Your Cores Are Slacking Off—Or Why OS Scheduling Is a Hard Problem

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As a central component of resource management, the OS thread scheduler must make sure that ready threads are scheduled on available cores. As surprising as it may seem, we found that this simple rule is often broken in Linux. Cores may stay idle for seconds while ready threads are waiting in run queues, delaying applications and wasting energy. This phenomenon is not due to an intentional design but to performance bugs. These bugs can slow down scientific applications many-fold and degrade performance of workloads like kernel compilation and OLAP on a widely used commercial database by tens of percent, particularly on machines with a large number of cores. The root cause of the bugs is the increasing scheduler complexity, linked to rapid evolution in modern hardware. In this article, we describe the bugs and their effects and reflect on ways to combat them.

Our recent experience with the Linux scheduler revealed that the pressure to work around the challenging properties of modern hardware, such as non-uniform memory access (NUMA) latencies, high costs of cache coherency and synchronization, and diverging CPU and memory latencies, resulted in a scheduler with an incredibly complex implementation. As a result, the very basic function of the scheduler, which is to make sure that runnable threads use idle cores, fell through the cracks. We have discovered four performance bugs that cause the scheduler to leave cores idle while runnable threads are waiting for their turn to run. Resulting performance degradations are in the range 13–24% for typical Linux workloads, and reach many-fold slowdowns in some corner cases. In this article, we describe three of the four bugs. For the complete description, please refer to our extended paper [7].

Detecting the aforementioned bugs is difficult. They do not cause the system to crash or hang, but eat away at performance, often in ways that are difficult to notice with standard performance monitoring tools. For instance, when executing the OLAP workload TPC-H on a widely used commercial database, the symptom occurred many times throughout the execution, but each time it lasted only a few hundreds of milliseconds—too short to detect with tools like htop, sar, or perf. Yet, collectively, these occurrences did enough damage to slow down the most affected query by 23%. Even in cases where the symptom was present for a much longer duration, the root cause was difficult to discover because it was a result of many asynchronous events in the scheduler.

In the rest of this article we provide relevant background on the Linux scheduler, describe the bugs and their root causes, demonstrate their performance effects, and finally reflect on ways to combat them, focusing especially on the tools that were crucial for the bug discovery.

The Linux Scheduler

Linux's Completely Fair Scheduling (CFS) is an implementation of the weighted fair queueing (WFQ) scheduling algorithm, wherein the available CPU cycles of each core are divided among threads in proportion to their weights. To support this abstraction, CFS time-slices the CPU cycles among the running threads.

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The scheduler defines a fixed time interval during which each thread in the system must run at least once. The interval is divided among threads proportionally to their *weights*. The resulting interval (after division) is what we call the *timeslice*. A thread's weight is essentially its priority, or *niceness* in UNIX parlance. Threads with lower niceness have higher weights and vice versa.

When a thread runs, it accumulates `vruntime` (the runtime of the thread divided by its weight). Once a thread's `vruntime` exceeds its assigned timeslice, the thread is preempted from the CPU if there are other runnable threads available. A thread might also get preempted if another thread with a smaller `vruntime` is awoken.

Threads are organized in *run queues*. As a matter of efficiency, there is one run queue per core. When a core looks for a new thread to run, it picks the thread in its run queue that has the smallest `vruntime`.

For the overall system to be efficient, run queues must be kept balanced. To this end, CFS periodically runs a load-balancing algorithm that will keep the queues roughly balanced.

CFS balances run queues based on a metric called *load*, which is the combination of the thread's weight and its average CPU utilization. Intuitively, if a thread does not use much of a CPU, its load will be decreased accordingly. Additionally, the load-tracking metric accounts for varying levels of multithreading in different processes.

When a thread belongs to a group of threads (called a `cgroup`), its load is further divided by the total number of threads in its `cgroup`. `Cgroups` are used to group threads or processes that logically belong together, such as threads in the same application or processes launched from the same terminal (`tty`). This is done for fairness purposes, such that the CPU is shared among *applications* rather than individual instruction streams.

CFS implements a hierarchical load-balancing strategy. The cores are logically organized in a hierarchy, at the bottom of which is a single core. How the cores are grouped at the hierarchy's next levels depends on how they share the machine's physical resources. On the example machine illustrated in Figure 1, pairs of cores share functional units, such as the

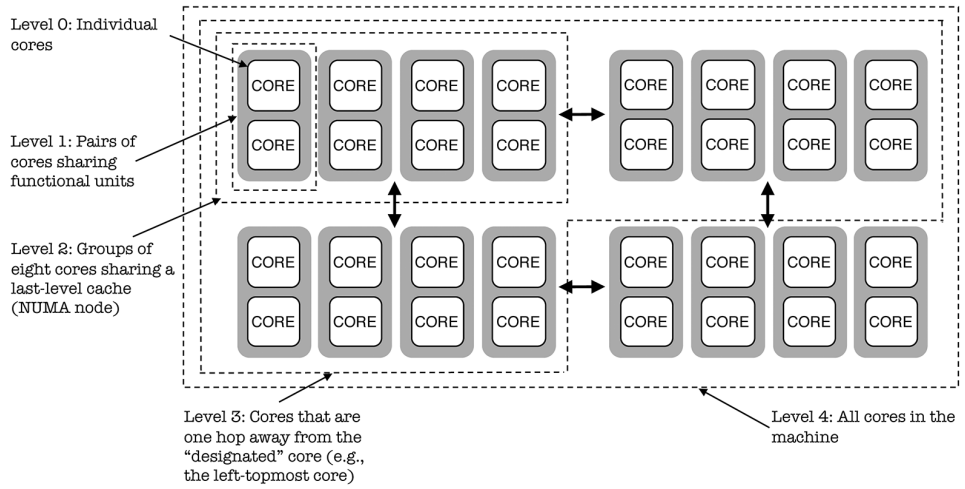


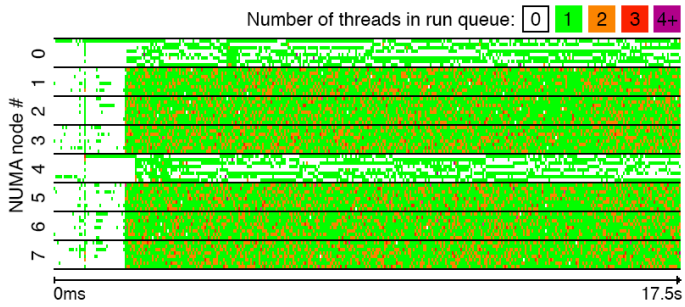
Figure 1: A machine with 32 cores, four NUMA nodes (eight cores per node sharing a last-level cache), and pairs of cores sharing a floating point unit. The dashed lines outline the scheduling domains as perceived by the left-topmost core. Level 3 of the hierarchy shows a group of three nodes: that is because these nodes are reachable from the left-topmost core in a single hop. (See Figure 3 for a detailed overview of node connectivity in our system.) At the fourth level, we have all the nodes of the machine, because they can be reached from the left-topmost core in at most two hops.

floating point unit, and groups of eight cores share a last-level cache; these groups of eight also form a NUMA node. As a result, at the second level of the hierarchy we have pairs of cores, and at the third level we have NUMA nodes. NUMA nodes are further grouped according to their level of connectivity. This is where things become a bit tricky, because the hierarchy is constructed from the point of view of a particular "designated" core; in the load-balancing algorithm it is the core that performs load balancing. In Figure 1 the hierarchy levels are shown as if the left-topmost core were designated. Hence, the third level of the hierarchy includes all nodes that can be reached from that designated core in one hop. The fourth level includes the nodes that can be reached from it in at most two hops, i.e., all nodes in the system.

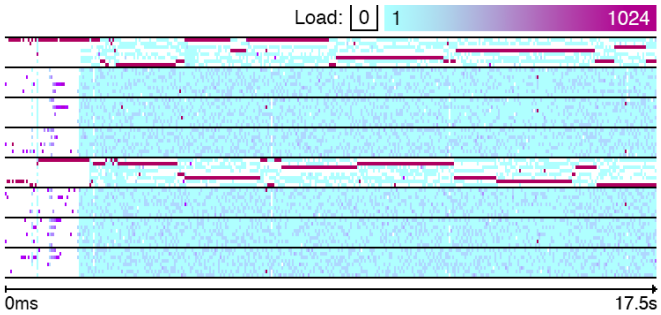
Each level of the hierarchy is called a *scheduling domain*. If a scheduling domain includes sub-domains, such as the NUMA-node domain including core-pair domains, those sub-domains are referred to in Linux terminology as *scheduling groups*.

At the high level, the load-balancing algorithm works as follows. Load balancing is run for each scheduling domain, starting from the lowest level of the hierarchy that contains more than a single core (the pair-of-cores level in our example) to the top. At each level, the algorithm is run by the designated core. The core is designated if it is either the first idle core of the domain or, if none of the cores are idle, the core with the lowest ID in the domain. The designated core computes the average load for each scheduling group of the domain and picks the busiest group, based on the load and on heuristics that favor overloaded and imbalanced groups. If the load of the busiest group is higher than the load of the designated core's home group, the designated core steals threads from the busiest group so as to balance the load.

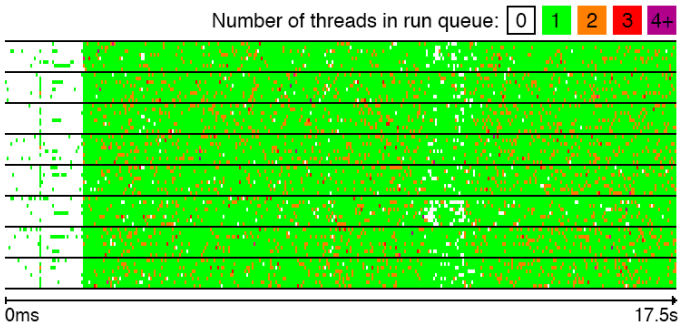
The scheduler implements a set of optimizations to improve the efficiency of the load-balancing mechanism, but as we will see later they increase complexity and nurture bugs. For example, in earlier versions of Linux, idle cores, which are typically transitioned into a lower power state, were always awoken on every clock tick; at this point they would run the load-balancing algorithm. Since version 2.6.21, Linux included the option, now enabled by default, to avoid periodically waking up sleeping cores. It is the responsibility of overloaded cores to wake up the sleeping cores when needed. Another set of optimizations has to do with the placement of threads that become unblocked. Normally when a thread wakes up, after sleeping or waiting for a resource like a lock or I/O, the scheduler tries to place it on the idlest core. However, when a thread is awoken by another "waker" thread, the scheduler will favor cores sharing a cache with the waker thread to improve cache reuse.



(a) # threads in each core's run queue over time



(b) Load of each core's run queue over time



(c) Same as (a), with fix applied

Figure 2: The Group Imbalance bug. The y-axis shows CPU cores. Nodes are numbered 0–7. Each node contains eight cores.

The Group Imbalance Bug

The first bug we encountered is illustrated in Figures 2a and 2b. The figures show the state of the scheduler when we execute a workload on an eight-node NUMA system summarized in Table 1. The x-axis shows the time and the y-axis shows the cores, grouped by their node number. In the time period shown in the figure, the machine was executing a compilation of the kernel (`make` with 64 threads) and running two `R` processes (each with one thread). The `make` and the two `R` processes were launched from three different `ssh` connections (i.e., three different `ttys`). Figure 2a is a heatmap showing the number of threads in each

CPUs	4 × 16-core Opteron 6272 CPUs (64 threads in total)
Clock rate	2.1 GHz
Caches	64 KB shared L1 i-cache
(Each core)	16 KB L1 d-cache
	2 MB shared L2
	8 MB shared L3
Memory	512 GB of 1.6 GHz DDR-3
Interconnect	HyperTransport 3.0 (see Figure 3)

Table 1: Hardware of our AMD Bulldozer machine

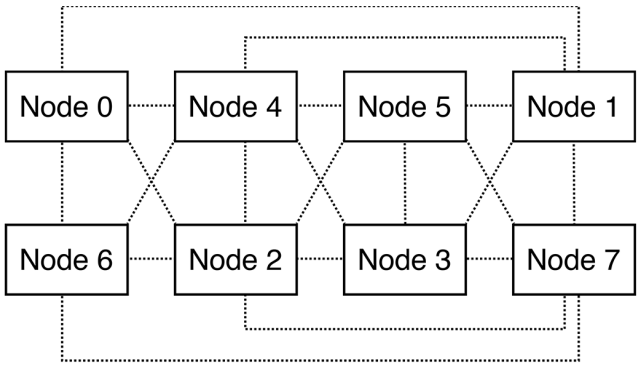


Figure 3: Topology of our 8-node AMD Bulldozer machine

core's run queue over time. The chart shows that there are two nodes (zero and four) whose cores run either only one thread or no threads at all, while the rest of the nodes are overloaded, with many of the cores having two threads in their run queue.

After investigation, we found that the scheduler is not balancing the load properly. Remember that a thread's load is a combination of its weight and its CPU utilization. Threads launched from the same `tty` belong to the same `cgroup`, and their load is thus divided by the number of threads in their `cgroup`. As a result, a thread in the 64-thread `make` process has a load roughly 64 times smaller than a thread in a single-threaded `R` process.

Discrepancies between threads' loads are illustrated in Figure 2b, which shows the combined load of threads in each core's run queue: a darker color corresponds to a higher load. Nodes 0 and 4, the ones running the `R` processes, each have one core with a very high load. These are the cores that run the `R` threads.

The Linux load balancer steals work from other run queues based on load; obviously the underloaded cores in Nodes 0 and 4 should not steal from the overloaded core in their own node, because that core runs only a single thread. However, they must be able to steal from the more loaded cores in other nodes. This is not happening for the following reason. Remember that to limit algorithmic complexity, the load-balancing algorithm uses a hierarchical design. When a core attempts to steal work from another node or, in other words, from another scheduling group, it does not examine the load of every core in that group, it only looks at the group's *average* load. If the average load of the victim group is greater than that of its own, it will attempt to steal threads from that group; otherwise it will not. In our case, the idle core looking for work is in the same group as the high-load `R` thread. So the average load for that group is actually the same as the load of the group with many overloaded cores. As a result, no stealing occurs, despite the victim group having overloaded cores with waiting threads.

To fix this bug, we changed the part of the algorithm that compares the load of scheduling groups. Instead of comparing the average loads, we compare the *minimum* loads. The minimum load is the load of the least loaded core in that group. Intuitively, if the minimum load of one scheduling group is lower than the minimum load of another scheduling group, it means that the first scheduling group has a core that is less loaded than *any* core in the other group, and thus a core in the first group must steal from the second.

Figure 2c is a visualization of the same workload after we fixed the bug (showing a heatmap of run queue sizes, in the same fashion as Figure 2a). We observe that the imbalance disappears. With the fix, the completion time of the `make` job, in the `make/R` workload decreased by 13%. Performance impact could be much higher in other circumstances. For example, in a workload running `lu` from the NPB (NASA Advanced Supercomputing Parallel Benchmarks) suite with 60 threads, and four single-threaded `R` processes, `lu` ran 13x faster after fixing the Group Imbalance bug. `lu` experienced a super-linear speedup, because the bug exacerbated lock contention when multiple `lu` threads ran on the same core.

The Scheduling Group Construction Bug

Linux defines a command, called `taskset`, that enables pinning applications to run on a subset of the available cores. The bug we describe in this section occurs when an application is pinned on nodes that are two hops apart. For example, in Figure 3, which demonstrates the topology of our NUMA machine, Nodes 1 and 2 are two hops apart. The bug will prevent the load-balancing algorithm from migrating threads between these two nodes.

The bug results from the way scheduling groups are constructed, which is not adapted to modern NUMA machines such as the one we use in our experiments. In brief, the groups are constructed from the perspective of a specific core (Core 0), whereas they should be constructed from the perspective of the core responsible for load balancing on each node, the `designated` core. We explain with an example.

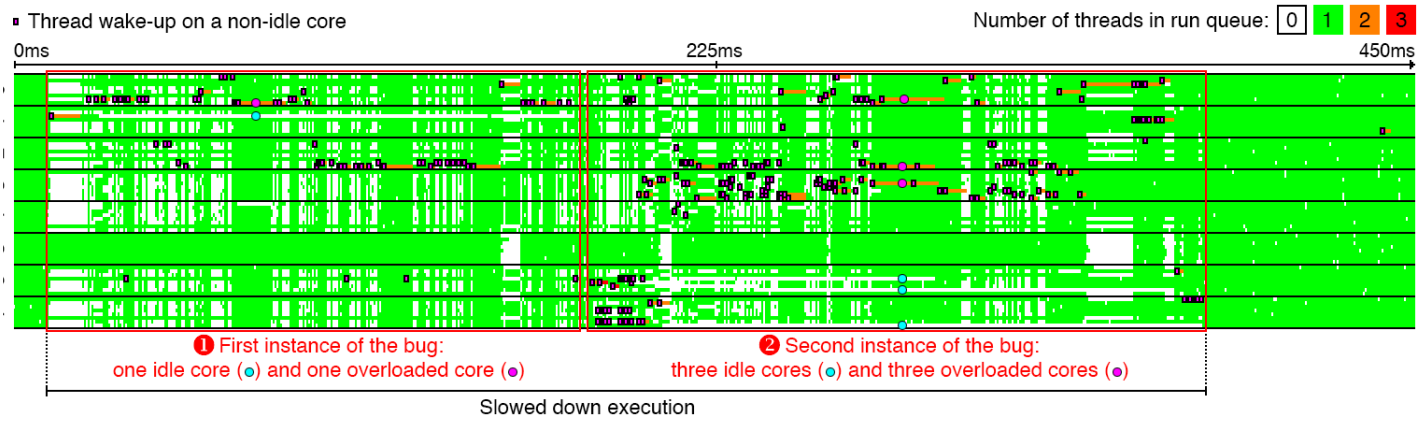


Figure 4: Several instances of the Overload-on-Wakeup bug

Let us walk through the key steps of the load-balancing algorithm when the balancing is performed at the top of the hierarchy, i.e., at the scheduling domain including all the machine's nodes. The algorithm will construct the scheduling groups (the sub-domains) included within that scheduling domain. The first scheduling group on the machine in Figure 3 will include Node 0 plus all the nodes that are one hop apart from Node 0, namely Nodes 1, 2, 4, and 6. The second group will include the lowest-numbered node that was not included in the first group: Node 3, in this case, and all nodes that are one hop apart from Node 3: Nodes 1, 2, 4, 5, 7. The two scheduling groups are thus: {0, 1, 2, 4, 6} and {1, 2, 3, 4, 5, 7}.

Suppose that an application is pinned on Nodes 1 and 2 and that all of its threads are being *created* on Node 1. Eventually we would like the load to be balanced between Nodes 1 and 2. However, when a core in Node 2 looks for work to steal, it will compare the load between the two scheduling groups shown earlier. Since each scheduling group contains both Nodes 1 and 2, the average loads will be the same, so Node 2 will not steal any work!

The bug originates from an attempt to improve the performance of Linux on large NUMA systems. Before the introduction of the bug, Linux would balance the load inside NUMA nodes and then across all NUMA nodes. New levels of hierarchy (nodes one hop apart, nodes two hops apart, etc.) were introduced to increase the likelihood for threads to remain close to their original NUMA node.

To fix the bug, we modified the construction of scheduling groups so that each core uses scheduling groups constructed from its own perspective. After the fix, the cores were able to detect the imbalance and to steal the work. Table 2 presents the performance difference in NPB applications with and without the Scheduling Group Construction bug. Applications are launched on two nodes with as many threads as there are cores. The maximum slowdown of 27x is experienced by `lu`. The slowdown is a lot more than the expected 2x because of locking effects.

Application	Time w/ bug	Time w/o bug	Speedup
	(sec)	(sec)	factor (x)
bt	99	56	1.75
cg	42	15	2.73
ep	73	36	2
ft	96	50	1.92
is	271	202	1.33
lu	1040	38	27
mg	49	24	2.03
sp	31	14	2.23
ua	206	56	3.63

Table 2: Execution time of NPB applications with the Scheduling Group Construction bug and without it

The Overload-on-Wakeup Bug

The gist of this bug is that a thread that was asleep may wake up on an overloaded core while other cores in the system are idle. The bug was introduced by an optimization in the wakeup code (`select_task_rq_fair` function). When a thread goes to sleep on Node *X* and the thread that wakes it up later is running on that same node, the scheduler only considers the cores of Node *X* for scheduling the awakened thread. If all cores of Node *X* are busy, the thread will wake up on an already busy core and miss opportunities to use idle cores on other nodes. This can lead to a significant under-utilization of the machine, especially on workloads where threads frequently wait.

The rationale behind this optimization is to maximize cache reuse. Essentially, the scheduler attempts to place the woken up thread physically close to the waker thread, e.g., so both run on cores sharing a last-level cache, in consideration of producer-consumer workloads where the woken up thread will consume

the data produced by the waker thread. This seems like a reasonable idea, but for some workloads, waiting in the run queue for the sake of better cache reuse does not pay off.

This bug was triggered by and affected the runtime of a widely used commercial database configured with 64 worker threads (one thread per core) and running an OLAP (TPC-H) workload.

Figure 4 illustrates several instances of the Overload-on-Wakeup bug. During the first time period (1), one core is idle while a thread that ideally should be scheduled on that core keeps waking up on other cores, which are busy. During the second time period (2), there is a triple instance of the bug: three cores are idle for a long time, while three extra threads that should be scheduled on those cores keep waking up on other busy cores. The Overload-on-Wakeup bug is typically caused when a transient thread is scheduled on a core that runs a database thread. When this happens, the load balancer observes a heavier load on the node that runs the transient thread (Node *A*) and migrates one of the threads to another node (Node *B*). This is not an issue if the transient thread is the one being migrated, but if it is the database thread, then the Overload-on-Wakeup bug will kick in. Node *B* now runs an extra database thread, and threads of Node *B*, which often sleep and wake up, keep waking up on that node, even if there are no idle cores on that node. This occurs because the wakeup code only considers cores from the local node for the sake of better cache reuse and results in a core running multiple threads when some cores that are always idle are present on other nodes.

To fix this bug, we alter the code that is executed when a thread wakes up. We wake up the thread on the local core—i.e., the core where the thread was scheduled last—if it is idle; otherwise, if there are idle cores in the system, we wake up the thread on the core that has been idle for the longest amount of time. If there are no idle cores, we fall back to the original algorithm to find the core where the thread will wake up.

Our bug fix improves performance by 22.6% on the 18th query of TPC-H, and by 13.2% on the full TPC-H workload.

Discussions and Lessons Learned

The first question to ask is whether these bugs could be fixed with a new, cleaner scheduler design that is less error-prone and easier to debug, but still maintains the features we have today. Historically, though, this does not seem like a long-term solution, in addition to the fact that the new design would need to be implemented and tested from scratch. The Linux scheduler has gone through a couple of major redesigns. The original scheduler had high algorithmic complexity, which resulted in poor performance when highly multithreaded workloads became common. In 2001, it was replaced by a new scheduler with O(1) complexity and better scalability on SMP systems. It was initially successful but soon required modifications for new architectures like NUMA and SMT (simultaneous multithreading). At the same time, users wanted better support for desktop use cases such as interactive and audio applications, which required more changes to the scheduler. Despite numerous modifications and proposed heuristics, the O(1) scheduler was not able to meet expectations and was replaced by CFS in 2007. Interestingly, CFS sacrifices O(1) complexity for O(log (# threads)), but it was deemed worthwhile to provide the desired features.

As the hardware and workloads became more complex, CFS, too, succumbed to bugs. The addition of autogroups (i.e., the automatic grouping of threads from the same `tty` into a `cgroup`) coupled with hierarchical load balancing introduced the Group Imbalance bug. Asymmetry in new, increasingly complex NUMA systems triggered the Scheduling Group Construction bug. Cache-coherency overheads on modern multi-node machines motivated the cache locality optimization that caused the Overload-on-Wakeup bug.

The takeaway is that new scheduler designs come and go. However, a new design, even if clean and purportedly bug-free initially, is not a long-term solution. Linux is a large open-source system developed by dozens of contributors. In this environment, we will inevitably see new features and "hacks" retrofitted into the source base to address evolving hardware and applications.

The recently released Linux 4.3 kernel features a new implementation of the load metric. This change is reported to be "done in a way that significantly reduces complexity of the code" [1]. Simplifying the load metric could get rid of the Group Imbalance bug, which is directly related to it. However, we confirmed, using our tools (see [7] for a full description of our tools and the end of this article for a link to the code), that the bug is still present.

Kernel developers rely on mutual code review and testing to prevent the introduction of bugs. This could potentially be effective for bugs, like the Scheduling Group Construction bug, that are easier to spot in the code (of course, it still was not effective in these cases), but it is unlikely to be reliable for the more arcane types of bugs.

Catching these bugs with testing or conventional performance monitoring tools is tricky. They do not cause the system to crash or to run out of memory, but they do silently eat away at performance. As we have seen with the Group Imbalance and the Overload-on-Wakeup bugs, they introduce short-term idle periods that "move around" between different cores. These microscopic idle periods cannot be noticed with performance monitoring tools like `htop`, `sar`, or `perf`. Standard performance regression testing is also unlikely to catch these bugs, as they occur in very specific situations (e.g., multiple applications with different thread counts launched from distinct `ttys`). In practice, performance testing on Linux is done with only one application running at a time on a dedicated machine—this is the

standard way of limiting factors that could explain performance differences.

One of the most important lessons we learned in the process of finding and diagnosing these bugs is that it was crucially important to have the tools that trace and visualize microscopic events during the execution, such as the state of the kernel run queues and the transitions of threads between the cores. The visualizations that we relied on for detection and diagnosis of the bugs are shown in Figures 2 and 4. We built our own tools that perform precise tracing of kernel events and plot them as the space/time charts shown earlier.

Although we found it convenient to build our own tools, there is also a variety of powerful third-party dynamic tracing tools, such as DTrace, LTTNG, Event Tracing for Windows, Ftrace, and SystemTap. Unfortunately, effective visual front-ends and trace analysis tools that are necessary to make the traces useful are lacking. Most of the user-friendly performance tools available today rely on sampling and display averages and aggregates, which is not powerful enough for detecting performance anomalies like those caused by the scheduler bugs. We strongly feel that the software engineering community must embrace dynamic tracing and visualization for efficient diagnosis of egregious performance anomalies.

Reflection on the Future of OS Scheduling

The bugs we described resulted from increasingly more optimizations in the scheduler, whose purpose was mostly to cater to complexity of modern hardware. As a result, the scheduler, that once used to be a simple isolated part of the kernel, grew into a complex monster whose tentacles reached into many other parts of the system, such as power and memory management. The optimizations studied in this paper are part of the mainline Linux, but even more scheduling optimizations were proposed in the research community.

Since 2000, dozens of papers have described new scheduling algorithms catering to resource contention, coherency bottlenecks, and other idiosyncrasies of modern multicore systems. There were algorithms that scheduled threads so as to minimize contention for shared caches, memory controllers, and multithreaded CPU pipelines [2, 6, 8]. There were algorithms that reduced communication distance among threads sharing data [10]. There were algorithms that addressed scheduling on asymmetric multicore CPUs [4, 9] and algorithms that integrated scheduling with the management of power and temperature [3]. Finally, there were algorithms that scheduled threads to minimize communication latency on systems with an asymmetric interconnect [5]. All of these algorithms showed positive benefits, either in terms of performance or power, for some real applications. However, few of them were adopted in mainstream operating systems, mainly because it is not clear how to integrate all these ideas in the scheduler safely.

If every good scheduling idea is slapped as an add-on to a single monolithic scheduler, we risk more complexity and more bugs, as we saw from the case studies in this paper. Rapid evolution of hardware that we are witnessing today will motivate more and more scheduler optimizations. Instead of producing yet another monolithic scheduler design, what we may need is to switch to a more modular architecture..

One possible avenue is to decouple time management from space management. Historically, on single-core systems, the scheduler was tasked with managing time, that is, sharing the CPU cycles among the threads. On multicore systems, the scheduler evolved to also manage space, that is to decide where to place the threads. Several researchers postulated that space management need not be done at as fine a time granularity as time management, and this idea becomes more and more feasible in the age where machines are evolving to have more cores than most applications need. Perhaps space management could be done at coarse time intervals by placing groups of threads on subsets of cores such that each thread always has a free core whenever it needs one. Then time management would be largely out of the picture, and the space manager would deal with issues like NUMA locality and resource contention. It would adjust the mapping of threads to cores somewhat infrequently to reflect the changes in application behavior over time. Still, understanding how to combine different, perhaps conflicting, space optimizations and reason about how they interact remains an open research problem.

Our bug fixes and tools are available at http://git.io/vaGOW.

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