Make RCU do less (& later) !

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Intel power data courtesy: Sitanshu Nanavati.

Linux Plumbers Conference

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Overview

- 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?

- 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 GCs old object after waiting (**update**)

What RCU does?

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- 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.

What RCU does?

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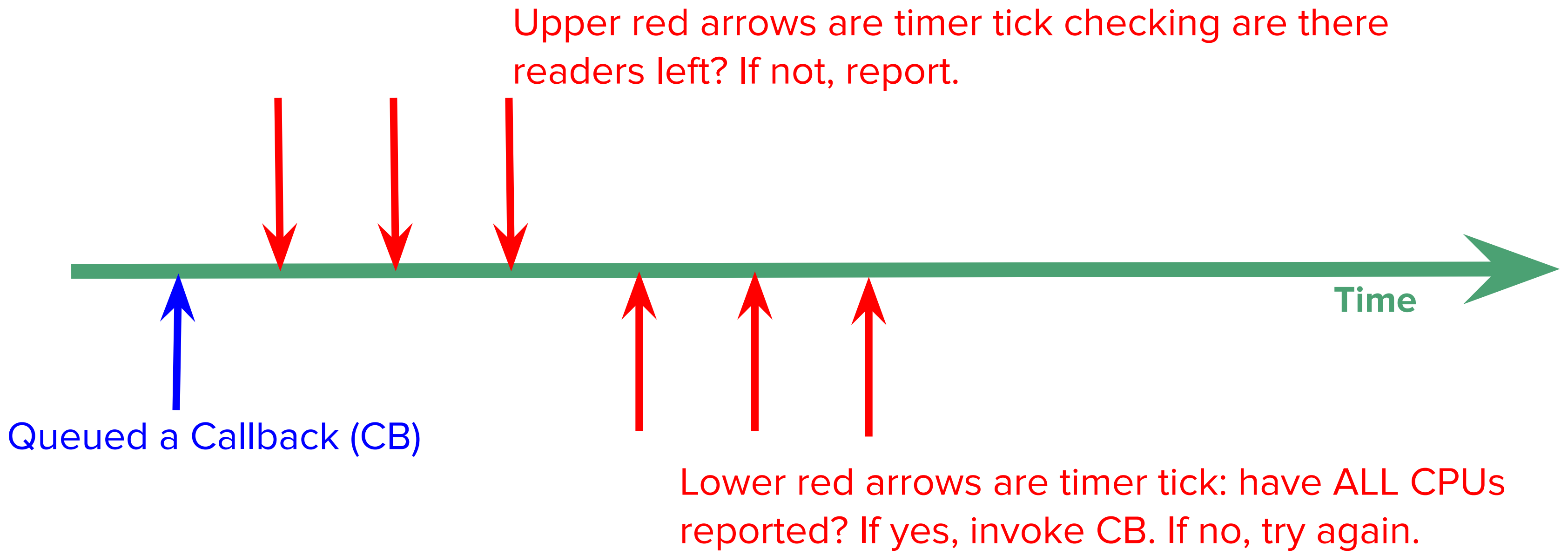
- On a local CPU (running in **kernel mode** with CB queued).



What RCU does?

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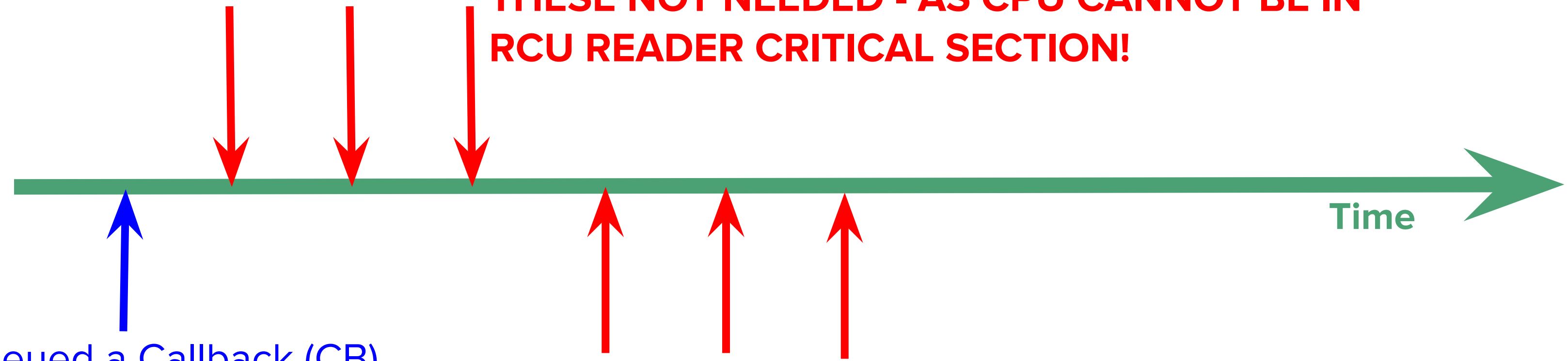
- On a local CPU (running in **idle mode** with CB queued).

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)

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 the main RCU maintainer, this issue is courtesy of the use case queuing a lot of RCU Callbacks on otherwise idle CPUs, in the first place).

What RCU does?

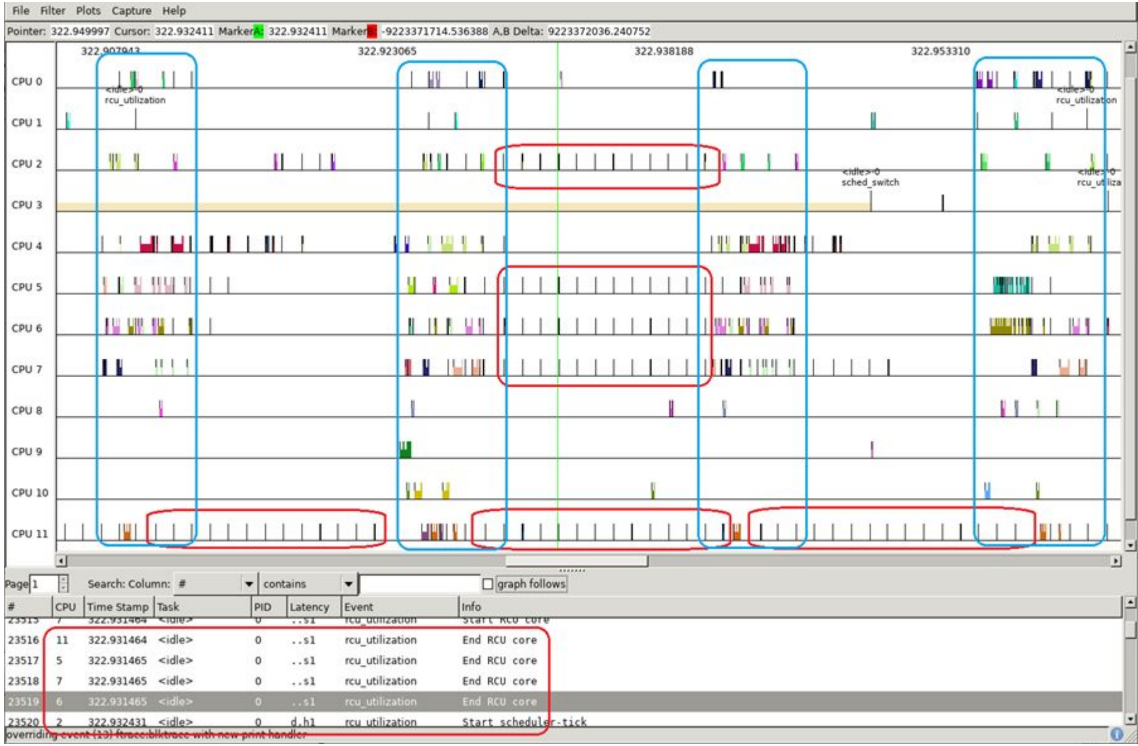
- This happens even in user mode
- NOHZ_FULL systems typically turn tick off.
- RCU can keep it on (if CBs are queued on a ‘nohz full’ CPU)

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

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

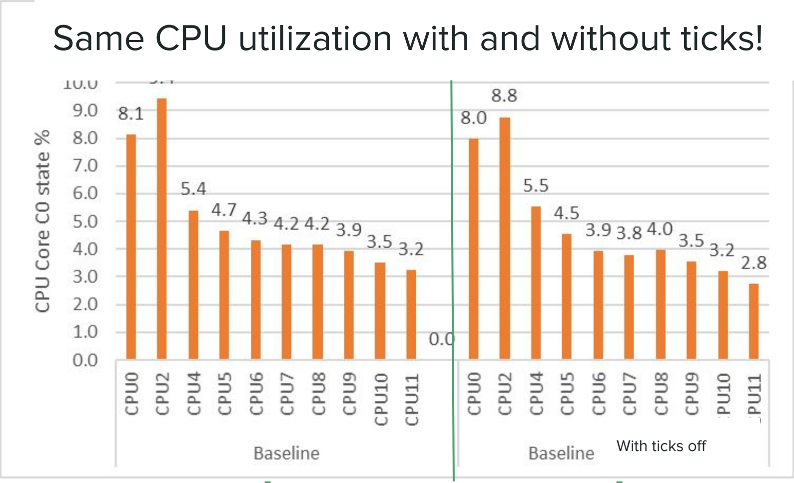
- RCU wakes are seen at HZ rate (red boxes) between graphics 16.6ms activity (blue boxes)

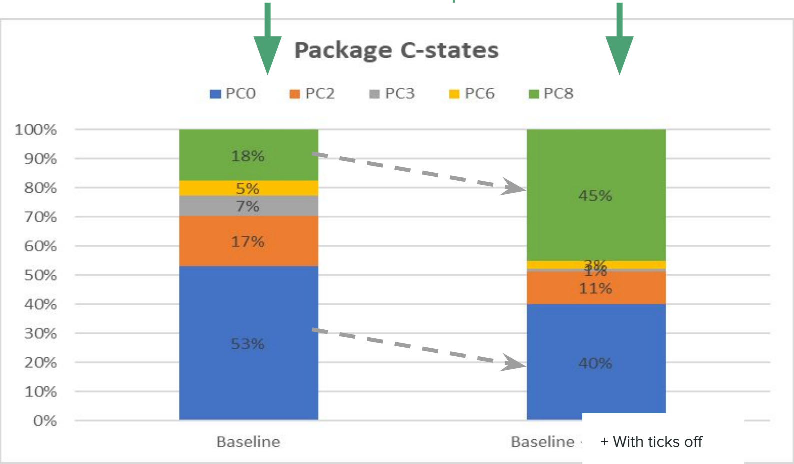
- Blocks deeper Package C-states. Impacts power



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, RCU 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 idle ticks are so bad for power

What are package C-states?

- Traditionally ACPI C-states were CPU 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.
- 1000 HZ ticks do not block core C-states much
- E.g. Sandy Bridge C-states table (2011)

```
static struct cpuidle_state snb_cstates[] __initdata = {
        {
                .name = "C1",
                .exit_latency = 2,
                .target_residency = 2,
        {
                .name = "C1E",
                .exit_latency = 10,
                .target_residency = 20,
        {
                .name = "C3",
                .exit_latency = 80,
                .target_residency = 211,
        {
                .name = "C6",
                .exit_latency = 104,
                .target_residency = 345,
        {
                .name = "C7",
                .exit_latency = 109,
                .target_residency = 345,
        {
                .enter = NULL }
};
```

Why idle ticks are so bad for power

What are package C-states?

SoC architecture provides opportunity to extend the OS C-states hints to power manage the entire SoC.

SoCs have power management unit (HW + microcode), which coordinates CPU, IP blocks and common logic, to put entire SoC in low power mode.

Package C-states add extended C-states with high exit latency & target residency.

1000 HZ ticks would impact deeper package C-states,

E.g. AlderLake C-state table 2021

```
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

Why was RCU keeping the tick on?

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

Advantages:

- Timely detection of GP end and thus execution of queued CBs.
- 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!

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

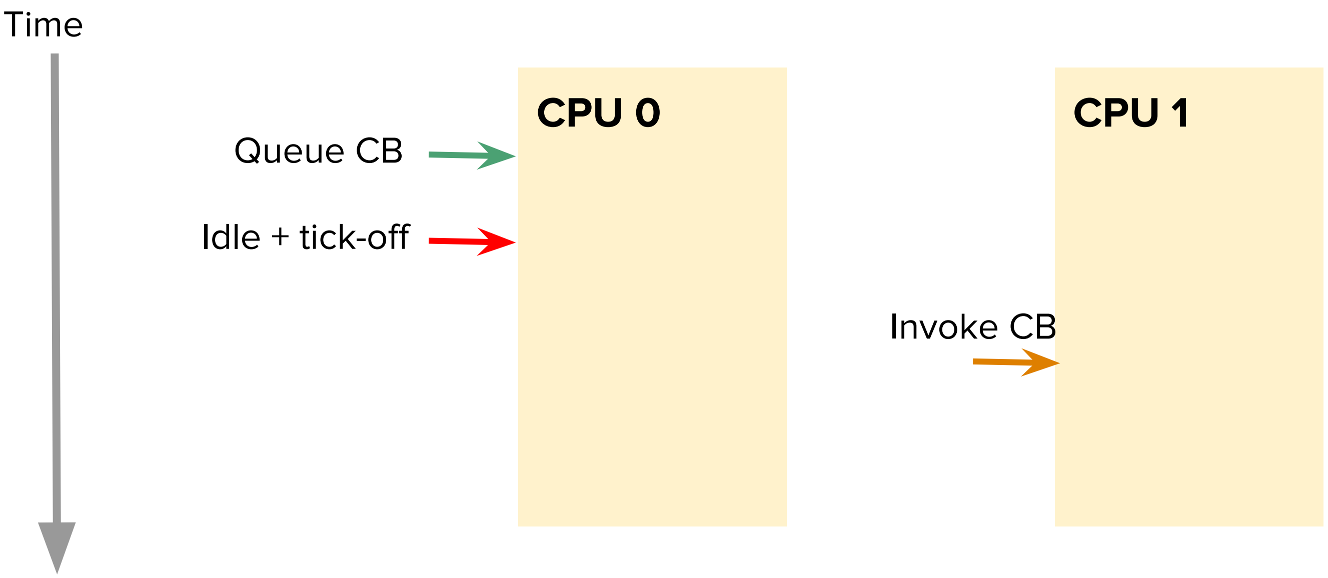
Possible solution: Using `CONFIG_FAST_NOHZ` option

- CPUs enter the dyntick-idle state (the state where the tick is turned off) even if they have CBs queued.

- Idle CPUs with callbacks check RCU state every 4 jiffies.
  - 4 jiffies for non-kfree CBs.
  - 6 jiffies or so for kfree CBs.

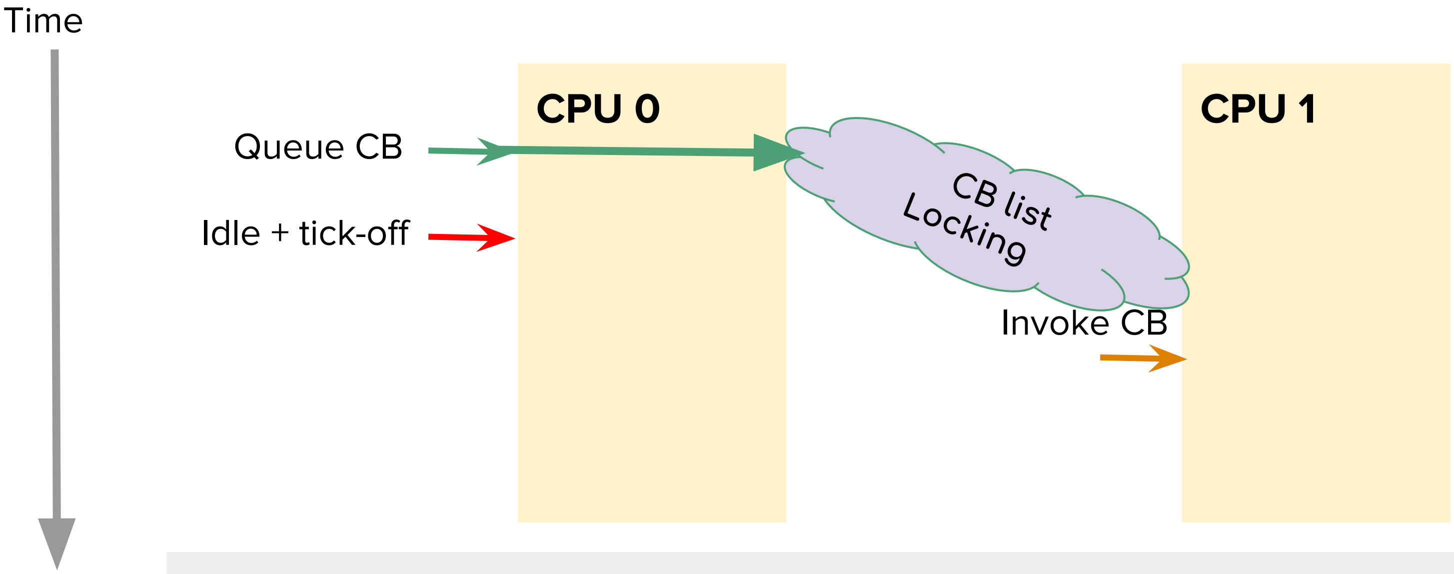
Issue 1: RCU keeping the scheduler tick ON when idle.

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.

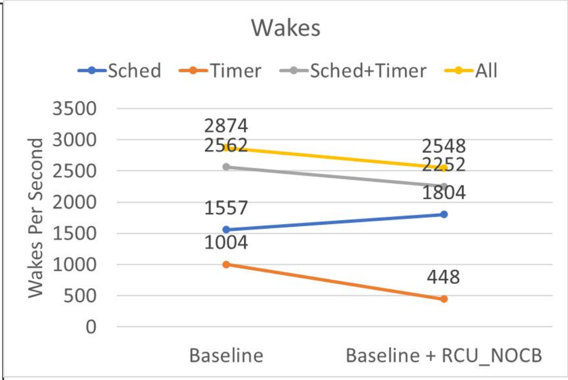
Solution for newer kernels: CONFIG_RCU_NOCB_CPU

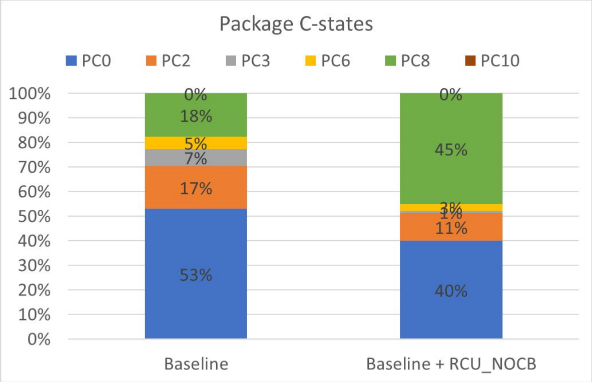
However, can be great for power and CPU isolation…

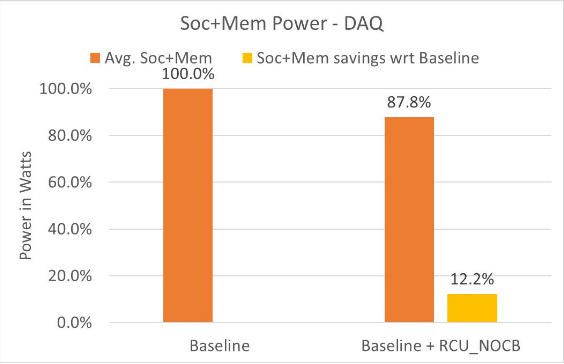
- Scheduler may move threads to non-idle CPUs thus leaving more idle.
- **Both** starting of new grace periods, and executing CBs are moved out of the softirq context and into threads.

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

- 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.

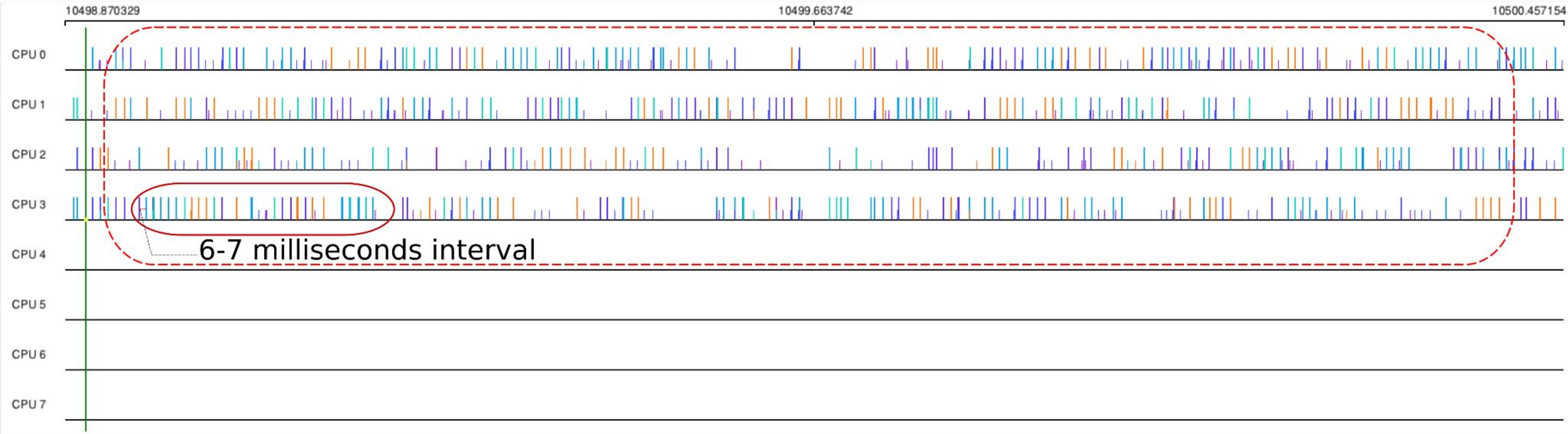
Observation: Logging in Android (as example)

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

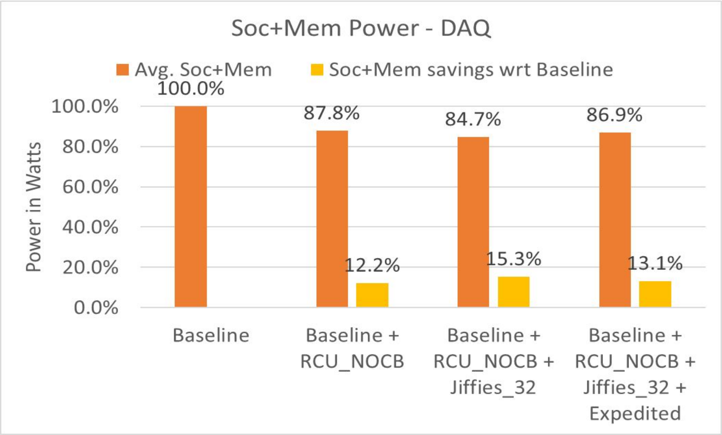
- RCU used to toggle atomic-mode and vice versa
- Can badly hurt paths that don’t really want to free memory but use call_rcu() for some other purposes. Like suspend.
- `call_rcu()` slow down affects percpu refcounters
- These counters use RCU when switching to atomic-mode
  - `__percpu_ref_switch_mode()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

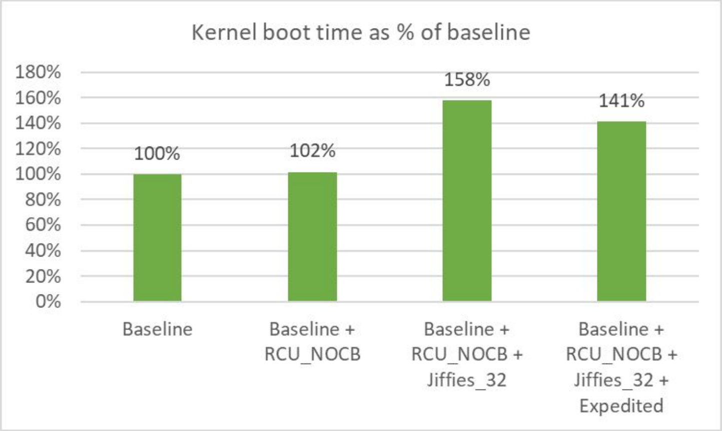
This is why, we cannot assume `call_rcu()` users will mostly just want to free memory. There could be cases just like this, and blanket slow down of call_rcu() might bite unexpectedly.

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.





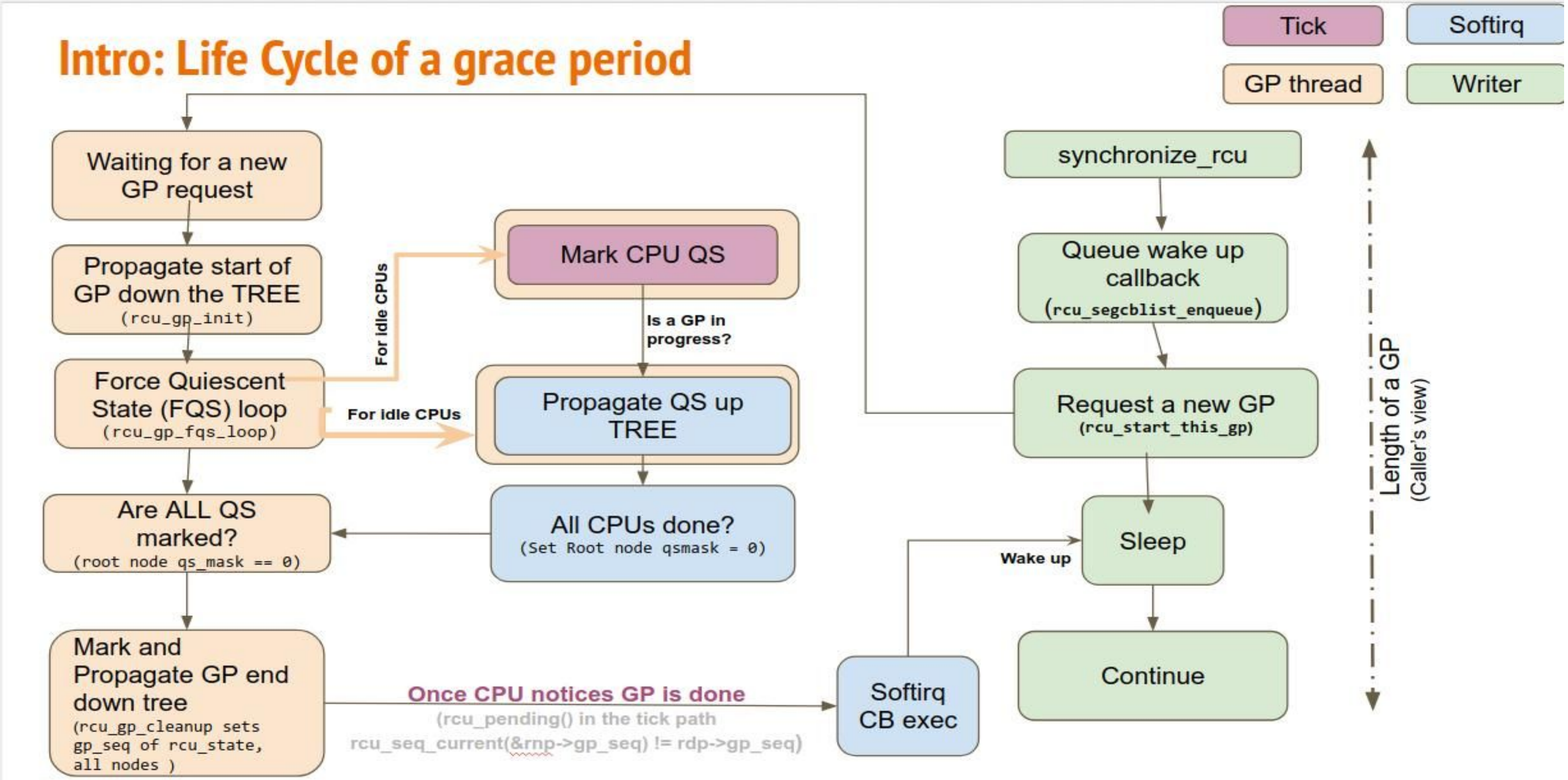
Issue 2: RCU queuing CBs on lightly loaded system

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.

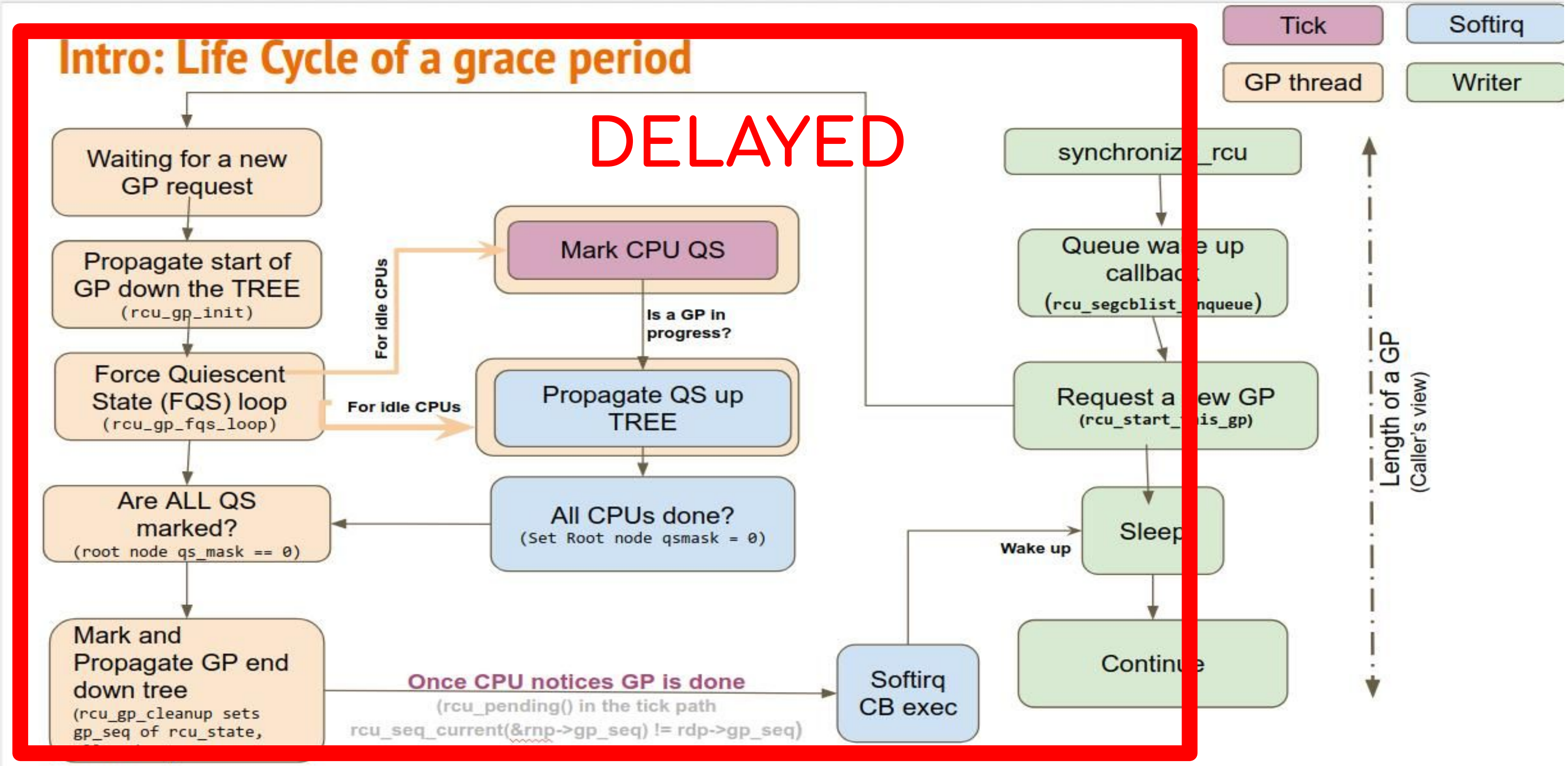
Issue 2: RCU queuing CBs on lightly loaded system

Solution 2: Delay RCU CB processing (Lazy RCU)



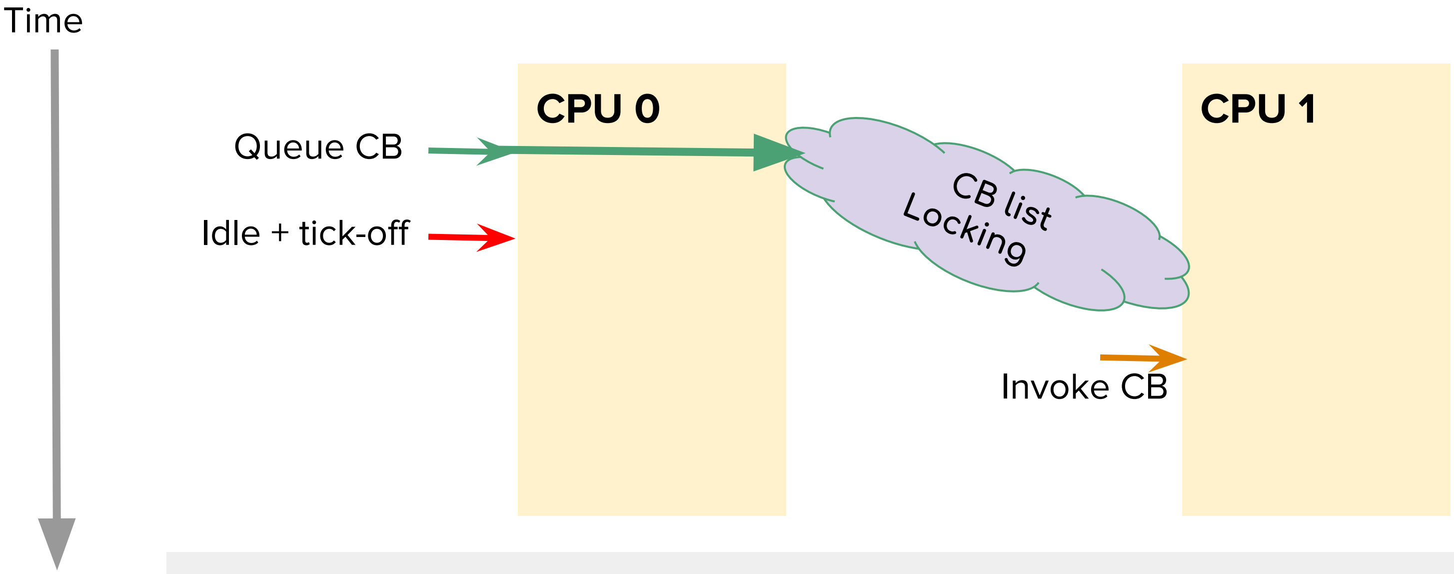
Issue 2: RCU queuing CBs on lightly loaded system

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!

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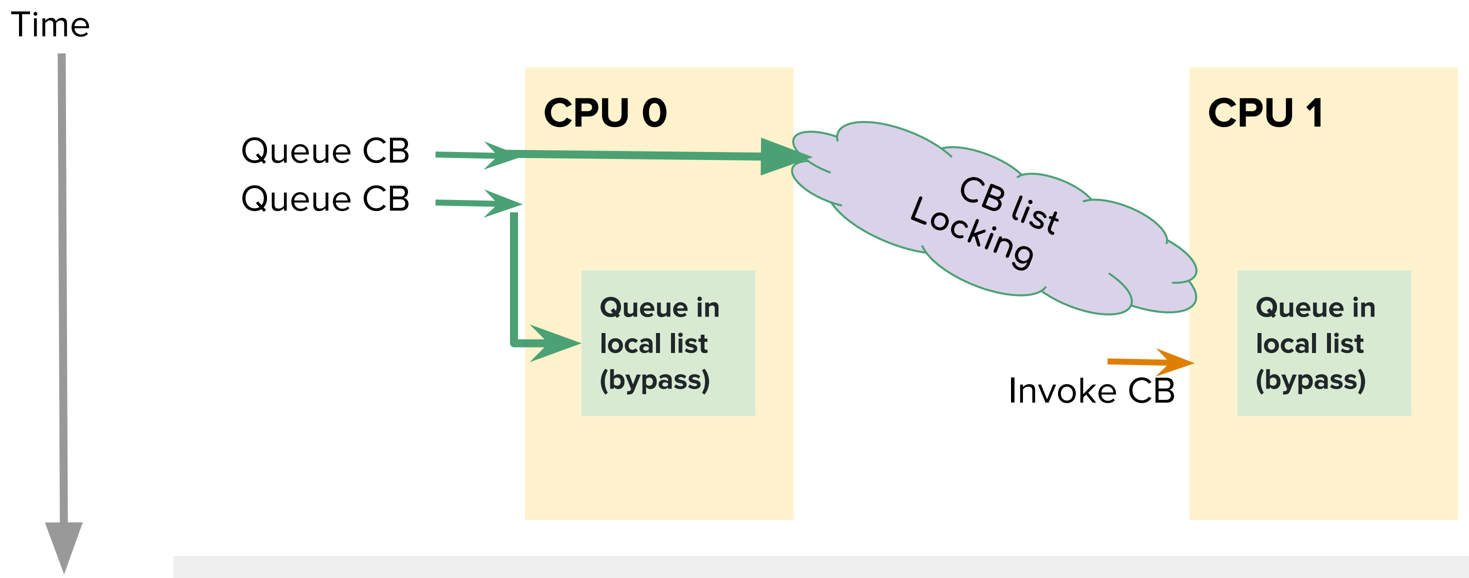
Lazy RCU: design approach - re-use the **bypass list.**



By-pass list is per-cpu and (almost) lock free!

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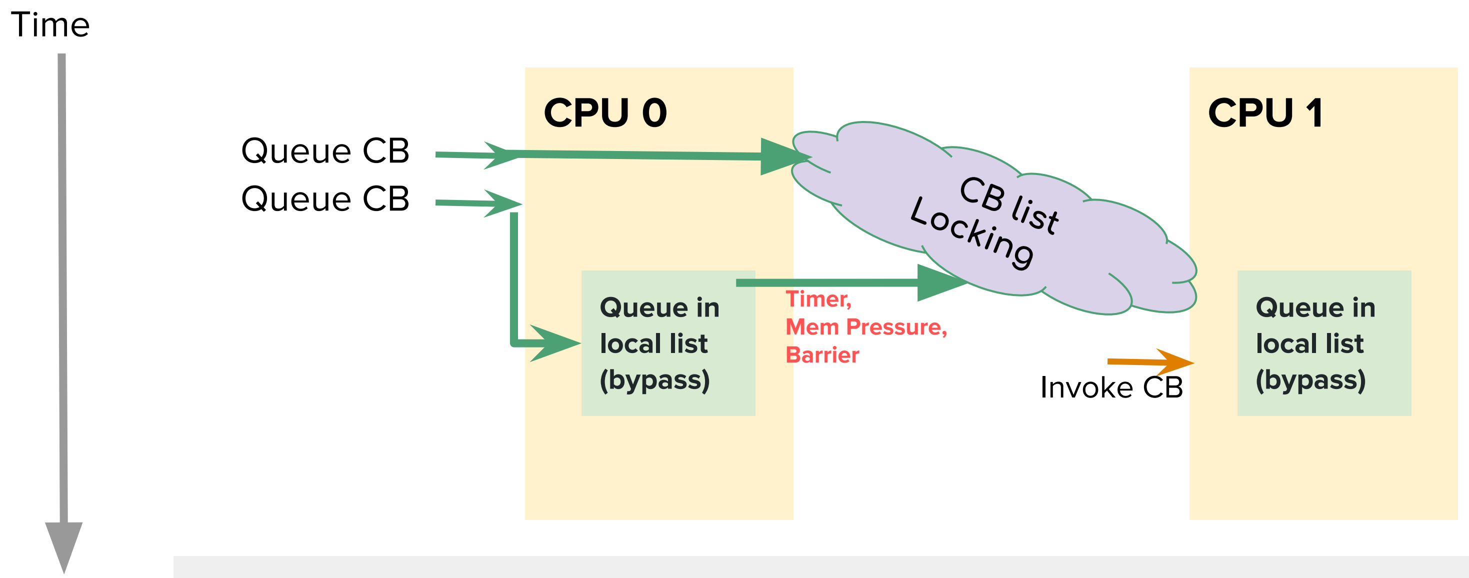
Lazy RCU: design approach - re-use the **bypass list.**

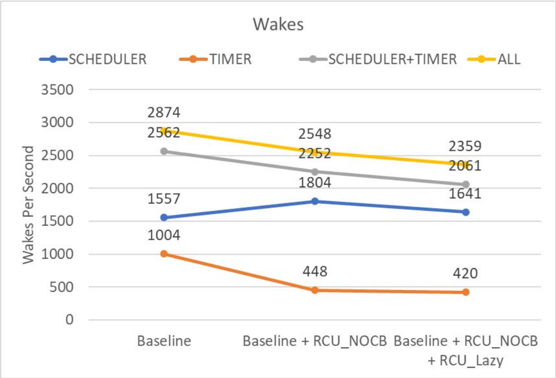


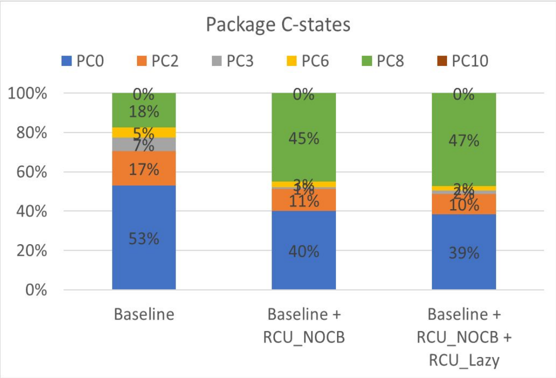
Flush the bypass list if there is memory pressure, or lengthy timer expires!

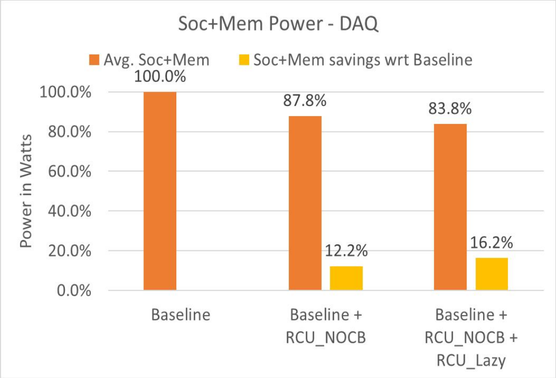
Issue 2: RCU queuing CBs on lightly loaded system

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

Issue 2: RCU queuing CBs on lightly loaded system

Solution 2: Delay RCU CB processing (Lazy RCU)

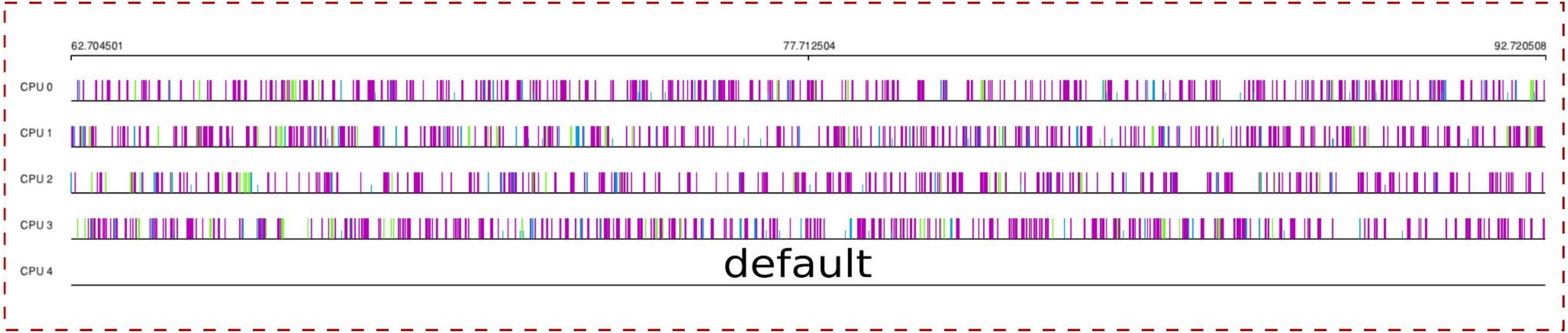
Latest Patches:

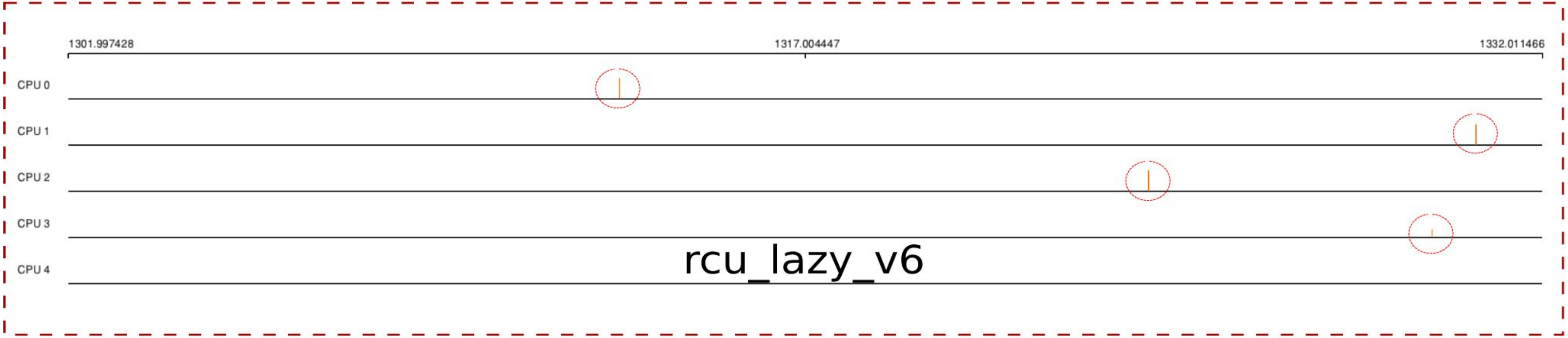
https://lore.kernel.org/all/20220819204857.3066329-1-joel@joelfernandes.org/

Summary:

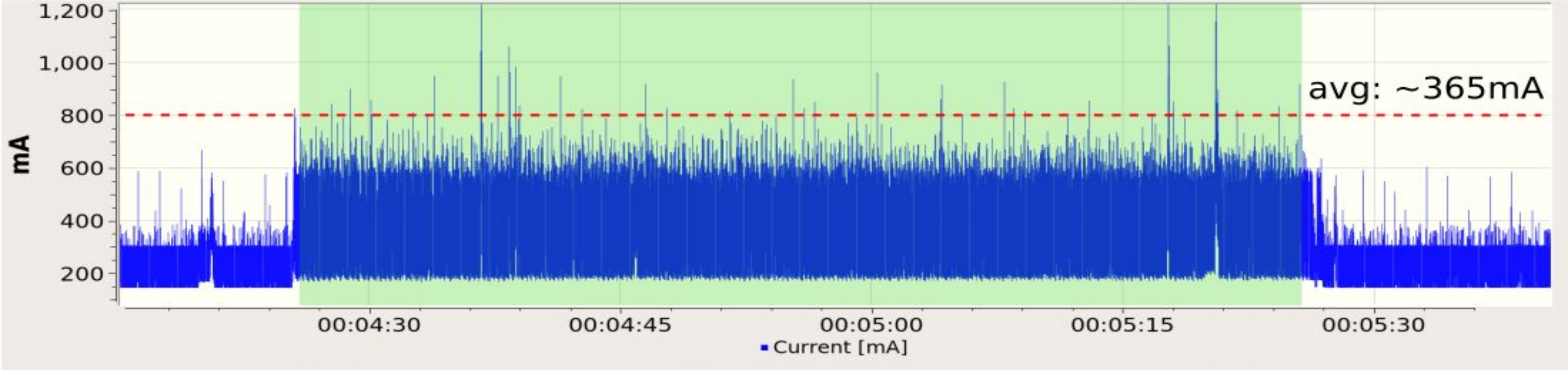
- Introduce new API for lazy-RCU (`call_rcu_lazy`).
- Queue CBs into the Bypass list.
- Flush the Bypass list when:
  - Non-Lazy CBs show up.
  - Bypass list grows too big.
  - Memory is low.
- Several corner cases now handled (`rcu_barrier`, CPU hotplug etc).

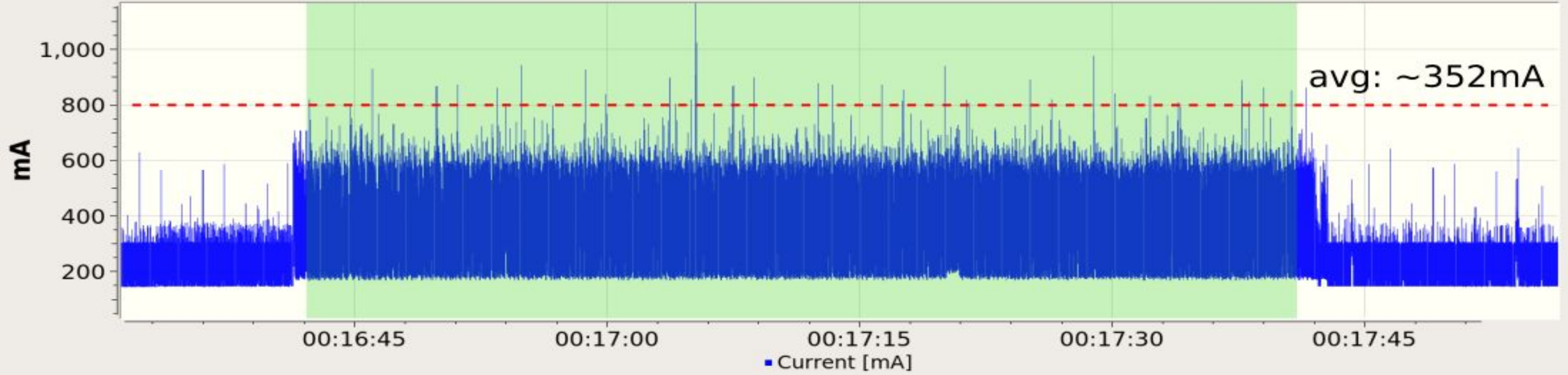
Home screen swipe (as example)





Home screen swipe power(~3% delta)





Observation: ChromeOS when idle

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- 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?