Core Scheduling

Taming the hyper-threads to be secure!

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Agenda

- Problem Statement
- Core Scheduling Introduction
- Core Scheduling Implementation
- Testing & benchmarking
- Core Scheduling Future work
- Conclusion

A brief history of side-channel attacks

- Meltdown
  - Exploits the out of order execution during an exception
  - Data left in L1 cache after out of order execution effects are reverted
  - Attack during context switch to kernel in the same cpu
  - Fix: Page Table Isolation
- Spectre variant 1
  - Exploits the speculative execution of conditional branches
  - Data left in L1 cache after out of speculation execution effects are reverted
  - Attack from userspace to kernel.
  - Process attacks are possible if a process(attacker) can pass data to another(victim)
  - Fix: usercopy/swapgs barriers, __user pointer sanitization

A brief history of side-channel attacks (Contd...)

- Spectre variant 2
  - Exploits the speculative execution of indirect branches
    - Data left in L1 cache after out of speculation execution effects are reverted
  - Attacks possible from userspace to kernel, user process to user process, VM to Host and VM to VM
  - Fix: Hardware(IBPB, IBRS, STIBP), Software(retpoline)
- L1TF
  - Exploits the speculative execution during a page fault when the present bit is cleared for a PTE
    - Data left in L1 cache after out of speculation execution effects are reverted
    - Any physical page can be leaked
  - Fix : L1D cache flush on privilege boundaries

A brief history of side-channel attacks (Contd...)

- MDS
  - Data leak from microarchitectural temporary buffers
  - MSBDS
    - Store buffer not shared across Hyper-Threads, but repartitioned on entering idle
  - MFBDS
    - Fill buffer shared
  - MLPDS
    - Load ports shared
  - MDSUM : Special case of all the above

Fix

- L1TF Vulnerable CPUs
  - L1TF mitigations fixes MDS as well
- Non L1TF CPUs
  - CPU Buffers flush on privilege boundaries

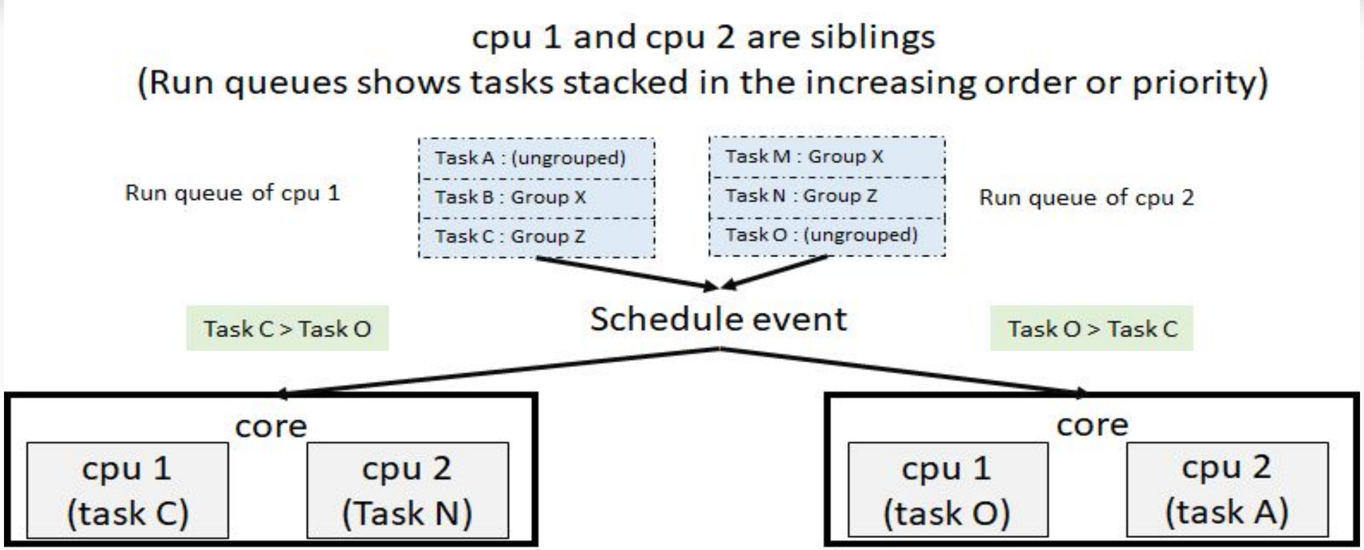
A brief history of side-channel attacks (Summary)

- There are no mitigations that are SMT-safe for L1TF and MDS
  - Attack by leaking information from shared resources (caches, micro-architectural buffers) of a core
  - Mitigations mostly involve cache flush and micro-architectural buffer flushes on privilege boundarie switches, but concurrent execution on siblings cannot leverage this.
- So the current state is:
  - Process running on a logical CPU cannot trust the process running on its sibling
  - Disabling SMT is the only safe option
- Disabling SMT has a noticeable performance impact on several types of workloads
- What if, we can make sure that non-trusting threads never gets to share resources exposed by SMT?

Core Scheduling: Concepts

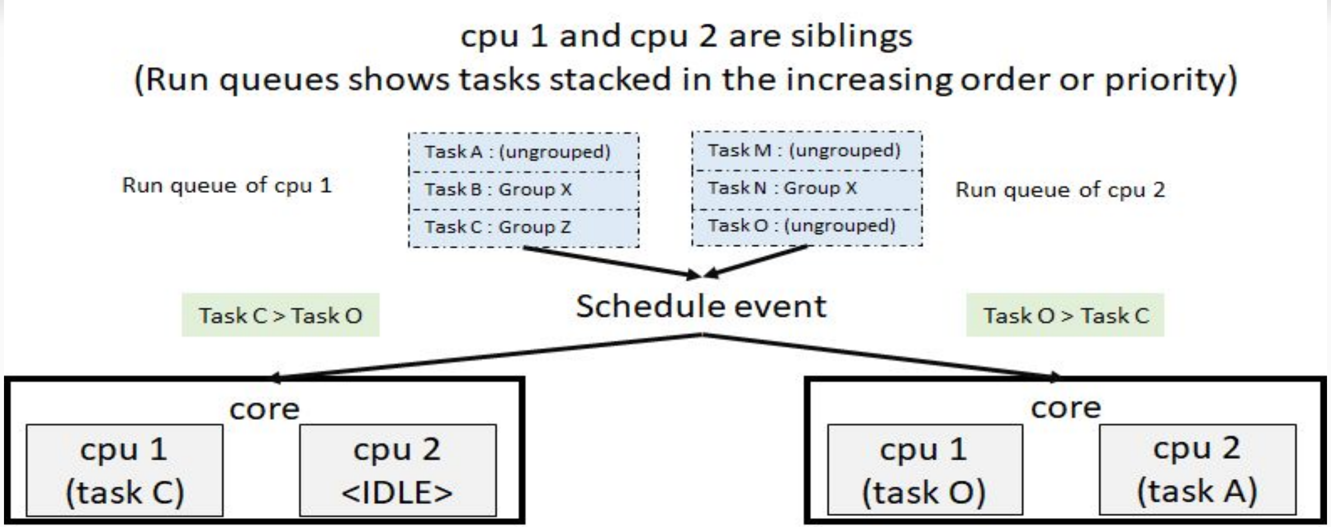
- Have a core wide knowledge when deciding what to schedule on cpu instances
- Grouping of trusted tasks and a mechanism to quickly search for a runnable trusted task in a group
- Forcing a sibling to not run any tasks if it cannot find a runnable trusted task in the same group as the other sibling
- Load balance the cpus so that groups of trusted tasks are spread evenly on the siblings.
    - When a cpu is forced idle, search for a runnable task with matching cookie and migrate it to the forced idle cpu.

Core Scheduling : task match




```
If task C has more priority than  Task O
        Schedule Task C and Task N together (same group)
else
        Schedule Task O and task A (no groups)
```

Core Scheduling : no task match




```
If task C has more priority than  Task O
         Schedule Task C on cpu1 and force cpu2 to be idle
         (Task C do not have a matching task in cpu 2's rq)
else
         Schedule Task O and task A (no groups)
```

Core Scheduling: History

- Core Scheduling patch for KVM
  - vcpu threads trust only other vcpu threads from the same VM
- Generic Core scheduling iteration
  - Generic solution to the initial core scheduling patches
  - Grouping of trusted processes which could be scheduled together on a core.
  - Policy to determine group of tasks that trust each others
    - Initial prototype uses cpu cgroups
      - Quick and easy to prototype

Core Scheduling: KVM based approach

https://github.com/pdxChen/gang/commits/sched_1.23-base

- VCPU threads of the same VM are tagged with a cookie
- To efficiently search for a runnable thread with the same cookie, cookie ordered rbtree in each cpu's run queue.
- Per core shared data to track the state(sched_domain_shared)
- When a vcpu thread is runnable, it IPI's its sibling. Sibling on __schedule() checks if there is a matching vpcu thread and if yes, coschedules both
  - On no match, it picks the idle thread so that sibling does not run an untrusted thread.
- Matching logic took care of the various synchronization points
  - VMEXIT, Interrupts, schedule

Core Scheduling Generic Approach

- Core wide knowledge used when scheduling on siblings
  - One sibling's rq is selected to store the shared data and that rq->lock becomes the core wide lock for core scheduling.
- While picking the next task in __schedule() if a tagged process is selected, we initiate a selection process
  - Tries to pick the highest priority task from all the siblings of a core and then matches it with a trusted task from the other sibling.
    - If the highest priority process is tagged, find a process with same tag on the other sibling
    - If the highest priority process is untagged, highest untagged process from the other sibling is selected.
    - If a match cannot be found on a sibling, it is forced idle

Core Scheduling Implementation details

- Grouping trusted processes together
  - cpu cgroups: processes under a cgroups are tagged if cpu.tag = 1
  - Cookie is a 64bit value - using the task group address
  - Quick and easy implementation for the initial prototype - Not final
- Tracking tagged processes
  - rq maintains an rbtree ordered by cookie
  - Only tagged processes enqueued
  - Allows to quickly search for a task with a specified tag when trying to match with a tagged task on the sibling.

Core Scheduling: Iterations

- Initial implementation (v1)
  - https://lwn.net/Articles/780084/
- v2
  - https://lwn.net/Articles/786553/
  - Build and stability fixes
- v3
  - https://lwn.net/Articles/789756/
  - Bug fixes and performance optimizations

Core Scheduling: Implementation Issues

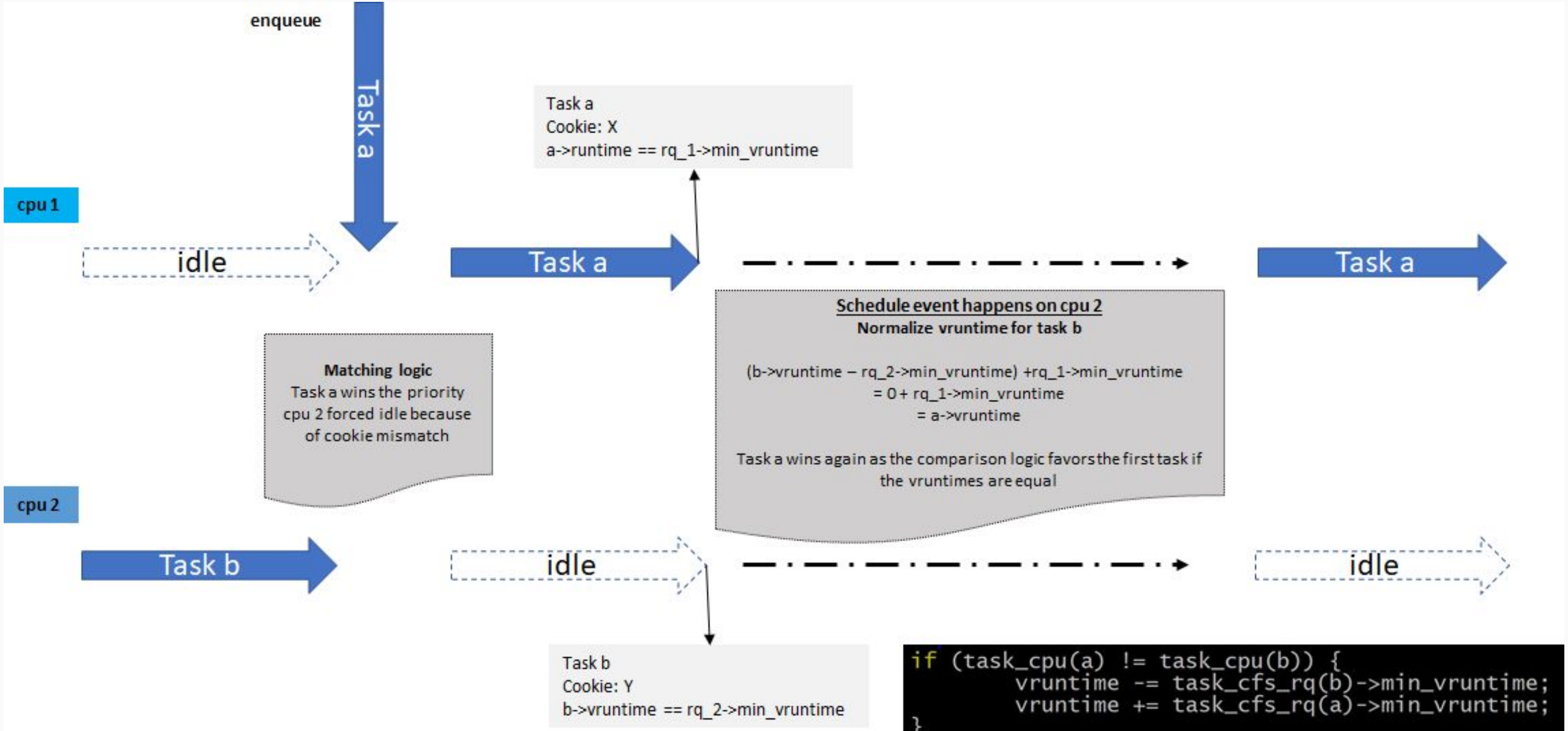
- Vruntime comparison across cpus is not perfect
- Forced idle corner cases
- Starvation of interactive tasks when competing with cpu intensive tasks
- Difference in performance between tagged and untagged process

Core Scheduling: vruntime comparison

- Need to compare process priority across the siblings to perform the selection logic.
    - Not straightforward as each queue maintains its on min vruntime
    - V2 fix: Normalize the vruntime when comparing
        - Decrement rq's minvruntime from task's runtime
        - Increment sibling rq's minvruntime to the above before comparing with a task in the sibling
        - Fixes the initial starvation seen in v1.

```
/*
 * Normalize the vruntime if tasks are in different cpus.
 */
if (task_cpu(a) != task_cpu(b)) {
        vruntime -= task_cfs_rq(b)->min_vruntime;
        vruntime += task_cfs_rq(a)->min_vruntime;
}
```

Vruntime comparison corner cases after normalization




```
if (task_cpu(a) != task_cpu(b)) {
        vruntime -= task_cfs_rq(b)->min_vruntime;
        vruntime += task_cfs_rq(a)->min_vruntime;
}

return !((s64)(a->se.vruntime - vruntime) <= 0);
```

Forced idle corner case example

- Each sibling has only one task each, but with different cookies
- One cpu has to go idle forcing its runnable task to be preempted
- Now, the running task if compute intensive would not hit __schedule unless there is any event that triggers schedule.
- Idle thread also will not wake up as task_tick for idle is nop
- So the idle cpu stays on idle for a considerable period until some schedule event happens on either of the siblings in the core

Proposed Solutions

- Forced Idle Issue
  - Accounting of forced idle time to trigger scheduling
  - Instead of using idle thread on cpu, introduce a per cpu task that idles so that scheduler does not confuse idle with forced idle
  - Special checks in idle thread to differentiate between idle and forced idle
- Vruntime comparison across cpu
  - Check the vruntime of parent entity going all the way to the root entity of the cfs_rq of cpu.
  - Core wide vruntime

Testing methodology

- Correctness validation with perf/LTTng + Python for parsing the CTF traces
  - "Are there incompatible tasks running at the same time on the core ?"
  - "Why is a particular task not running while the whole core is idle ?"
- Debugging with ftrace (using `trace_printk`)
  - "Why is one task not getting CPU time at that moment ?"
- eBPF for runtime efficiency statistics
  - "How much time a running task is off cpu ?"

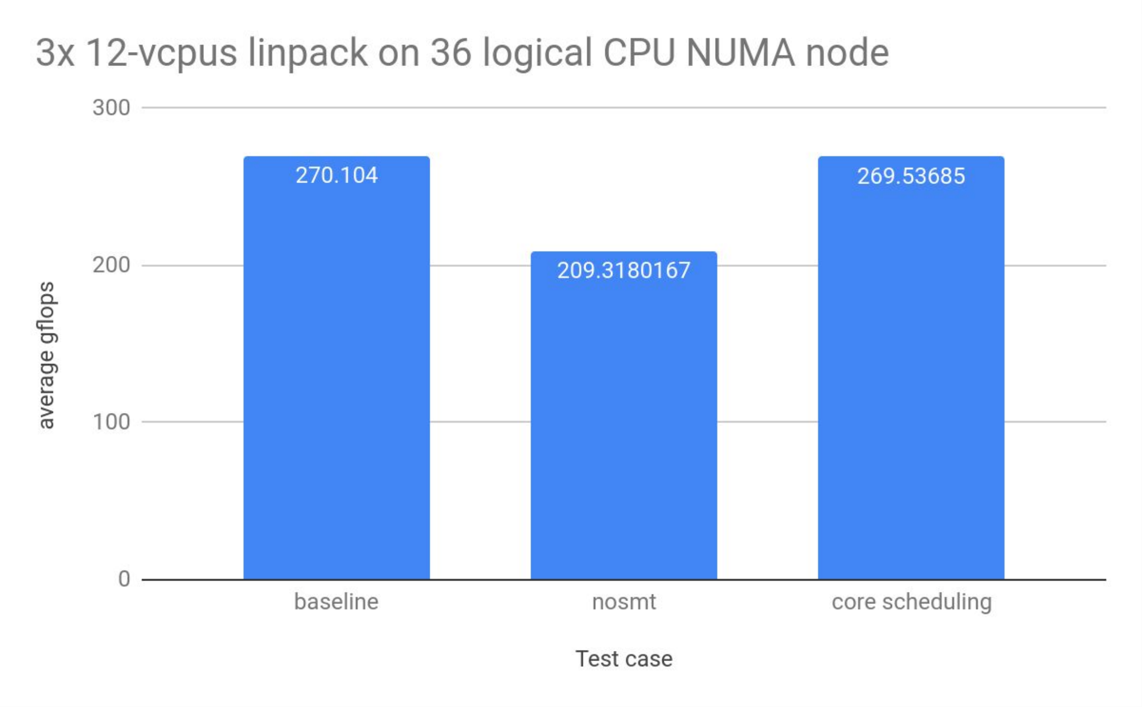
Co-scheduling stats example

```
Process 21687 (qemu-system-x86):
  - total runtime: 2758219964112 ns,
  - local neighbors (total: 1085548229756 ns,  39.357 % of process runtime):
    - qemu-system-x86 (21687): 972049547 ns
    - CPU 9/KVM (21721): 87202088965 ns
    - CPU 3/KVM (21714): 1594287115 ns
    - CPU 0/KVM (21707): 158177274295 ns
[...]
  - idle neighbors (total: 1636163538574 ns,  59.320 % of process runtime):
    - swapper/4 (0): 63532547226 ns
    - swapper/10 (0): 4000441661 ns
[...]
  - foreign neighbors (total: 2174790665 ns,  0.079 % of process runtime):
    - qemu-system-x86 (22059): 38360466 ns
    - CPU 4/KVM (22085): 11039429 ns
[...]
  - unknown neighbors  (total: 15999442846 ns,  0.580 % of process runtime)
```

Performance validation

- Micro benchmarks with worst cases:
  - 2 incompatible cpu-intensive tasks each pinned on a different sibling of the same core
  - Over-committed cores
- Real-world scenarios:
  - Large busy virtual machines (ex: TPCC benchmark in a 12 vcpus VM)
  - IO intensive VMs
  - CPU intensive VMs
  - Various configurations:
    - Alone on the NUMA node
    - With other similar on the same NUMA node
    - With noise (mostly-idle) VMs

Early performance results: CPU



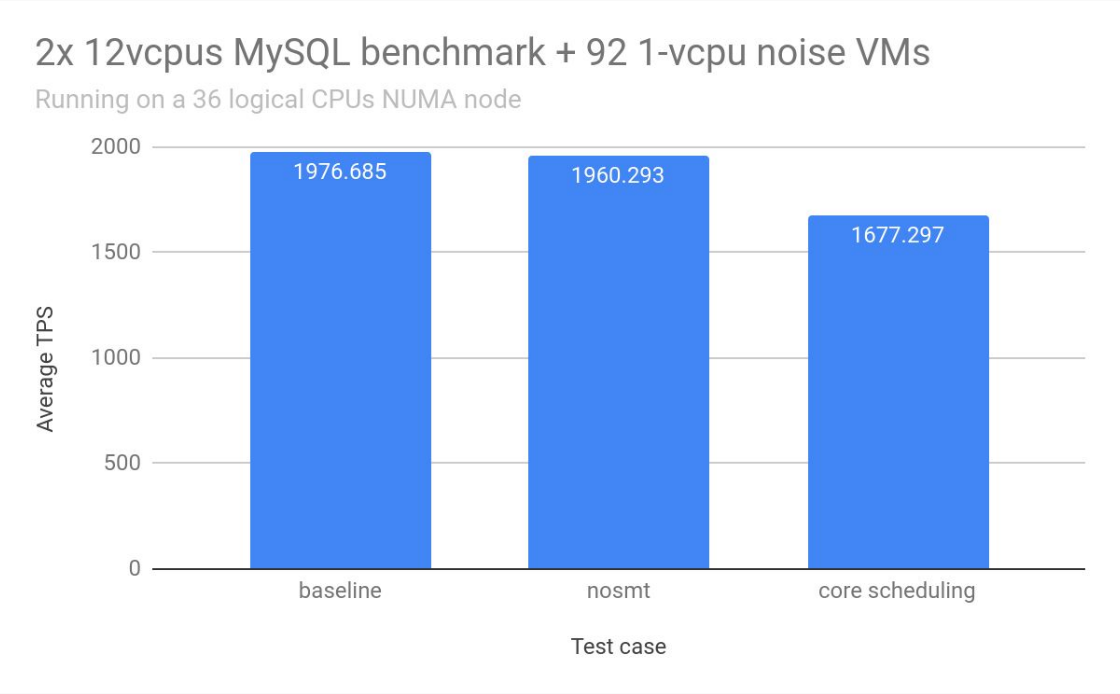
Early performance results: CPU

- cpu-intensive workloads in multi-vcpu VMs with all physical CPUs used:
    - Core scheduling performs better than when we disable SMT (N-cpu/2)
- If N/2 is not overcommitted nosmt performs better
    - Side note: there are signs that the load balancer should be SMT-aware to place the tasks more adequately

Early performance results: IO

- For IO-intensive workloads:
    - No major difference between no-SMT and core scheduling

Early performance results: mixed resources



Early performance results: mixed resources

- In mixed workloads with noise (TPCC benchmark + semi idle VMs) nosmt is more performant than core scheduling if %idle is ~> 40%

Core Scheduling : Post v3 and beyond

- Process selection and process matching logic needs a rework
  - Current implementation does not go beyond the highest priority task in each class.
- syscalls/interrupts and VMEXIT can cause kernel to be co-scheduled along with a untrusted task in the user space and would need protection
  - This might be very costly
  - L1TF or VM-only workloads, needs only protection on VMEXIT
    - This was done in the first iteration of core scheduling (KVM based)
- Define the right interface to group trusted processes
  - cgroup is currently used because it was easy for prototyping

Thank You!

- Discussions to continue @ core scheduling MC
  - https://linuxplumbersconf.org/event/4/contributions/430/
- Resources
  - https://github.com/pdxChen/gang/commits/sched_1.23-base
  - https://lwn.net/Articles/780703/
  - https://lwn.net/ml/linux-kernel/20190218165620.383905466@infradead.org/
  - https://lwn.net/ml/linux-kernel/cover.1556025155.git.vpillai@digitalocean.com/
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