Make RCU do less (& later) !

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Linux Plumbers Conference

Dublin, Ireland September 12-14, 2022

Overview

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- Discuss what RCU does at high-level (not how it works!).
- Discuss the 2 main issues we found:
  - On a mostly idle system, RCU activity can disturb the idleness.
    - RCU default config required to keep tick on when idle and CBs queued.
    - RCU constantly asked to queue callbacks on a lightly loaded system.
- Discuss possible solutions.
- Taking questions in the end as time permits (and then hallway)

What RCU does?

Data-Structure read/modification usecase:

- RCU reader critical section protected by “**read** lock”
- RCU writer critical section protected by regular locks.
- Reader and writer execute concurrently.
- Writer creates **copy** of obj, writes to it and switches object pointer to new one (release ordered write).
- Writer Garbage Collects old object after waiting (**update**)

What RCU does?

- That's just one use case, there are many uses of RCU.

All use cases need same basic tools:

- Lock-less markers of a critical section (CS). Call it "reader".
- Start waiting at some point in time (t = T0).
- Stop waiting after all readers that existed at T0 exited CS (t = T1).

Note: Start (T0) is when a "callback is queued", Stop is when a "callback is invoked".

What RCU does?

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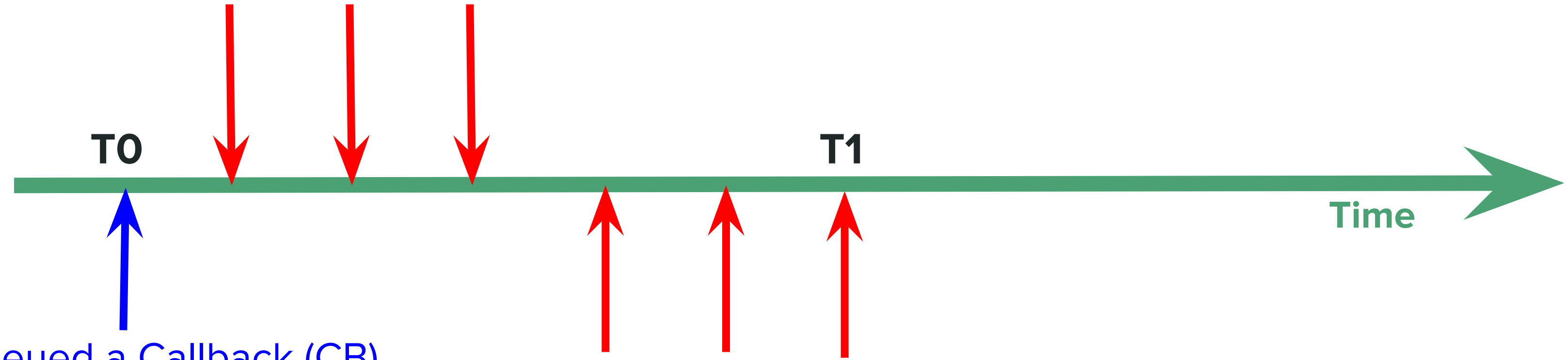
- On a local CPU (running in **kernel mode** with CB queued).

Upper red arrows are timer tick checking are there readers left? If not, report.



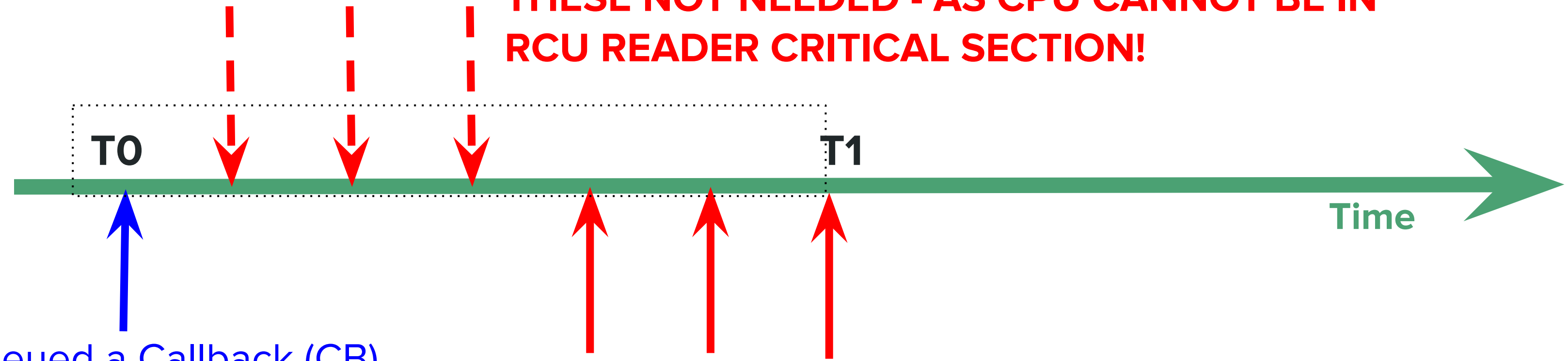
Queued a Callback (CB)

Lower red arrows are timer tick: have ALL CPUs reported? If yes, invoke CB. If no, try again.

What RCU does?

- On a local CPU (running in **idle mode** with CB queued).

Upper red arrows are timer tick checking are there readers left? If not, report.
THESE NOT NEEDED - AS CPU CANNOT BE IN RCU READER CRITICAL SECTION!



Queued a Callback (CB)
And soon go idle...

Lower red arrows are timer tick: have ALL CPUs reported? If yes, invoke CB. If no, try again.
THESE STILL NEEDED - AS local CPU has queued CB.

What RCU does?

- You see the problem?
  - RCU can block the timer tick from getting turned off!
  - Negates power-savings of CONFIG_NOHZ_IDLE

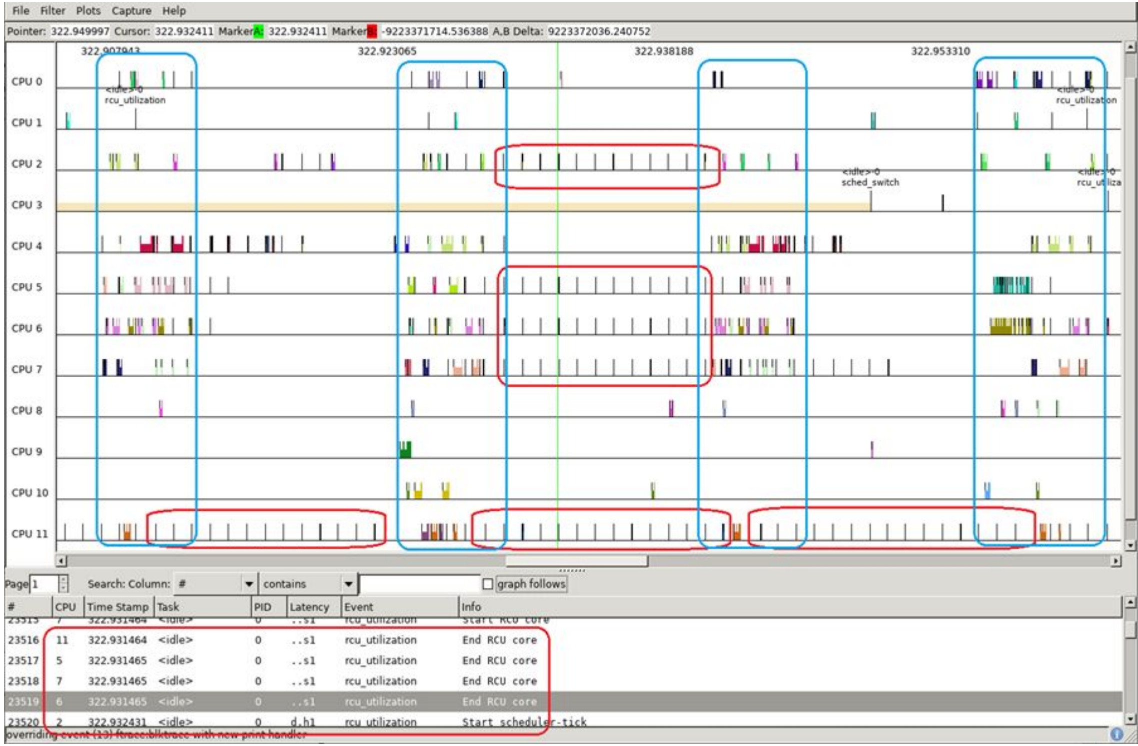
(To be fair to RCU, this workload queues a lot of RCU Callbacks on otherwise idle CPUs, requiring RCU to do work on these otherwise-idle CPUs).

Issue 1: RCU keeping the scheduler tick ON when idle.

- "Local Video Playback" use-case has 2500+ **timer wakes** per second. A large chunk of the wakes result from constantly queued RCU callbacks.

- RCU wakes are seen at HZ rate (red boxes) between graphics 16.6ms activity (blue boxes)

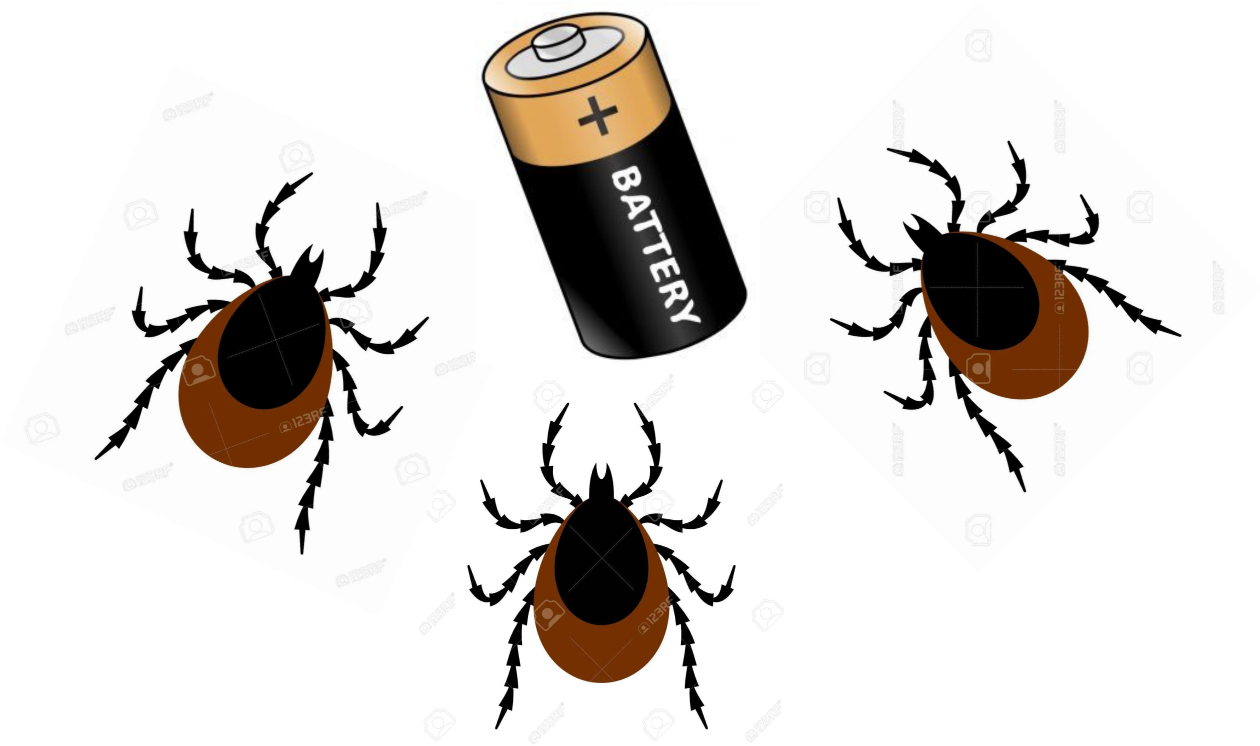
- Blocks deeper Package C-states. Impacts power



How bad are idle ticks for power

- We know idle ticks are bad for power, but we did not know how bad!
- In Video playback, **timer wakes** amount to < 2% CPU load, but blocked deepest package C-states (PC8) for 25+% of the time, causing 10+% in SoC + memory power.
- If you are profiling CPU load, then you will likely miss the impact of wakes (use powertop)

Why are idle ticks so bad for power?



What are package C-states

- Traditionally ACPI C-states are **CPU** low power states
- Idle governor picks C-states based on OS next event prediction and C-states exit latency & target residency
- CPU C-states have low exit latency & target residency, so doesn’t block much on ticks

- **System-On-Chip** architecture provides opportunity to extend the OS C-states hints to power manage the entire SoC.
- SoCs have power management unit which coordinates CPU, IP blocks and common logic, to put entire SoC in low power
- Package C-states add extended C-states with higher exit latency & longer power breakup time.

```
static struct cpuidle_state adl_cstates[] __initdata = {
	{
		.name = "C1",
		.exit_latency = 1,
		.target_residency = 1,
	{
		.name = "C1E",
		.exit_latency = 2,
		.target_residency = 4,
	{
		.name = "C6",
		.exit_latency = 220,
		.target_residency = 600,
	{
		.name = "C8",
		.exit_latency = 280,
		.target_residency = 800,
	{
		.name = "C10",
		.exit_latency = 680,
		.target_residency = 2000,
	{
		.enter = NULL }
};
```

New Extended C-states (C8, C10)

But why does some RCU configs keep tick on if so bad for cpuidle?

This is required in default RCU configurations as CBs are invoked on same CPU they were queued on, in a softirq.

Advantages:

- Executing CBs on queuing CPU eliminates need for CB list locking.
- No need for additional thread wake ups as local softirq execs CB.
- Cache-line is likely hot from queuing and CB would not incur misses.

These can be especially useful on busy systems and large #CPU server!

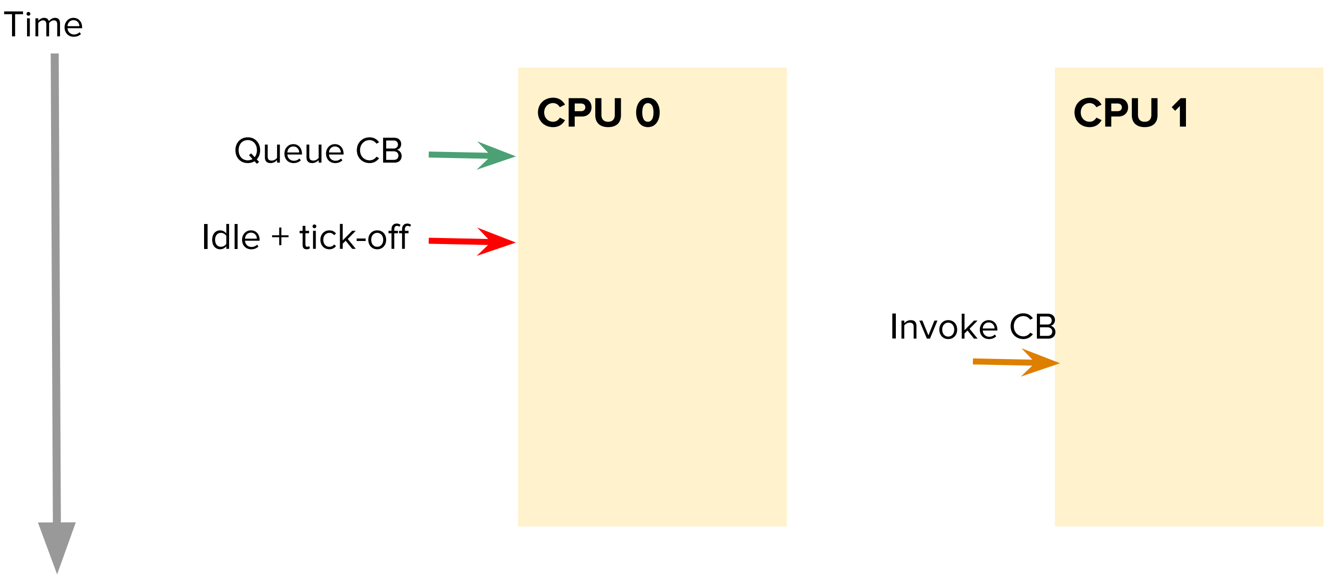
- Periodic tick check helps with timely detection of GP end and thus CB exec.

But why does some RCU configs keep tick on if so bad for cpuidle?

Say we don’t want any of those advantages, and just want tick off already…

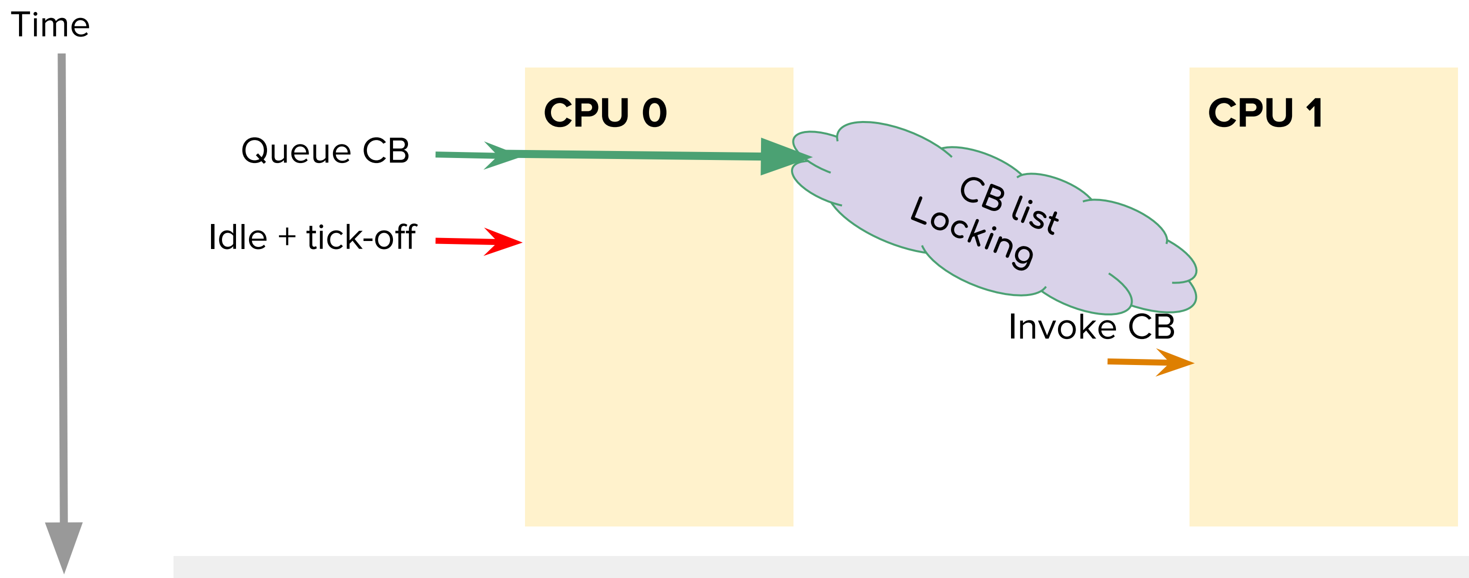
Issue 1: RCU keeping the scheduler tick ON when idle.

Solution for newer kernels: `CONFIG_RCU_NOCB_CPU` (Execute RCU CBs in per-cpu threads.)



Issue 1: RCU keeping the scheduler tick ON when idle.

Solution for newer kernels: `CONFIG_RCU_NOCB_CPU`



Can cause performance overhead on system with frequent CB queue/exec!

Issue 1: RCU keeping the scheduler tick ON when idle.

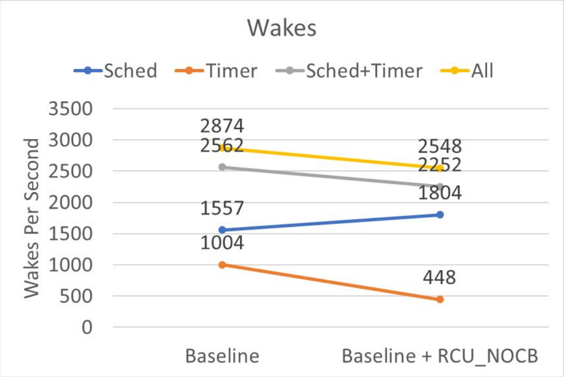
Solution for newer kernels: CONFIG_RCU_NOCB_CPU

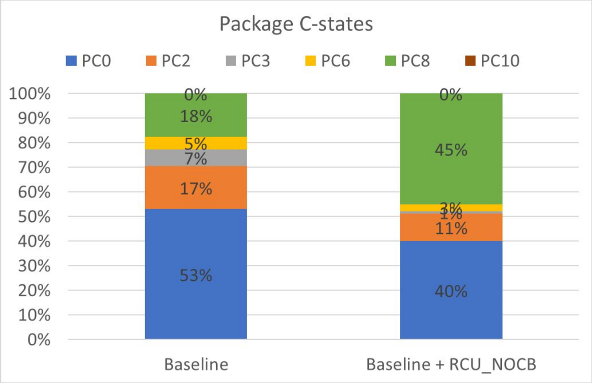
However, can be great for power and CPU isolation…

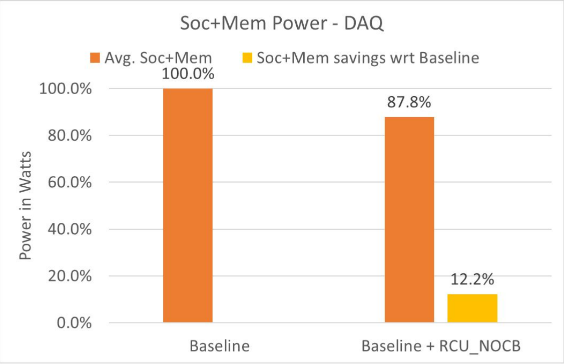
- Scheduler may move threads to non-idle CPUs thus leaving more idle.
- **Both** starting of new grace periods, and executing CBs are moved out of the softirq context and into threads.

CONFIG_RCU_NOCB_CPU saves lots of power

- RCU callback offload unblocks dynticks-idle and hence reduces timer wakes.
- RCU callback offload does increase the scheduler wakes marginally, but reduces total platform wakes.
- Improves Package C-states residency and hence SoC + Memory power.







<u>Use-case</u>: Local video playback via Chrome browser, VP9 1080p @ 30 fps content

<u>Device</u>: Chrome reference device, AlderLake Hybrid CPU with 2 Cores (with Hyperthreading) + 8 Atoms

New option: CONFIG_RCU_NOCB_CPU_ALL

- If you enable CONFIG_RCU_NOCB_CPU, you still need to specify rcu_nocbs=0-N to make it work.

  So…

- New option CONFIG_RCU_NOCB_CPU_ALL was added to just enable nocb for all CPUs by default.

Can we do even better?

Observations:

- When a system is mostly idle, most CBs don't need to execute right away, some can be delayed as long as needed!

- Some CBs in the system "trickle" frequently.

Observation: ChromeOS when idle

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- Some CBs in the system “trickle” frequently.
- Several callbacks constantly queued.

rcutop refreshing every 5 seconds. ChromeOS logged in with screen off. Device on battery power.

```
21:57:07 loadavg: 0.06 0.50 0.55 2/629 8945
```

Callback	Queued	Executed
inode_free_by_rcu	7	10
delayed_put_task_struct	7	15
k_itimer_rcu_free	9	9
radix_tree_node_rcu_free	16	27
rcu_work_rcufn	1	2
put_cred_rcu	4	8
delayed_put_pid	7	15
unbind_fence_free_rcu	4	5
dst_destroy_rcu	4	10
__i915_gem_free_object_rcu	5	10
thread_stack_free_rcu	3	7

Observation: ChromeOS Display pipeline

Display pipeline in ChromeOS constantly opens/close graphics buffers.

```
VizCompositorTh-1999  [006]  1472.325451: sys_enter_close:     fd: 0x00000033
VizCompositorTh-1999  [006]  1472.325457: sys_enter_close:     fd: 0x00000046
ThreadPoolSingl-6857  [010]  1472.325734: sys_enter_close:     fd: 0x00000025
ThreadPoolSingl-6857  [010]  1472.325743: rcu_callback:        rcu_preempt rhp=0xffff9f3edc718480 func=file_free_rcu 1
          chrome-1975  [000]  1472.344365: sys_enter_close:    fd: 0x0000002d
          DrmThread-1993  [002]  1472.344627: sys_enter_close: fd: 0x00000044
          DrmThread-1993  [002]  1472.344844: sys_enter_close: fd: 0x00000044
          chrome-1975  [000]  1472.345019: sys_enter_close:    fd: 0x00000046
VizCompositorTh-1999  [006]  1472.345071: sys_enter_close:     fd: 0x00000046
VizCompositorTh-1999  [006]  1472.345088: sys_enter_close:     fd: 0x00000044
          kworker/10:2-2105  [010]  1472.346603: rcu_callback: rcu_preempt rhp=0xffff9f41efa9f600 func=rcu_work_rcufn 1
          kworker/9:4-3546  [009]  1472.346603: rcu_callback:  rcu_preempt rhp=0xffff9f41efa5f600 func=rcu_work_rcufn 1
          kworker/0:4-3506  [000]  1472.346606: rcu_callback:  rcu_preempt rhp=0xffff9f41ef81f600 func=rcu_work_rcufn 1
          DrmThread-1993  [002]  1472.357990: sys_enter_close: fd: 0x0000002e
          DrmThread-1993  [002]  1472.358005: rcu_callback:    rcu_preempt rhp=0xffff9f3eb9328000 func=file_free_rcu 1
          chrome-1975  [000]  1472.358200: sys_enter_close:    fd: 0x00000038
VizCompositorTh-1999  [006]  1472.358367: sys_enter_close:     fd: 0x0000002e
          chrome-1975  [000]  1472.358539: sys_enter_close:    fd: 0x00000044
          chrome-1975  [000]  1472.358546: sys_enter_close:    fd: 0x0000002e
          chrome-1975  [000]  1472.358548: sys_enter_close:    fd: 0x00000038
VizCompositorTh-1999  [006]  1472.358778: sys_enter_close:     fd: 0x0000002e
VizCompositorTh-1999  [006]  1472.358784: sys_enter_close:     fd: 0x00000046
ThreadPoolSingl-6857  [010]  1472.359008: sys_enter_close:     fd: 0x00000025
ThreadPoolSingl-6857  [010]  1472.359019: rcu_callback:        rcu_preempt rhp=0xffff9f3e8d28e300 func=file_free_rcu 1
          chrome-1975  [000]  1472.377594: sys_enter_close:    fd: 0x0000002d
          DrmThread-1993  [002]  1472.377825: sys_enter_close: fd: 0x0000003f
          DrmThread-1993  [002]  1472.378043: sys_enter_close: fd: 0x0000003f
          chrome-1975  [000]  1472.378227: sys_enter_close:    fd: 0x00000046
VizCompositorTh-1999  [006]  1472.378341: sys_enter_close:     fd: 0x00000046
VizCompositorTh-1999  [006]  1472.378356: sys_enter_close:     fd: 0x0000003f
          kworker/2:1-7250  [002]  1472.378524: rcu_callback:  rcu_preempt rhp=0xffff9f41ef89f600 func=rcu_work_rcufn 1
          kworker/0:4-3506  [000]  1472.379626: rcu_callback:  rcu_preempt rhp=0xffff9f41ef81f600 func=rcu_work_rcufn 1
          kworker/10:2-2105  [010]  1472.380627: rcu_callback: rcu_preempt rhp=0xffff9f41efa9f600 func=rcu_work_rcufn 1
          DrmThread-1993  [002]  1472.391294: sys_enter_close: fd: 0x00000033
          DrmThread-1993  [002]  1472.391306: rcu_callback:    rcu_preempt rhp=0xffff9f3eb9328600 func=file_free_rcu 1
```

Observation: Logging in Android (as example)

Android uses CONFIG_RCU_NO_CB by default to offload all CPUs.

Observation: Logging in Android (as example)

Example: Logging during static image (Android).

Static image is important use-case for power testing on Android. The system is mostly idle to minimize a power drain of the platform:

- CPU stops refreshing panel and panel self-refreshes on it own.
- CPUs spend most of their time in deepest C-state
- SoC bandwidth is minimal (memory bus, CPU/cache frequencies, etc.).

Logging does constant file open/close giving RCU work when FDs get freed. As a side effect of such periodic light load, many wakeups happen due to frequent kicking an RCU-core for initializing a GP to invoke callbacks after it passes.

Observation: Logging in Android (as example)

Below is a post process of scheduler ftrace for static image use-case during 30 seconds

(this is with CONFIG_RCU_NOCB_CPU with all CPUs offloaded).

```
<wake-up-trace-log>
 rcuop/2     pid:     33   woken-up   36709      interval: min  1320     max       71837         avg  9807
 rcuop/3     pid:     40   woken-up   36944      interval: min  1582     max       78649         avg  9744
 rcuop/0     pid:     15   woken-up   40570      interval: min  1520     max       80442         avg  8873
 rcuop/1     pid:     26   woken-up   40695      interval: min  1414     max       80043         avg  8846
 rcuog/0     pid:     14   woken-up   57907      interval: min    73     max       27855         avg  6217
 idd@1.0.    pid:   1116   woken-up   89498      interval: min   231     max    17442186         avg  4005
 rcu_preempt pid:     13   woken-up   90203      interval: min    39     max        8505         avg  3991
 iddd        pid:   1195   woken-up   250398     interval: min    92     max       16375         avg  1437
<wake-up-trace-log>
```

A trace was taken on the ARM big.LITTLE system. It is obvious that the biggest part belongs to the “iddd logger” whereas a second place is fully owned by the RCU-core subsystem marked as red.

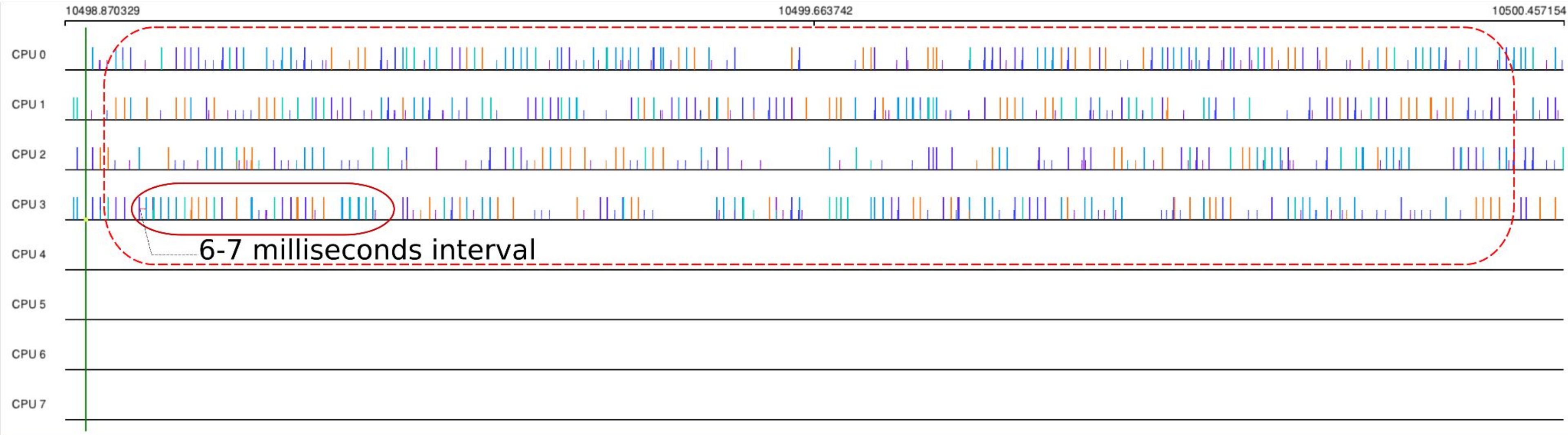
Observation: Logging in Android (as example)

RCU mostly invokes callbacks related to the VFS, SELinux subsystems during logging:

- `file_free_rcu()`
- `inode_free_by_rcu()`
- `i_callback()`
- `__d_free()`
- `avc_node_free()`

Since system is lightly loaded and a number of posted callbacks to be invoked are rather small, between 1-10, such pattern produce most of the wakeups (in static image use-case) to offload a CPU with __only__ few callbacks there.

Observation: Logging in Android



Search: Column # contains Next Prev ✓Graph follows

#	CPU	Time Stamp	Task	PID	Latency	Event	Info	
	2	10498.892424	rcuop/2	33	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=32 bl=10
	3	10498.892637	rcuop/3	40	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=10 bl=10
	1	10498.900003	rcuop/1	26	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=18 bl=10
	0	10498.900056	rcuop/0	15	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=10 bl=10
	2	10498.900083	rcuop/2	33	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=10 bl=10
	3	10498.900177	rcuop/3	40	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=18 bl=10
	0	10498.908245	rcuop/0	15	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=10 bl=10
	2	10498.908385	rcuop/1	26	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=17 bl=10
	0	10498.908493	rcuop/2	33	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=11 bl=10
	3	10498.908536	rcuop/3	40	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=25 bl=10
	0	10498.916187	rcuop/0	15	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=6 bl=10
	2	10498.916369	rcuop/1	26	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=17 bl=10
	3	10498.916574	rcuop/3	40	d..1	rcu/rcu_batch_start	rcu_preempt	CBs=29 bl=10

Only a few callbacks are invoked

Issue 2: RCU queuing CBs on lightly loaded system

Let us explore some solutions to this…

Issue 2: RCU queuing CBs on lightly loaded system

Solution 1: Delay RCU processing using `jiffies_till_{first,next}_fqs`

- Great power savings

`jiffies_till_first_fqs` & `jiffies_till_next_fqs`	Baseline (NOCB)	= 8, 8	= 16, 16	= 24, 24	= 32, 32
SoC+Memory, power savings w.r.t Baseline	0%	2%	3%	3.4%	3.2%

- Problem:
  - Causes slow down in ALL call_rcu() users globally whether they like it or not.
  - Causes slow down in synchronize_rcu() users globally.
  - Significantly regresses boot time.

Issue 2: RCU queuing CBs on lightly loaded system

Solution 1: Jiffies causes massive synchronize_rcu() slowdown.

- ChromeOS tab switching autotest
  - Due to `synchronize_rcu()` latency increases quickly from 23 ms to 169 ms (with changing jiffies from 3 to 32)

- The same evaluation with `synchronize_rcu_expedited()` gives us a latency of < 1 msec at jiffies = 32

Issue 2: RCU queuing CBs on lightly loaded system
Solution 1: Jiffies increase causing function tracer issues

Several paths in ftrace code uses `synchronize_rcu()`:

For but 2 examples:

- `pid_write()` triggered by write to `/sys/kernel/tracing/debug/tracing/set_ftrace_pid`
- ring buffer code such as `ring_buffer_resize()`

End result is `trace-cmd record -p function_graph` can take several more seconds to start and stop recording, than it would otherwise.

Issue 2: RCU queuing CBs on lightly loaded system

Solution 1: Jiffies causing boot-time issues (SELinux)

SELinux enforcing during ChromeOS boot up invokes synchronize_rcu()

```
[   17.715904]  => __wait_rcu_gp
[   17.715904]  => synchronize_rcu
[   17.715904]  => selinux_netcache_avc_callback
[   17.715904]  => avc_ss_reset
[   17.715904]  => sel_write_enforce
[   17.715904]  => vfs_write
[   17.715904]  => ksys_write
[   17.715904]  => do_syscall_64
```

Issue 2: RCU queuing CBs on lightly loaded system

Solution 1: Jiffies causing per-cpu refcount regression

- RCU used to toggle atomic-mode and vice versa
- Can badly hurt paths that don’t really want to free memory but use call_rcu() for some other purposes. Like suspend.
- `call_rcu()` slow down affects percpu refcounters
- These counters use RCU when switching to atomic-mode
  - `__percpu_ref_switch_mode() -> percpu_ref_switch_to_atomic_sync().`
- This call slows down for the per-cpu refcount users such as `blk_pre_runtime_suspend().`

This is why, we cannot assume `call_rcu()` users will mostly just want to free memory. There could be cases just like this, and blanket slow down of call_rcu() might bite unexpectedly.

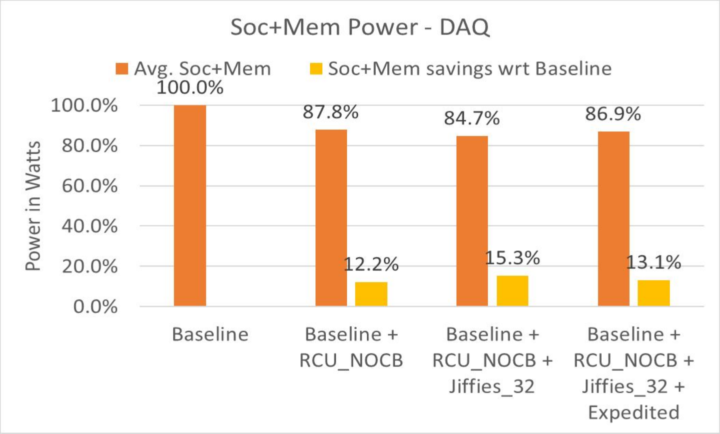
Issue 2: RCU queuing CBs on lightly loaded system

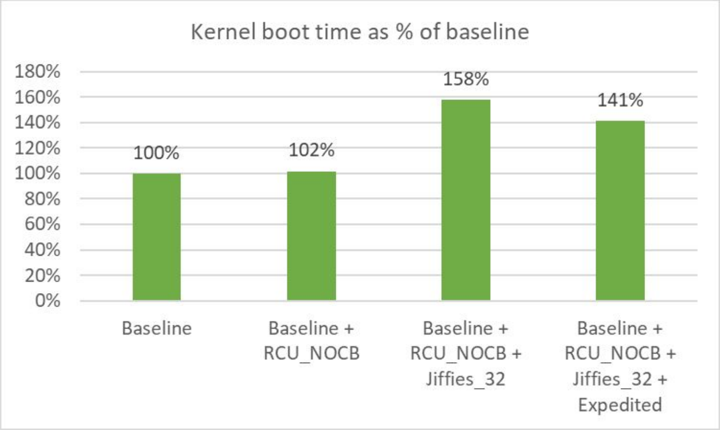
Solution 1: Jiffies with expedited option

- The previous synchronize_rcu() issues can be mitigated by using expedited boot option which expedites while ensuring good power efficiency.

- However, experiments showed that using expedited RCU with jiffies, still causes a boot time regression.

- Also, the expedited option is expensive, and can affect real-time workloads.





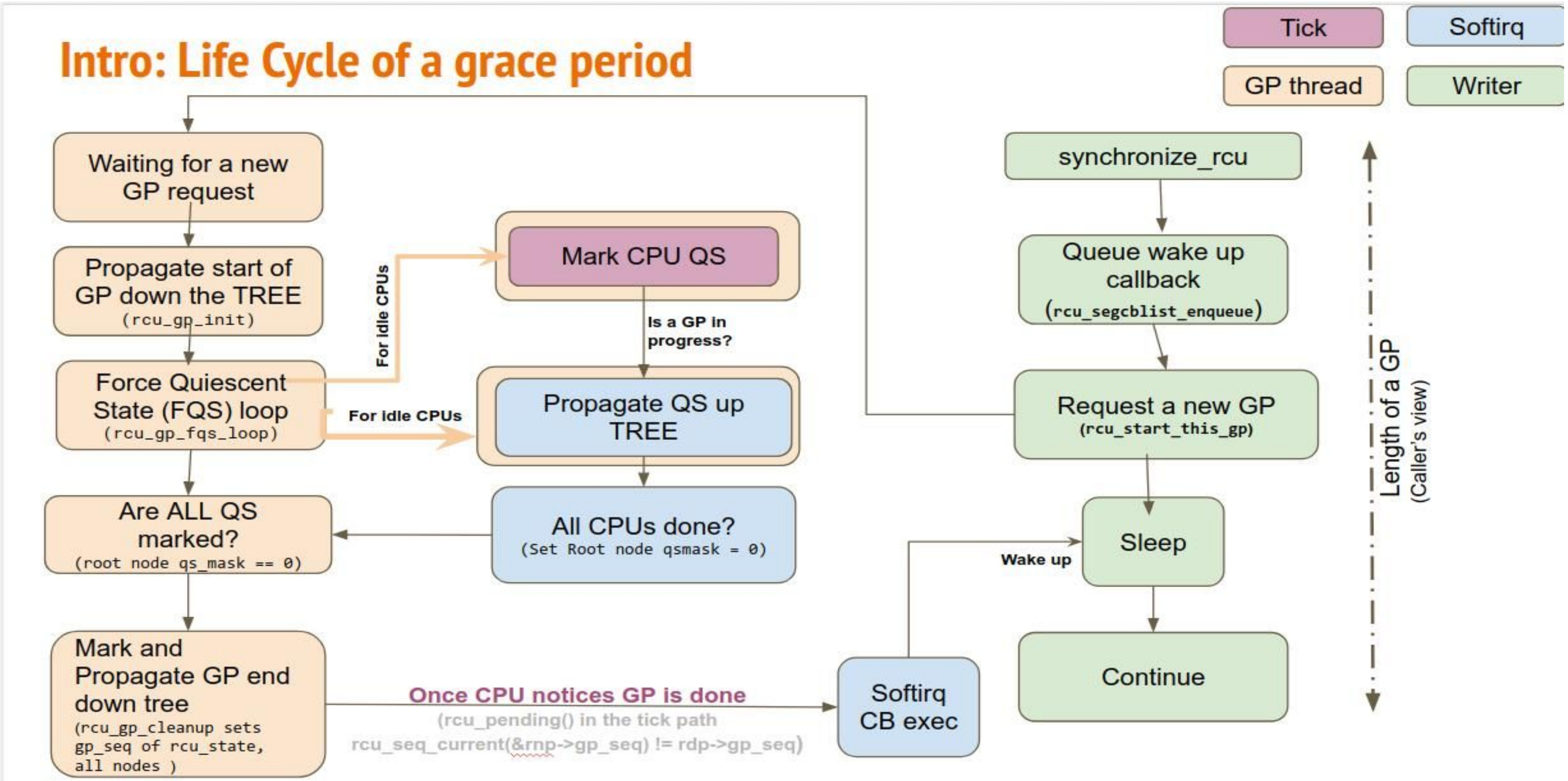
Issue 2: RCU queuing CBs on lightly loaded system

Solution 2: Delay RCU CB processing (Lazy RCU)

- Delay Callback execution as long as possible.
- Introduce new API for lazy-RCU (`call_rcu_lazy`).
- Need to handle several side-effects:
  - RCU barrier.
  - CPU hotplug etc
  - Memory pressure
  - Offloading and De-offloading.

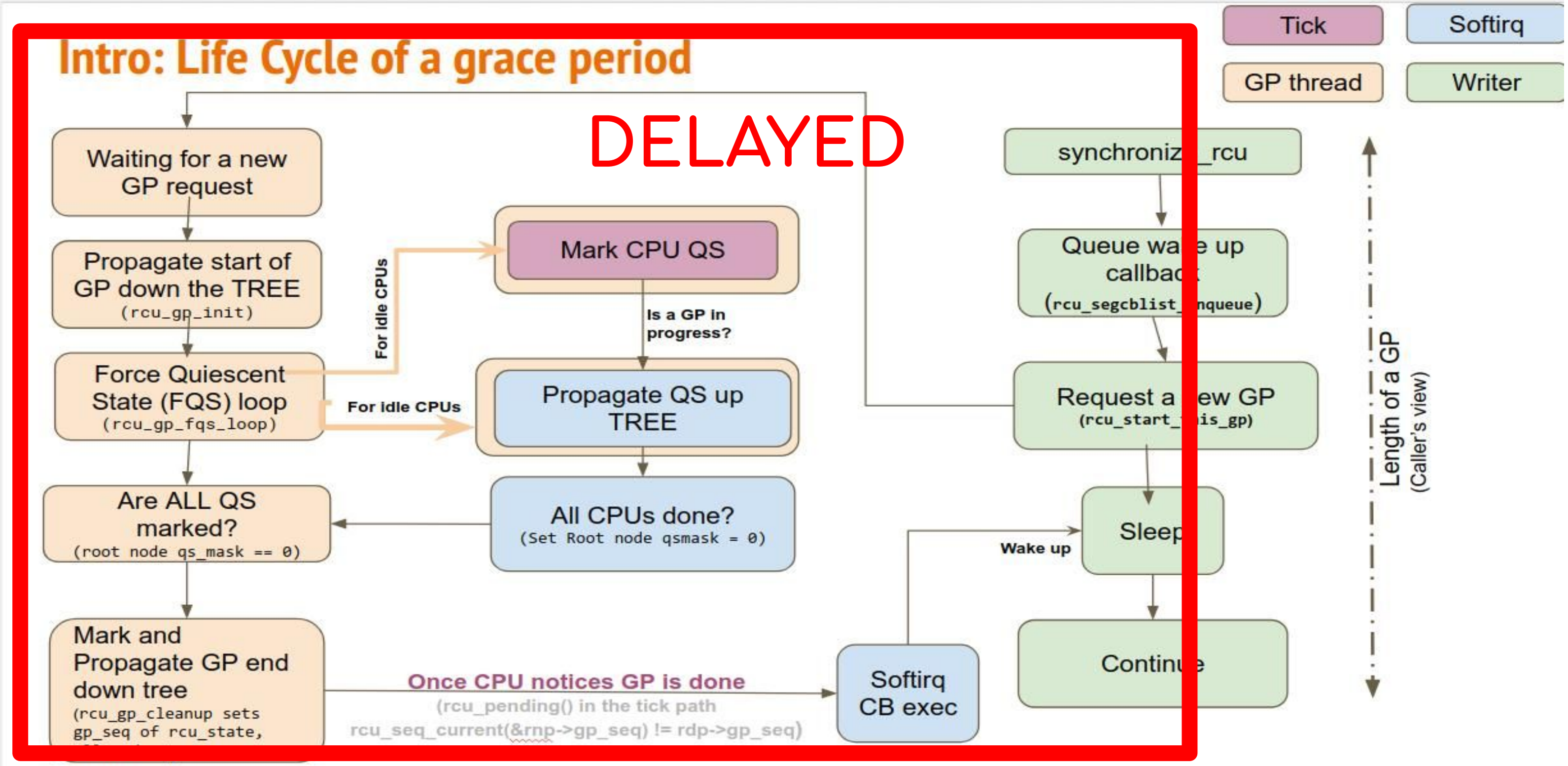
Issue 2: RCU queuing CBs on lightly loaded system

Solution 2: Delay RCU CB processing (Lazy RCU)



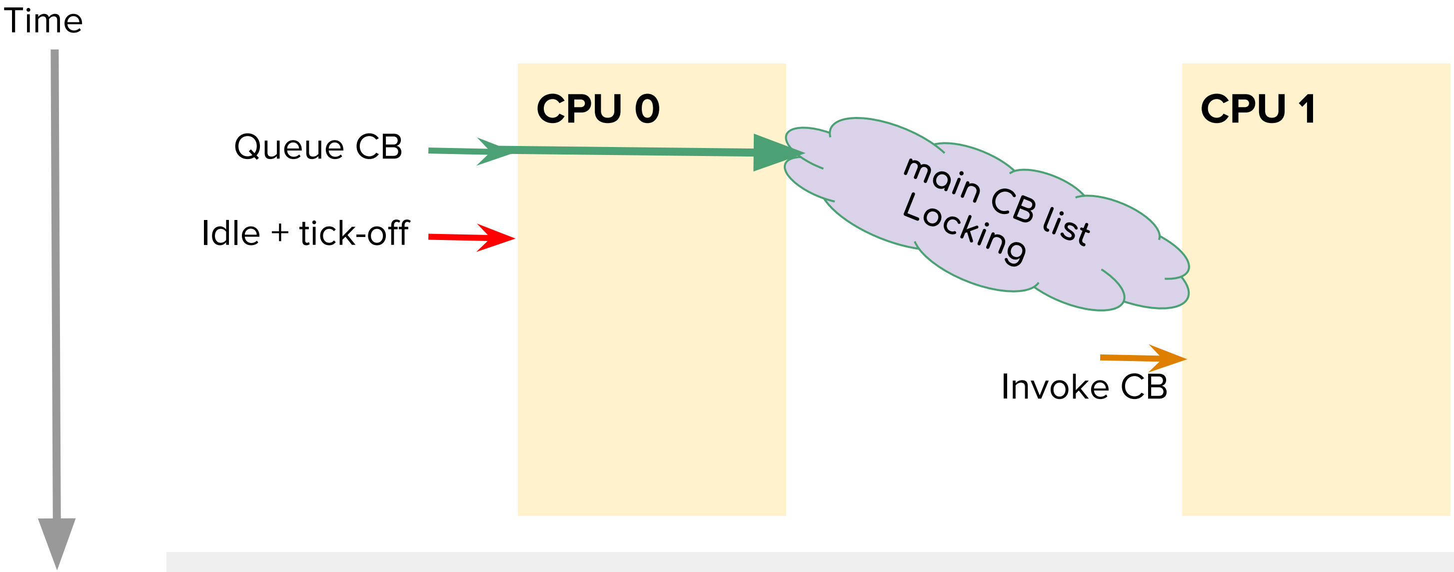
Issue 2: RCU queuing CBs on lightly loaded system

Solution 2: Delay RCU CB processing (Lazy RCU)



Issue 2: RCU queuing CBs on lightly loaded system

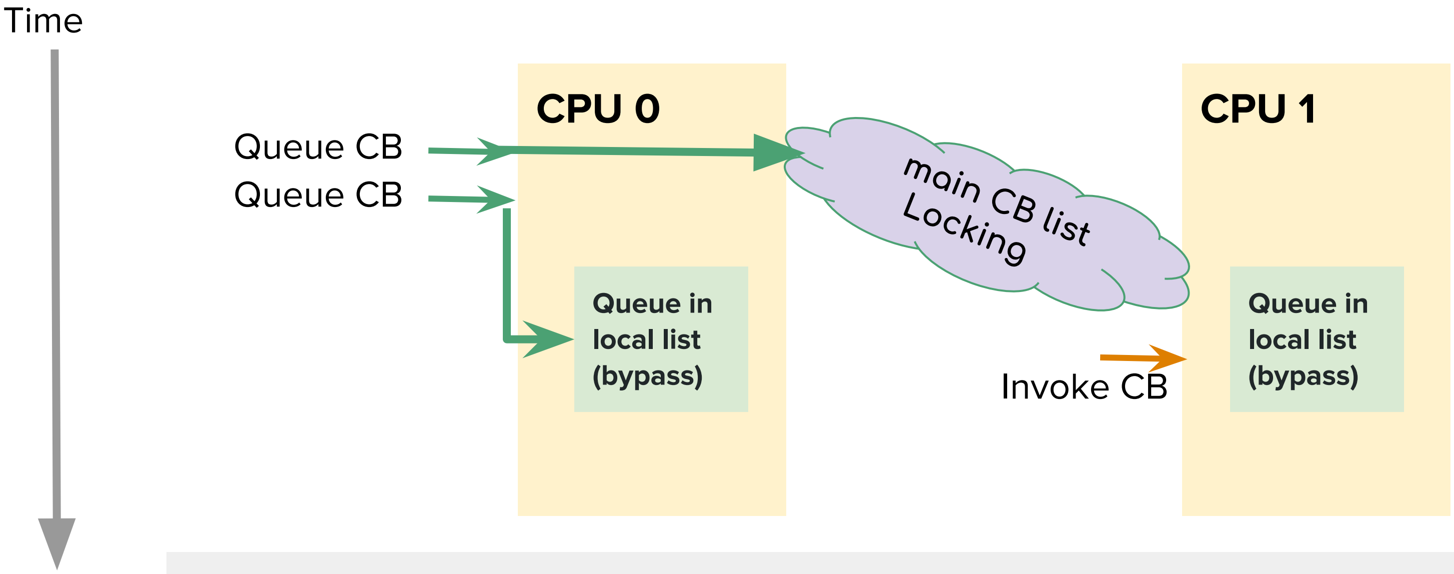
Lazy RCU: design approach



Can cause performance overhead on system with frequent CB queue/invoke due to locking!

Issue 2: RCU queuing CBs on lightly loaded system

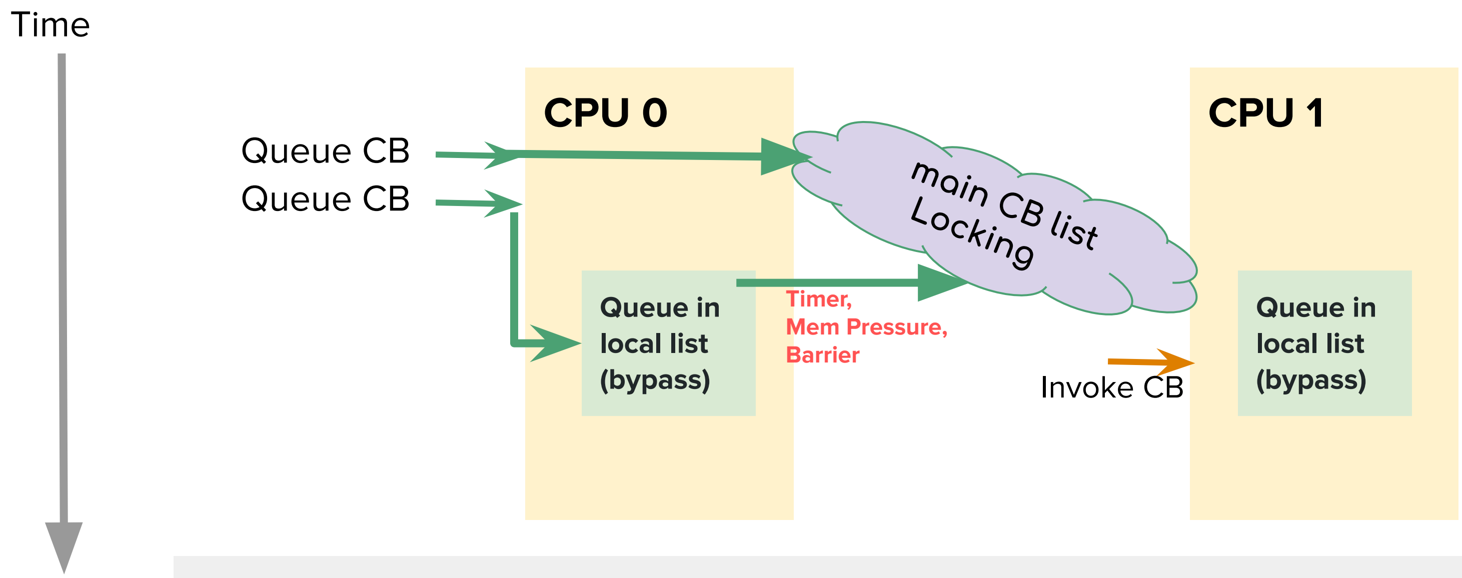
Lazy RCU: design approach - re-use the **bypass list.**



By-pass list is per-cpu and but batches CBs and wakes RCU 2 jiffy delay, and relieves lock contention on the main CB list.

Issue 2: RCU queuing CBs on lightly loaded system

Lazy RCU: design approach - re-use the **bypass list.**

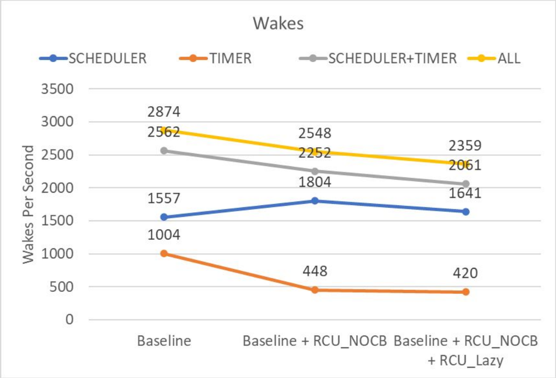


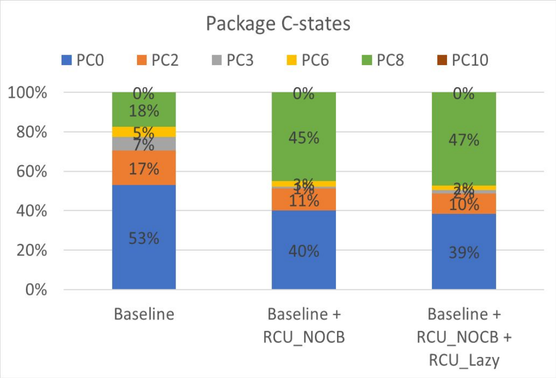
Flush the bypass list if there is memory pressure, or lengthy timer expires!

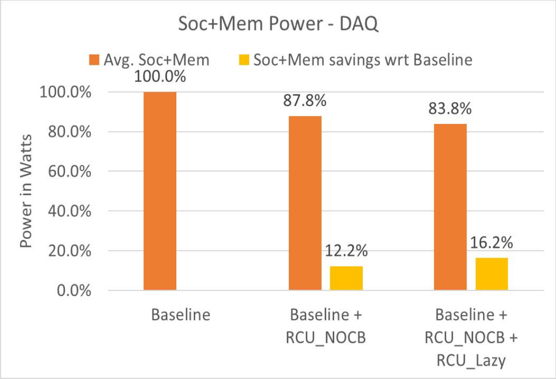
Issue 2: RCU queuing CBs on lightly loaded system

Solution 2: Delay RCU CB processing (Lazy RCU)

RCU lazy further reduces 300+ wakes per seconds, and improves SoC package C-states residency & Power







Use-case: Local video playback via Chrome browser, VP9 1080p @ 30 fps content

Device: Chrome reference device, AlderLake Hybrid CPU with 2 Cores (with Hyperthreading) + 8 Atoms

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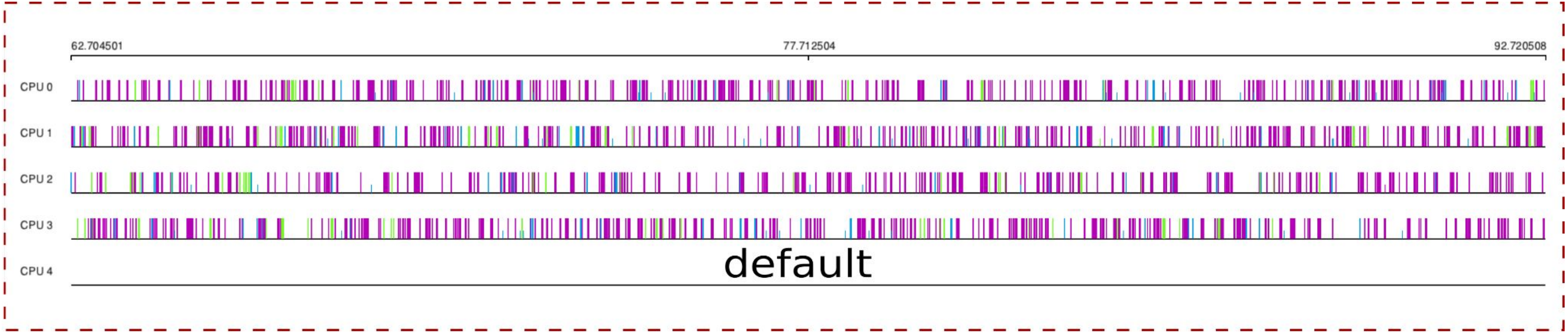
Latest Patches:

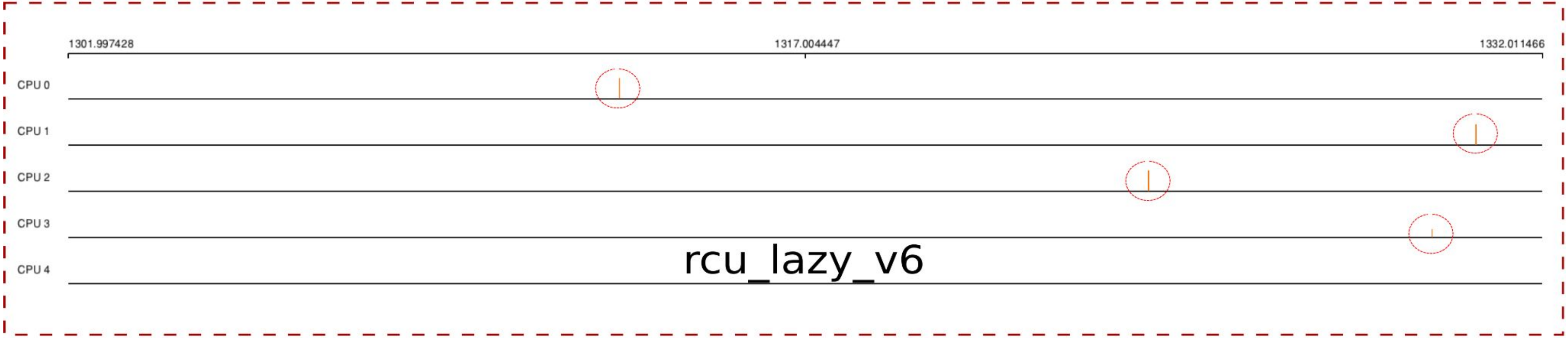
https://lore.kernel.org/all/20220819204857.3066329-1-joel@joelfernandes.org/

Summary:

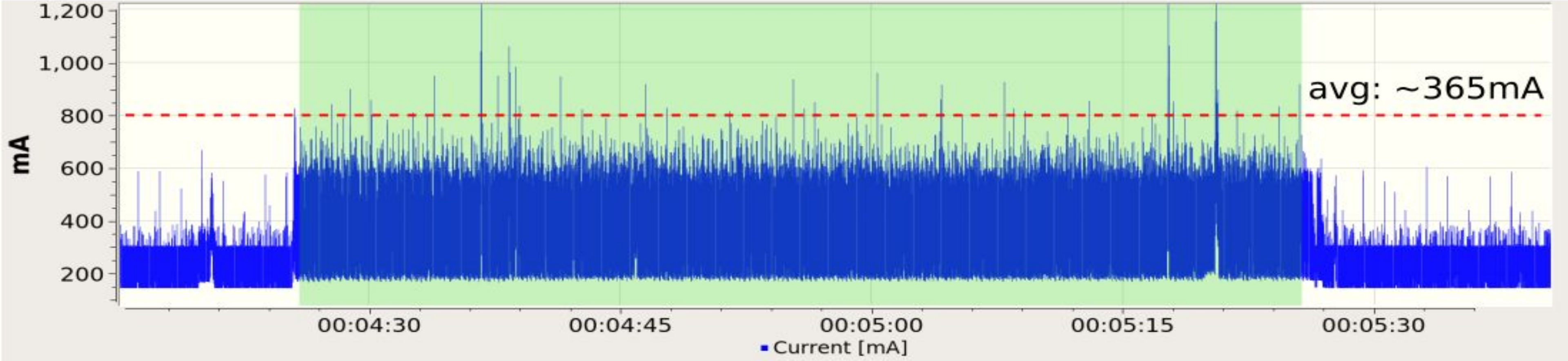
- Introduce new API for lazy-RCU (`call_rcu_lazy`).
- Queue CBs into the Bypass list.
- Flush the Bypass list when:
  - Non-Lazy CBs show up.
  - Bypass list grows too big or is too old.
  - Memory is low.
- Several corner cases now handled (`rcu_barrier`, CPU hotplug etc).

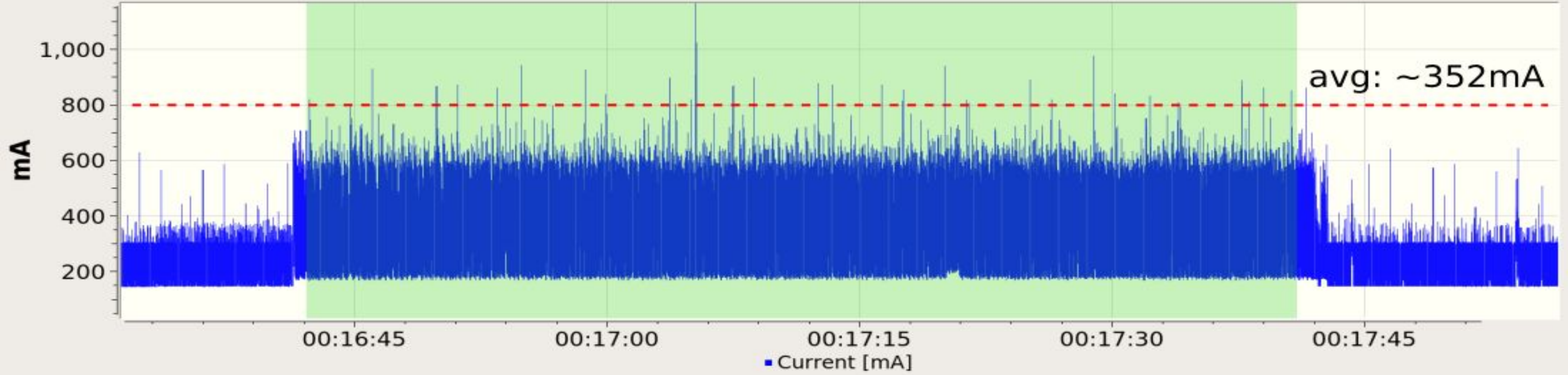
Home screen swipe (as example)





Home screen swipe power(~3% delta)





Observation: ChromeOS when idle

- Some CBs in the system “trickle” frequently.
- Several callbacks constantly queued.

```
21:57:07 loadavg: 0.06 0.50 0.55 2/629 8945
```

Callback	Queued	Executed
inode_free_by_rcu	7	10
delayed_put_task_struct	7	15
k_itimer_rcu_free	9	9
radix_tree_node_rcu_free	16	27
rcu_work_rcufn	1	2
put_cred_rcu	4	8
delayed_put_pid	7	15
unbind_fence_free_rcu	4	5
dst_destroy_rcu	4	10
__i915_gem_free_object_rcu	5	10
thread_stack_free_rcu	3	7

rcutop refreshing every 5 seconds. ChromeOS logged in with screen off. Device on battery power.

Callback	Queued	Executed
avc_node_free	41	0
k_itimer_rcu_free	5	0
thread_stack_free_rcu	23	0
file_free_rcu	576	0
delayed_put_pid	44	0
radix_tree_node_rcu_free	17	0
i_callback	55	0
__d_free	55	0
dst_destroy_rcu	2	0
epi_rcu_free	7	0
delayed_put_task_struct	44	0
inode_free_by_rcu	94	0

Drawbacks and considerations

- Depends on user of call_rcu() using lazy
  - If a new user of call_rcu() shows up, it would go unnoticed and negate the benefits.
  - Updates to docs may help: https://docs.kernel.org/RCU/whatisRCU.html#id11

- Risk of user using call_rcu_lazy() accidentally when they should really use call_rcu(). For example, a use case requiring synchronous wait.

- Risks on memory pressure:
  - Protection is enough on extreme condition?
  - Can test with more test cases such as ChromeOS memory pressure test.

Thanks!

- Paul McKenney (for putting up with us).
- Presenters.
- LPC sponsors and organizers.
- Frederic Weisbec for reviewing code.

Questions?