Timer issues are a recurrent theme (see later war story)

RCU Bugs Can Also Cause CPU Stalls

- When things are stuck for 21 seconds, no need to be dainty
  - ***False!!!*** As I spent a couple years learning...
- Stall-warning messages can cause the stall to end
  - After part of the message is printed... This case now flagged
- Extremely quiet embedded systems have their own issues
  - They can enter states noisy systems avoid!!!
- **RCU kthread wakeup failures**

Evolution of RCU Grace-Period Handling

Pre-v3.8:
RCU state machine driven via softirq

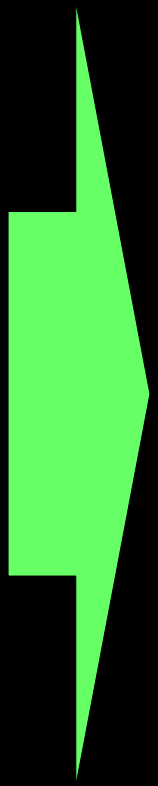


First Clue of Large-System RT-Response Importance

wikimedia.org

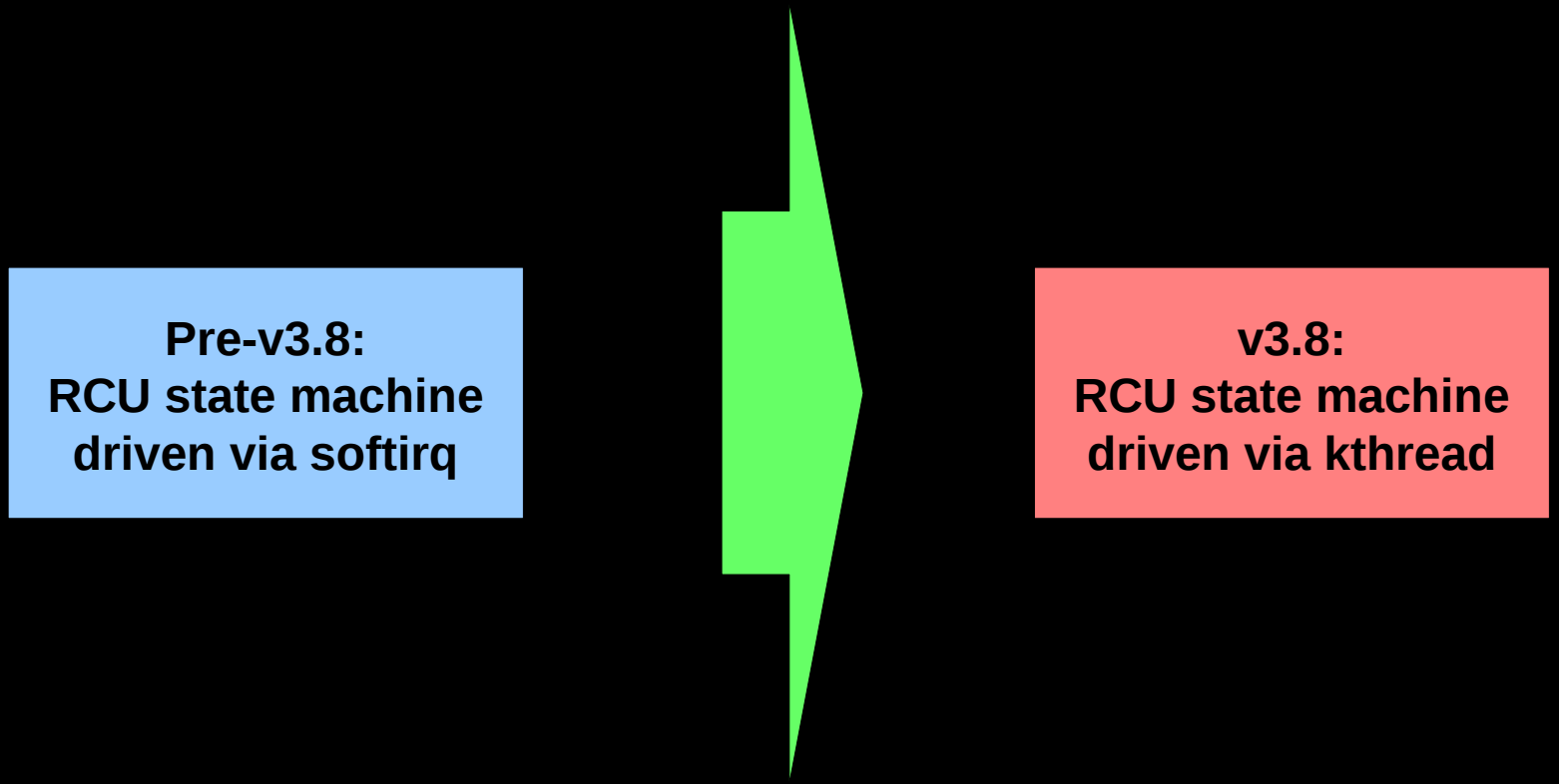
Evolution of RCU Grace-Period Handling

Pre-v3.8:
RCU state machine driven via softirq



v3.8:
RCU state machine driven via kthread

Evolution of RCU Grace-Period Handling



RCU Grace-Period Kernel Thread Wakeup Failures

```
rcu_bh kthread starved for 21134 jiffies! g18446744073709551396
c18446744073709551395 f0x0 RCU_GP_WAIT_FQS(3) ->state=0x0 ->cpu=0
rcu_bh          R  running task    14968     9      2 0x00080000
Call Trace:
 __schedule+0x20b/0x6c0
 schedule+0x31/0x80
 schedule_timeout+0x170/0x2f0
 ? call_timer_fn+0x130/0x130
 rcu_gp_kthread+0x4be/0xd90
 kthread+0x104/0x140
 ? rcu_oom_notify+0xf0/0xf0
 ? kthread_park+0x60/0x60
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```

RCU Grace-Period Kernel Thread Wakeup Failures

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rcu_bh          R  running task    14968     9      2 0x00080000
Call Trace:
 __schedule+0x20b/0x6c0
 schedule+0x31/0x80
 schedule_timeout+0x170/0x2f0
 ? call_timer_fn+0x130/0x130
 rcu_gp_kthread+0x4be/0xd90
 kthread+0x104/0x140
 ? rcu_boom_notify+0xf0/0xf0
 ? kthread_park+0x60/0x60
 ret_from_fork+0x22/0x30
```

`rcu_bh kthread starved for 21134 jiffies`

RCU cannot do much for you if you don't let its kthreads run!!!

RCU Grace-Period Kernel Thread Wakeup Failures

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rcu_bh kthread starved for 21134 jiffies! g18446744073709551396
c18446744073709551395 f0x0 RCU_GP_WAIT_FQS(3) ->state=0x0 ->cpu=0
rcu_bh          R  running task    14968     9      2 0x00080000
Call Trace:
 __schedule+0x20b/0x6c0
 schedule+0x31/0x80
 schedule_timeout+0x170/0x2f0
 ? call_timer_fn+0x130/0x130
 rcu_gp_kthread+0x4be/0xd90
 kthread+0x104/0x140
 ? rcu_oom_notify+0xf0/0xf0
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 ret_from_fork+0x22/0x30
```

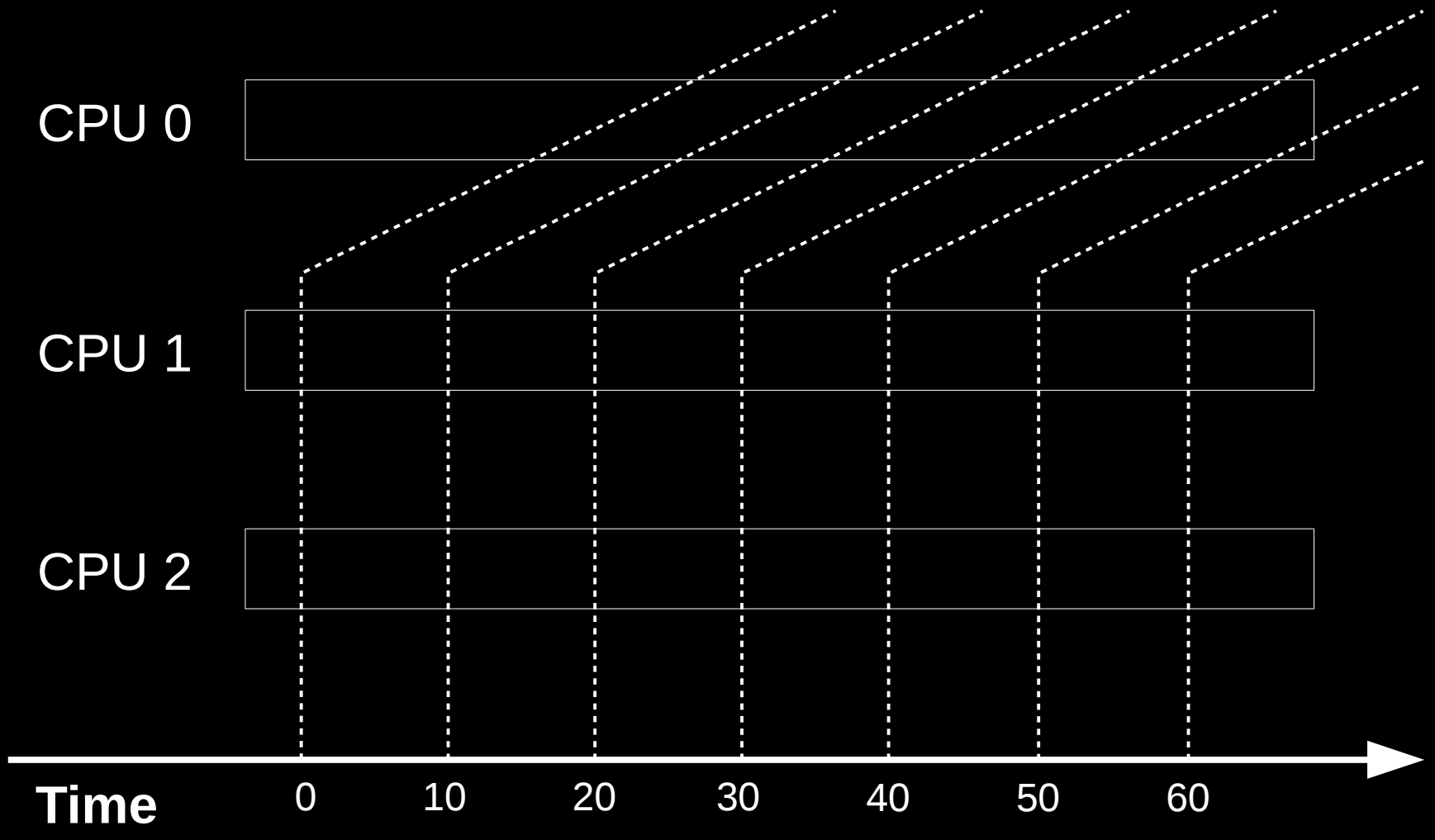
And RCU expects a three-jiffy schedule_timeout() to take way less than 21 seconds

Fixing this is a work in progress: Kudos to Anna-Maria, Thomas, and Sebastian

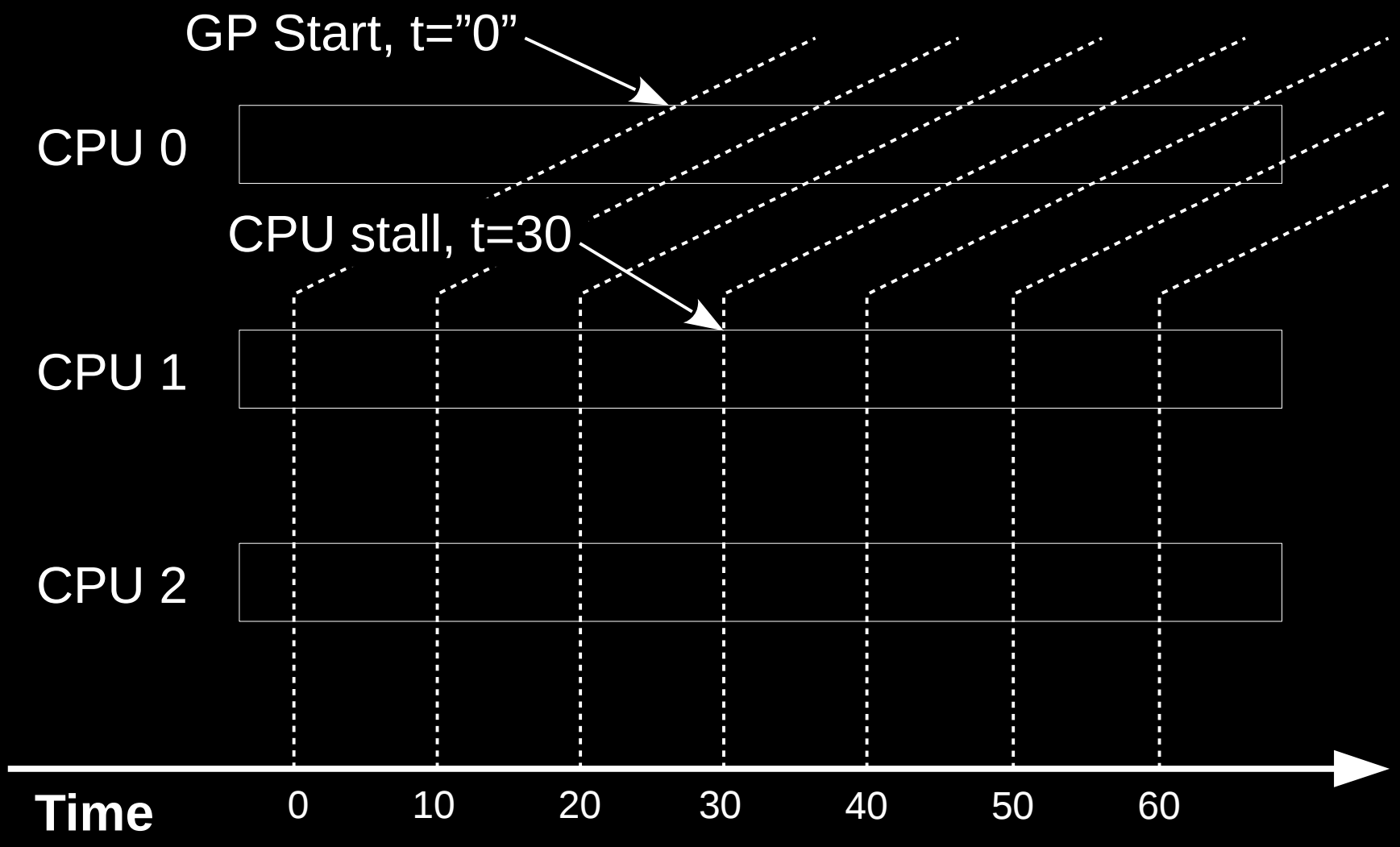
Obligatory War Stories

My Favorite? “CPU-0 Standard Time”

“CPU-0 Standard Time”

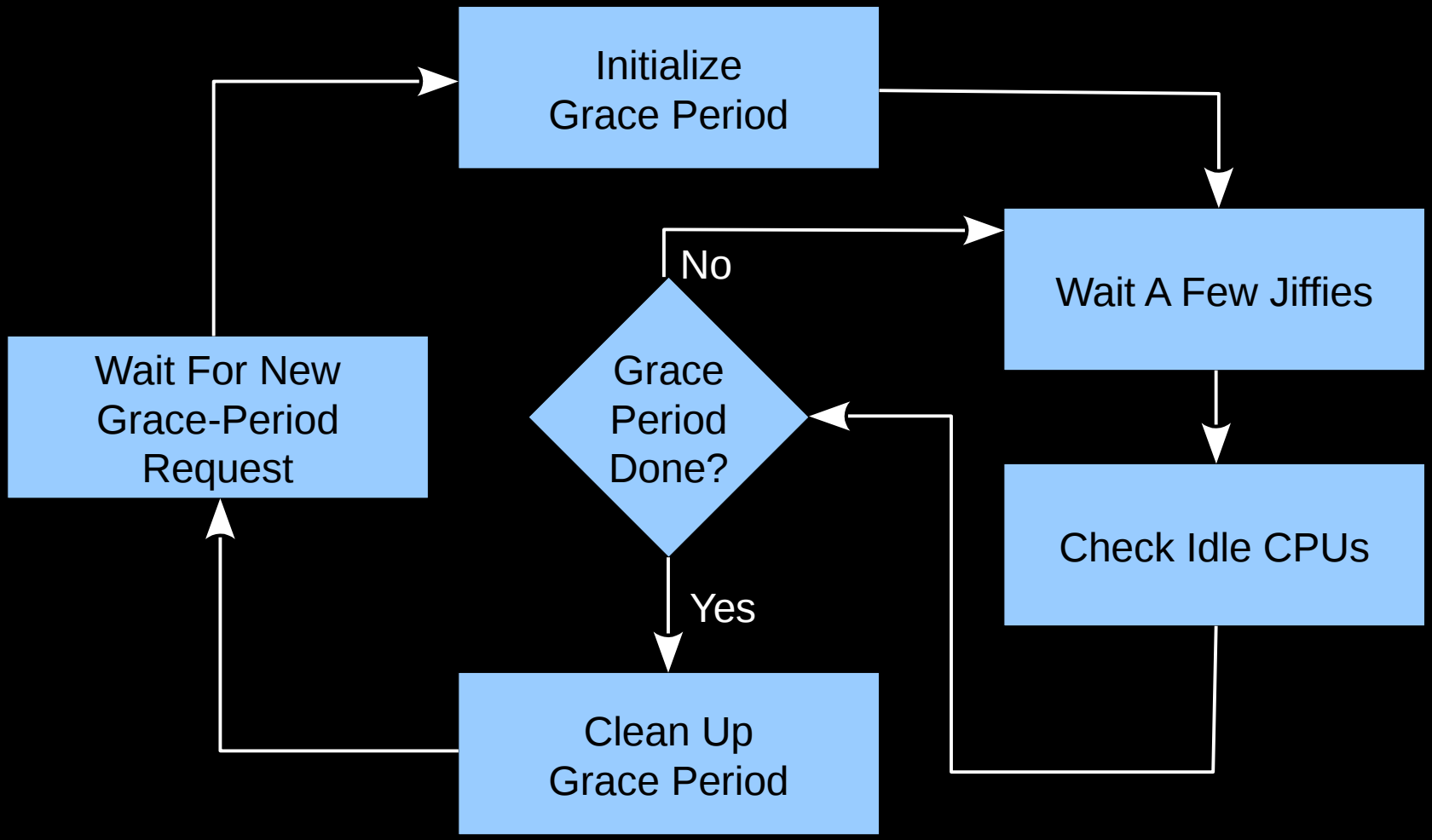


“CPU-0 Standard Time”

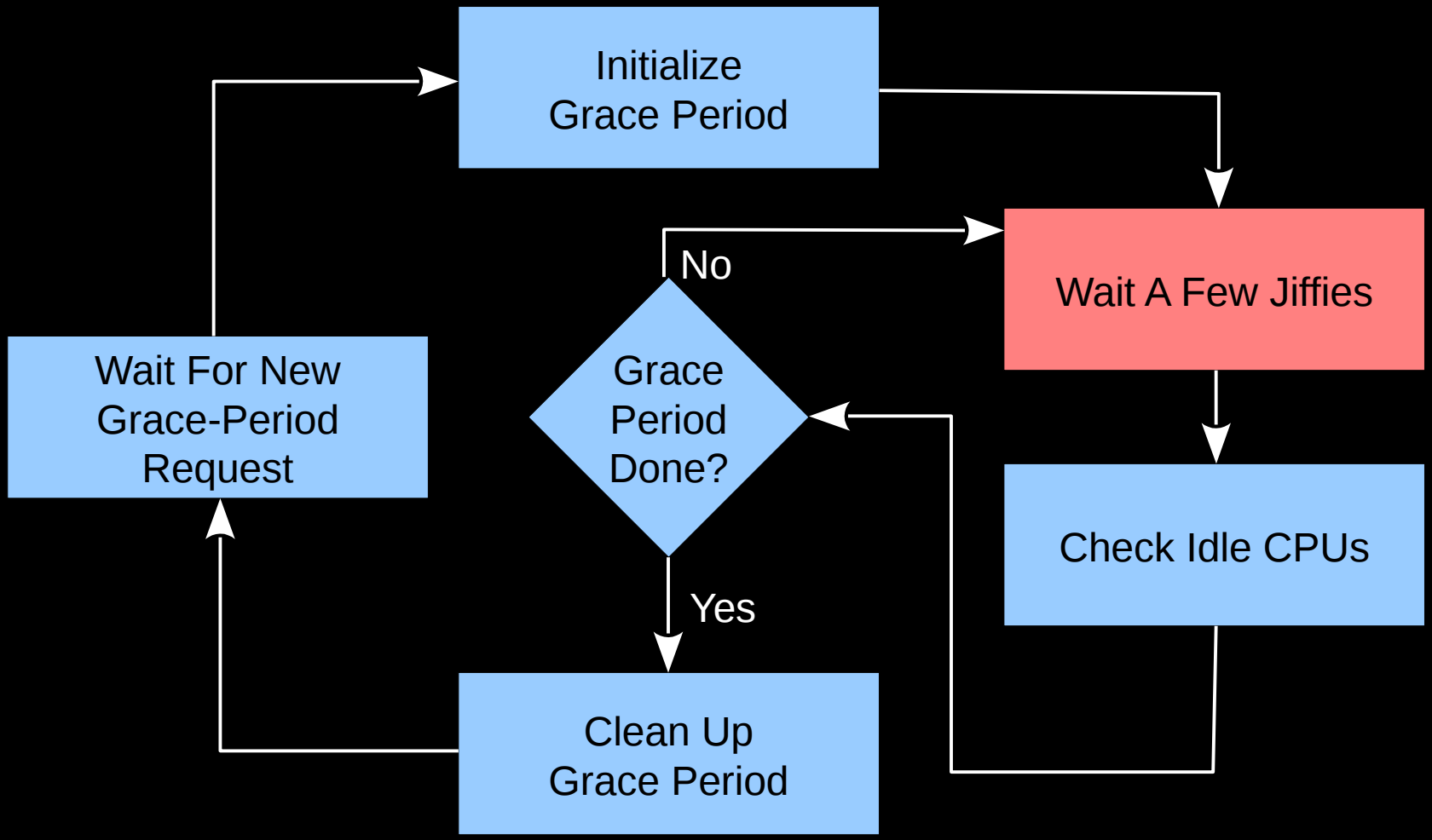


Time Waits For No One, But...

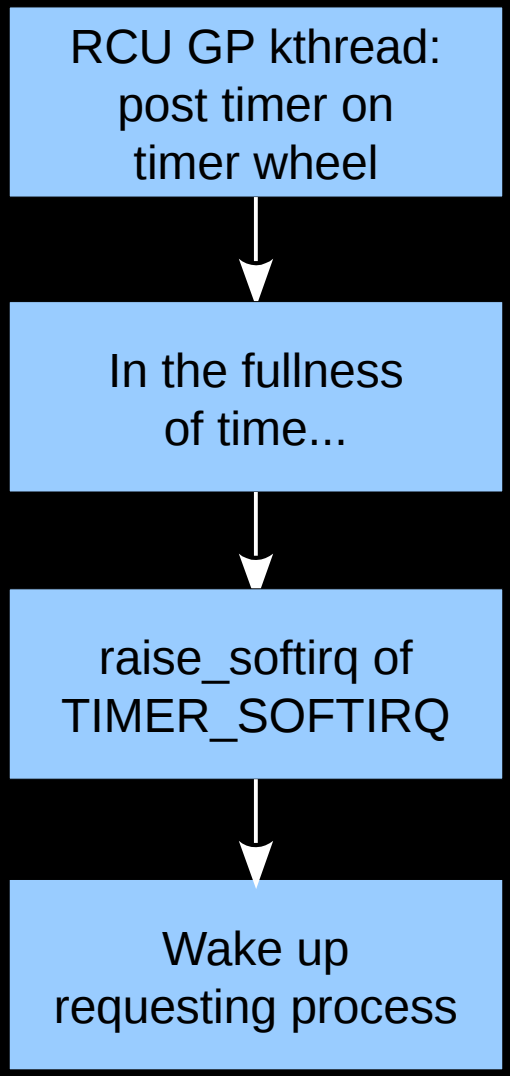
High-Level RCU Grace-Period Processing



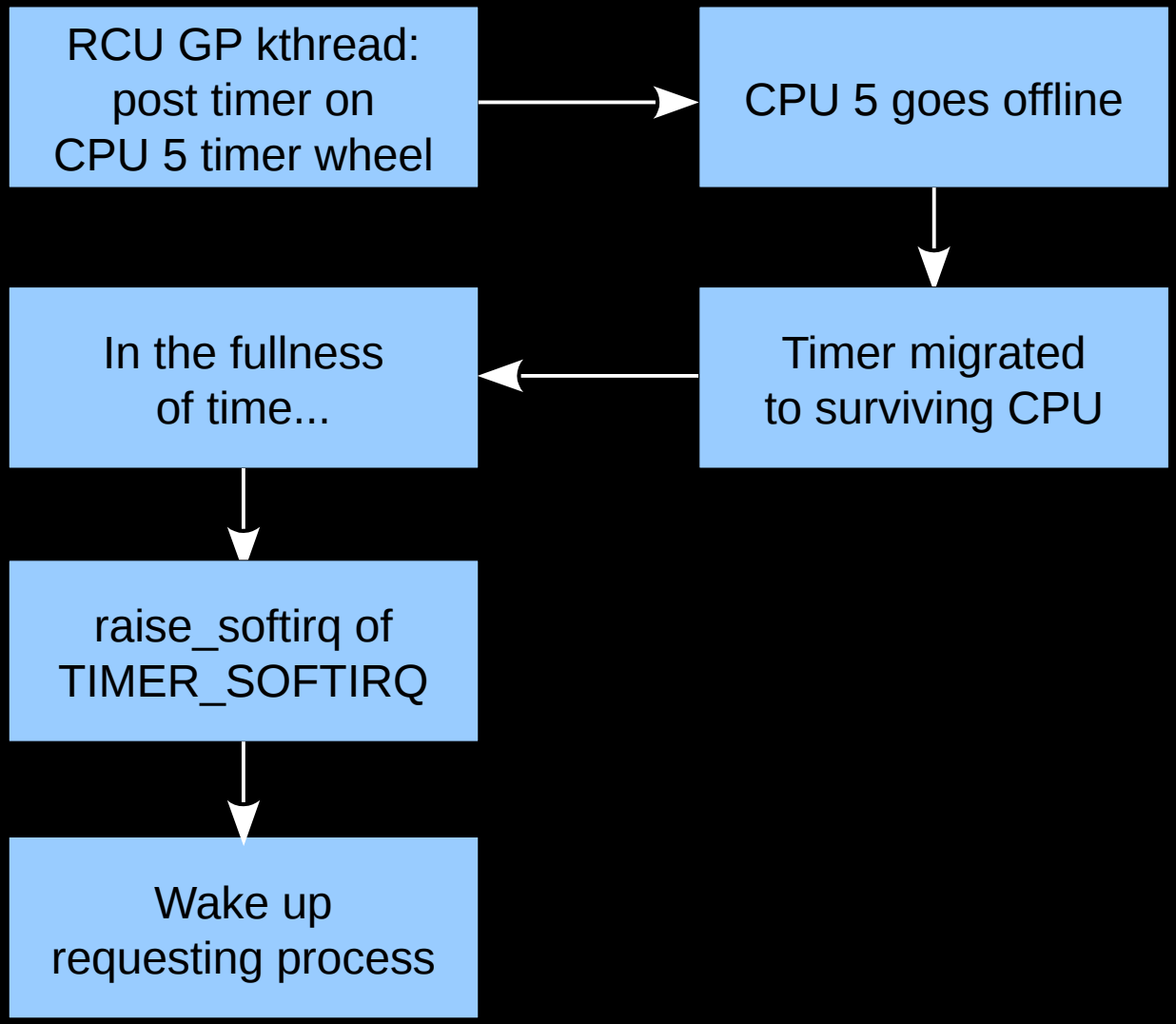
High-Level RCU Grace-Period Processing



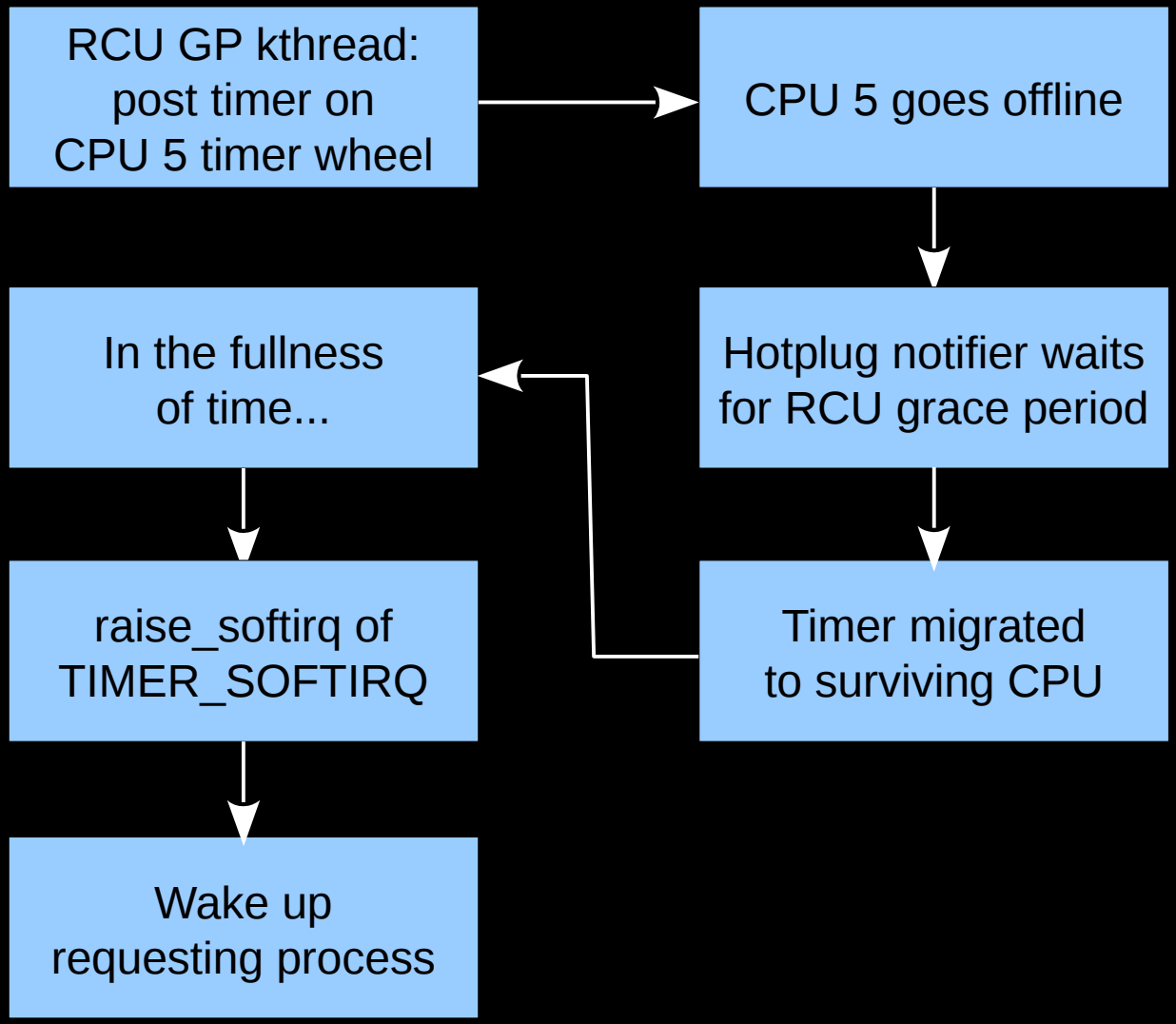
High-Level Timer Processing



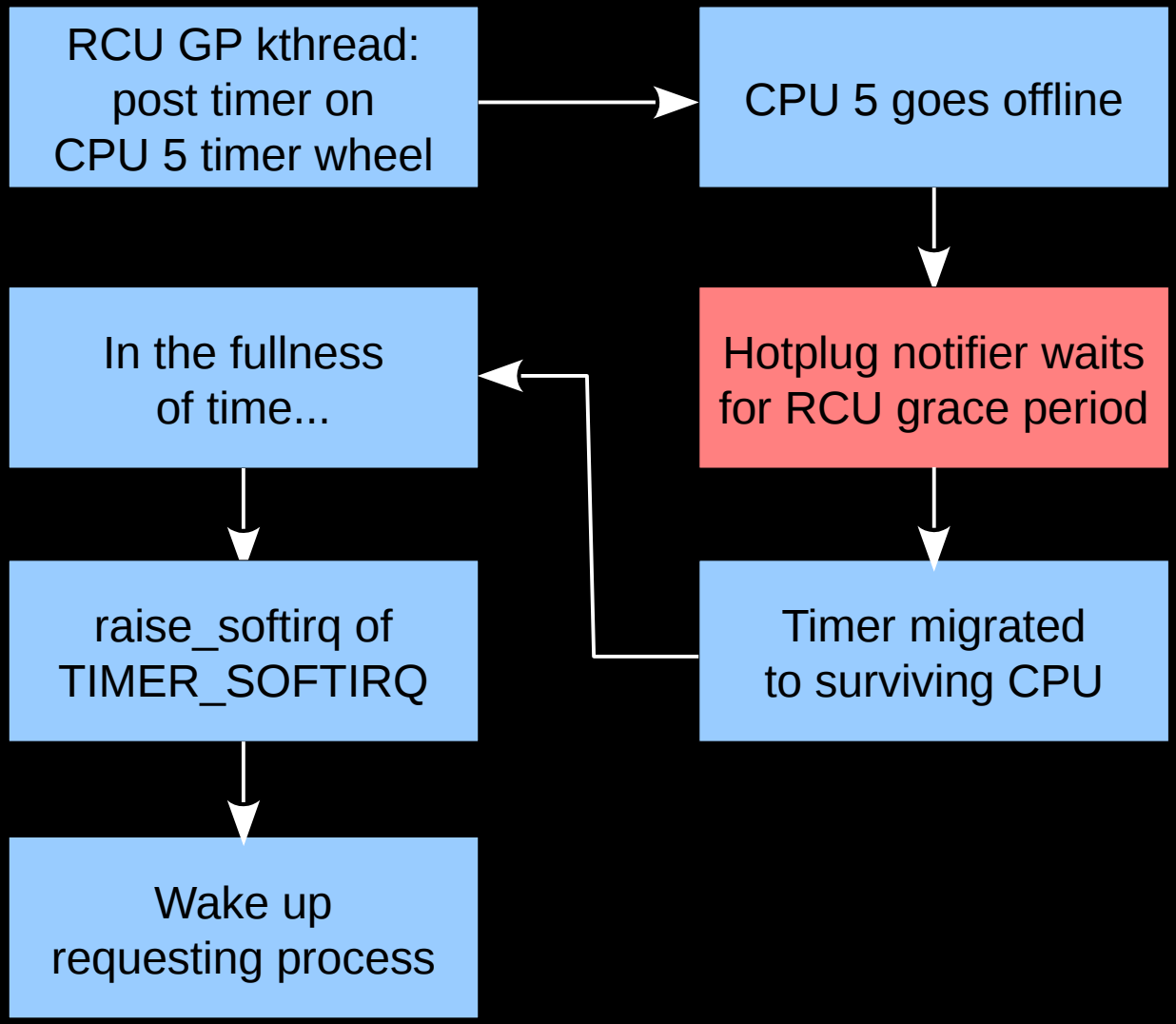
High-Level Timer Processing, CPU Offline



High-Level Timer Processing, CPU Offline, RCU



High-Level Timer Processing, CPU Offline, RCU



Time Waits For No One, But It Can Deadlock With CPU-Hotplug Offline and RCU Grace Periods!!!

Time Waits For No One, But It Can Deadlock With CPU-Hotplug Offline and RCU Grace Periods!!!

```
/*
 * On the tear-down path, timers_dead_cpu() must be invoked
 * before blk_mq_queue_reinit_notify() from notify_dead(),
 * otherwise a RCU stall occurs.
 */
```

Summary

Summary

- RCU CPU stall warnings are a valuable diagnostic tool
  - CPUs stuck in various unhelpful states
  - Extreme overload
  - Priority issues
  - Temporal anomalies
  - Low-level software issues
  - Hardware problems
  - RCU bugs
- Prevention:
  - Pause points in unbounded loops
  - Test on deployment-class systems (or adjust CPU-stall timeout)
  - Assign priorities carefully
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Summary

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- Prevention:
  - Pause points in unbounded loops
  - Test on deployment-class systems (or adjust CPU-stall timeout)
  - Assign priorities carefully
  - Respect the passage of time
  - **Make sure this McKenney fellow doesn't mess up RCU!**

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Questions?