THE OS SCHEDULER: A PERFORMANCE-CRITICAL COMPONENT IN LINUX CLUSTER ENVIRONMENTS

KEYNOTE FOR BPOE-9 @ASPLOS2018
THE NINTH WORKSHOP ON BIG DATA BENCHMARKS, PERFORMANCE, OPTIMIZATION AND EMERGING HARDWARE

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CLUSTER COMPUTING

- **Multicore servers with dozens of cores**
  - Common for e.g., a hadoop cluster, a distributed graph analytics engine, multiple apps...
  - High cost of infrastructure, high energy consumption

- **Linux-based software stack**
  - Low (license) cost, yet high reliability

- **Challenge: don’t waste cycles!**
  - Reduces infrastructure and energy costs
  - Improves bandwidth and latency
WHERE TO HUNT FOR CYCLES?

Applications, libraries: often main focus

Storage: optimized since decades! E.g., many filesystems, RDBMSes bypassing the OS

Network stack, NICs, reducing network usage (e.g. HDFS): common optimizations

NUMA, bus usage: Placement, replication, interleaving, many recent papers

The scheduler??? Generally trusted!
IS THE SCHEDULER WORKING IN YOUR CLUSTER?

- It must be! 15 years ago, Linus Torvalds was already saying:
  
  “And you have to realize that there are not very many things that have aged as well as the scheduler. Which is just another proof that scheduling is easy.”

- Since then, people have been running applications on their multicore machines all the time, and they run, CPU usage is high, everything seems fine.

- But would you notice if some cores remained idle intermittently, when they shouldn’t?
  - Do you keep monitoring tools (htop) running all the time?
  - Even if you do, would you be able to identify faulty behavior from normal noise?
  - Would you ever suspect the scheduler?
Over the past few years of working on various projects, we sometimes saw strange, hard to explain performance results.

An example: running a TPC-H benchmark on a 64-core machine, our runs much faster when pinning threads to cores than when we let the Linux scheduler do its job.

Memory locality issue? Impossible, hardware counters showed no difference in the % of remote memory accesses, in cache misses, etc.

Contention over some resource (spinlock, etc.)? We investigated this for a long time, but couldn't find anything that looked off.

Overhead of context switches? Threads moved a lot but we proved that the overhead was negligible.

We ended up suspecting the core behavior of the scheduler.

We implemented high-resolution tracing tools and saw that some cores were idle while others overloaded...
This is how we found our first performance bug. Which made us investigate more...

In the end: four Linux scheduler performance bugs that we found and analyzed

Always the same symptom: idle cores while others are overloaded
- The bug-hunting was tough, and led us to develop our own tools

Performance overhead of some of the bugs:
- 12-23% performance improvement on a popular database with TPC-H
- 137× performance improvement on HPC workloads

Not always possible to provide a simple, working fix...
- Intrinsic problems with the design of the scheduler?
Main takeaway of our analysis: more research must be directed towards implementing an efficient scheduler for multicore architectures, because contrary to what a lot of us think, this is *not* a solved problem!

Need convincing? Let’s go through it together...

...starting with a bit of background...
THE COMPLETELY FAIR SCHEDULER (CFS): CONCEPT

One runqueue where threads are globally sorted by runtime.

Cores get their next task from the global runqueue.

Of course, cannot work with a single runqueue because of contention.

When a thread is done running for its timeslice, enqueued again.

Some tasks have a lower niceness and thus have a longer timeslice (allowed to run longer).

Core 0
Core 1
Core 2
Core 3
CFS: IN PRACTICE

- One runqueue per core to avoid contention
- CFS periodically balances “loads”:

  \[
  \text{load(task)} = \text{weight}^1 \times \% \text{ cpu use}^2
  \]

  $^1$The lower the niceness, the higher the weight

  $^2$We don’t want a high-priority thread that sleeps a lot to take a whole CPU for itself and then mostly sleep!

- Since there can be many cores: hierarchical approach!

THE OS SCHEDULER: A PERFORMANCE-CRITICAL COMPONENT IN LINUX CLUSTER ENVIRONMENTS
CFS IN PRACTICE: HIERARCHICAL LOAD BALANCING

AVG(L)=2600  \[\overset{\text{Balanced!}}{\longleftrightarrow}\]  AVG(L)=3600

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CFS IN PRACTICE: HIERARCHICAL LOAD BALANCING

- Note that only the average load of groups is considered.
- If for some reason the lower-level load-balancing fails, nothing happens at a higher level.

<table>
<thead>
<tr>
<th>Level</th>
<th>Load Balance</th>
<th>Core 0</th>
<th>Core 1</th>
<th>Core 2</th>
<th>Core 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>L=0</td>
<td>Balanced!</td>
<td>L=0</td>
<td>L=100</td>
<td>L=3000</td>
<td>L=0</td>
</tr>
<tr>
<td>L=100</td>
<td></td>
<td>L=1000</td>
<td>L=1000</td>
<td>L=1000</td>
<td>L=1000</td>
</tr>
<tr>
<td>L=3000</td>
<td></td>
<td>L=3000</td>
<td>L=1000</td>
<td>L=1000</td>
<td>L=1000</td>
</tr>
</tbody>
</table>

AVG(L)=3000

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CFS IN PRACTICE: MORE HEURISTICS

- Load calculations are actually more complicated, use more heuristics.
- One of them aims to increase fairness between “sessions”.
- **Objective:** making sure that launching lots of threads from one terminal doesn’t prevent other processes on the machine (potentially from other users) from running.
  - Otherwise, easy to use more resources than other users by spawning many threads...
CFS IN PRACTICE: MORE HEURISTICS

- Load calculations are actually more complicated, use more heuristics.
- One of them aims to increase fairness between “sessions”.

50% of a CPU

Unfair!
CFS IN PRACTICE: MORE HEURISTICS

- Load calculations are actually more complicated, use more heuristics.
- Solution: divide the load of a task by the number of threads in its tty...

THE OS SCHEDULER: A PERFORMANCE-CRITICAL COMPONENT IN LINUX CLUSTER ENVIRONMENTS
**BUG 1/4: GROUP IMBALANCE**

Load(thread) = $\%cpu \times \text{weight} \div \#\text{threads}$

\[
\begin{align*}
\text{Session (tty) 1} \\
\text{L=125} & \quad \text{L=125} \\
\text{L=125} & \quad \text{L=125} \\
\text{L=125} & \quad \text{L=125}
\end{align*}
\]

\[
\begin{align*}
\text{Load(thread)} & = 100 \times 10 \div 1 \\
\text{L} & = 1000
\end{align*}
\]

\[
\begin{align*}
\text{Session (tty) 2} \\
\text{L=125} & \quad \text{L=125} \\
\text{L=125} & \quad \text{L=125} \\
\text{L=125} & \quad \text{L=125}
\end{align*}
\]

\[
\begin{align*}
\text{Load(thread)} & = 100 \times 10 \div 8 \\
\text{L} & = 125
\end{align*}
\]

The OS Scheduler: A Performance-Critical Component in Linux Cluster Environments
BUG 1/4: GROUP IMBALANCE

AVG(L)=500

Balanced!

AVG(L)=500

Balanced!

Balanced!

Balanced!

THE OS SCHEDULER: A PERFORMANCE-CRITICAL COMPONENT IN LINUX CLUSTER ENVIRONMENTS
The bug happens at two levels:
- Other core on pair of core idle
- Other cores on NUMA node less busy...
**BUG 1/4: GROUP IMBALANCE**

- A simple solution: balance the minimum load of groups instead of the average load.

![Diagram showing load distribution among cores](image)

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THE OS SCHEDULER: A PERFORMANCE-CRITICAL COMPONENT IN LINUX CLUSTER ENVIRONMENTS
BUG 1/4: GROUP IMBALANCE

- A simple solution: balance the *minimum load* of groups instead of the average

- After the fix, make runs 13% faster, and R is not impacted

- A simple solution, but is it ideal? Minimum load more volatile than average...
  - May cause lots of unnecessary rebalancing. Revamping load calculations needed?

THE OS SCHEDULER: A PERFORMANCE-CRITICAL COMPONENT IN LINUX CLUSTER ENVIRONMENTS
**Hierarchical load balancing** is based on groups of cores named *scheduling domains*.
- Based on affinity, i.e., pairs of cores, dies, CPUs, NUMA nodes, etc.
- Each scheduling domain contains groups that are the lower-level scheduling domains.

**For instance, on our 64-core AMD Bulldozer machine:**
- At level 1, each *pair of core* (scheduling domains) contain *cores* (scheduling groups).
- At level 2, each *CPU* (s.d.) contain *pairs of cores* (s.g.).
- At level 3, each *group of directly connected CPUs* (s.d.) contain *CPUs* (s.g.).
- At level 4, the *whole machine* (s.d.) contains *group of directly connected CPUs* (s.g.).
Bulldozer 64-core: Eight CPUs, with 8 cores each, non-complete interconnect graph!
At the first level, the first core balances load with the other core on the same pair (because they share resources, high affinity).
At the 2\textsuperscript{nd} level, the first pair balances load with other pairs on the same CPU.
At the 3rd level, the first CPU balances load with directly connected CPUs.
At the 4th level, the first group of directly connected CPUs balances load with the other groups of directly connected CPUs.
Bug 2/4: Scheduling Group Construction

Groups of CPUs built by:

1. Picking first CPU and looking for all directly connected CPUs.
Groups of CPUs built by:

(2) picking first CPU not in a group and looking for all directly connected CPUs
And then stop, because all CPUs are in a group.

Wait, does that work?
Suppose we taskset an application on these two CPUs, two hops apart (16 threads).
And threads are created on this core.
Bug 2/4: Scheduling Group Construction

The OS scheduler: a performance-critical component in Linux cluster environments

Load gets correctly balanced on the pair of cores.
Load gets correctly balanced on the CPU
No stealing at level 3, because nodes not directly connected (1 hop apart)
At level 4, stealing between the red and green groups...

Overloaded node in both groups!
**Bug 2/4: Scheduling Group Construction**

**Fundamental Issue:**
with the scheduling hierarchy!

**The OS Scheduler:** A performance-critical component in Linux cluster environments

\[
\text{load(\text{red}) = 16 \times \text{load(thread)}}
\]

\[
\text{load(\text{green}) = 16 \times \text{load(thread)}}
\]
BUG 2/4: SCHEDULING GROUP CONSTRUCTION

- Fix: build the domains by creating one “directly connected” group for every CPU
- Instead of the first CPU and the first one not “covered” by a group

- Performance improvement of NAS applications on two nodes:

<table>
<thead>
<tr>
<th>Application</th>
<th>With bug</th>
<th>After fix</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT</td>
<td>99</td>
<td>56</td>
<td>1.75x</td>
</tr>
<tr>
<td>CG</td>
<td>42</td>
<td>15</td>
<td>2.73x</td>
</tr>
<tr>
<td>EP</td>
<td>73</td>
<td>36</td>
<td>2x</td>
</tr>
<tr>
<td>LU</td>
<td>1040</td>
<td>38</td>
<td>27x</td>
</tr>
</tbody>
</table>

- Very good improvement for LU because more threads than cores if can’t use 16 cores
- Solves spinlock issues (incl. potential convoys)
**Bug 3/4: Missing Scheduling Domains**

- In addition to this, when domains re-built, *levels 3 and 4 not re-built*...
- I.e., no balancing between directly connected or 1-hop CPUs (i.e. any CPU)
- Happens for instance when disabling and re-enabling a core

- **Launch an application, first thread created on CPU 1**
  - First thread will stay on CPU 1, next threads will be created on CPU 1 (default Linux)
  - All the threads will be on CPU 1 forever!

<table>
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<tr>
<th>Application</th>
<th>With bug</th>
<th>After fix</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT</td>
<td>122</td>
<td>23</td>
<td>5.2x</td>
</tr>
<tr>
<td>CG</td>
<td>134</td>
<td>5.4</td>
<td>25x</td>
</tr>
<tr>
<td>EP</td>
<td>72</td>
<td>18</td>
<td>4x</td>
</tr>
<tr>
<td>LU</td>
<td>2196</td>
<td>16</td>
<td>137x</td>
</tr>
</tbody>
</table>
BUG 4/4: OVERLOAD-ON-WAKEUP

- Until now, we analyzed the behavior of the periodic, (buggy) hierarchical load balancing that uses (buggy) scheduling domains

- But there is another way load is balanced: threads get to pick on which core they get woken up when they are done blocking (after a lock acquisition, an I/O)...

- Here is how it works: when a thread wakes up, it looks for non-busy cores on the same CPU in order to decide on which core it should wake up.

- Only cores that are on the same CPU, in order to improve data locality...

Wait, does that work?
Bug 4/4: Overload-on-wakeup

- Commercial DB with TPC-H, 64 threads on 64 cores, nothing else on the machine.
- With threads pinned to cores, works fine. With Linux scheduling, execution much slower, phases with overloaded cores while there are long-term idle cores!

What is happening?

Slowed down execution
Beginning: 8 threads / CPU, cores busy

Occasionally, 1 DB thread migrated to other CPU because transient thread appeared during rebalancing which looked like imbalance (only instant loads considered)

Now, 9 threads on one CPU, and 7 on another one. CPU with 9 threads slow, slows down all execution because all threads wait for each other (barriers), i.e. idle cores everywhere...

Barriers: threads keep sleeping and waking up, but extra thread never wakes up on idle core, because waking up algorithm only considers local CPU!

Periodic rebalancing can’t rebalance load most of the time because many idle cores
⇒ Hard to see an imbalance between 9-thread and 7-thread CPU...

“Solution”: wake up on core idle for the longest time (not great for energy)
WHERE DO WE GO FROM HERE?

- Load balancing on a multicore machine usually considered a solved problem
- To recap, on Linux, load balancing works that way:
  - Hierarchical rebalancing uses a metric named load,
    - Found fundamental issue here
  - to periodically balance threads between scheduling domains.
    - Found fundamental issue here
  - In addition to this, threads balance load by selecting core where to wake up.
    - Found fundamental issue here

Wait, was anything working at all? 😊
WHERE DO WE GO FROM HERE?

Many major issues went unnoticed for years in the scheduler...

How can we prevent this from happening again?

- **Code testing**
  - No clear fault (no crash, no deadlock, etc.)
  - Existing tools don’t target these bugs

- **Performance regression**
  - Usually done with 1 app on a machine to avoid interactions
  - Insufficient coverage

- **Model checking, formal proofs**
  - Complex, parallel code: so far, nobody knows how to do it...
WHERE DO WE GO FROM HERE?

- **Idea 1:** short-term hack — implemented a sanity checker

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Idle core while a core is overloaded?

- Yes
  - Monitor thread migrations, creations, destructions
  - Imbalance not fixed

- No
  - Report a bug

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Not an assertion/watchdog:
- might not be a bug
- situation has to last for a long time

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THE OS SCHEDULER: A PERFORMANCE-CRITICAL COMPONENT IN LINUX CLUSTER ENVIRONMENTS
WHERE DO WE GO FROM HERE?

- **Idea 2:** fine-grained tracers!
  - Built a simple one, turned out to be the only way to really understand what happens
  - Aggregate metrics (CPI, cache misses, etc.) not precise enough

- Could really be improved!
WHERE DO WE GO FROM HERE?

- **Idea 3:** produce a dedicated profiler!

  - Lack of tools!

- Possible to detect if slowdown comes from scheduler or application?
- Would avoid a lot of wasted time!

- Follow threads, and see if often on overloaded cores when shouldn’t have?
- Detect if threads unnecessarily moved to core/node that leads to many cache misses?
WHERE DO WE GO FROM HERE?

- **Idea 4:** produce good scheduler benchmarks!
  - Really needed, and virtually inexistent!

- **Not an easy problem:** insane coverage needed!
- **Using combination of many real applications:** configuration nightmare!

- Simulated workloads?
  - Have to do *elaborate work*: spinning and sleeping not efficient
  - Have to be *representative of reality*, have to *cover corner cases*
    - *Use machine learning? Genetic algorithms?*
WHERE DO WE GO FROM HERE?

- **Idea 5:** switch to simpler schedulers, easier to reason about!

Let’s take a step back: *why* did we end up in this situation?

- Linux used for many classes of applications (big data, n-tier, cloud, interactive, DB, HPC...)
- Multicore architectures increasingly diverse and complex!
- **Result:** very complex monolithic scheduler supposed to work in all situations!
  - Many heuristics interact in complex, unpredictable ways
  - Some features greatly complexify, e.g., load balancing (tasksets, cgroups/autogroups...)
- Keeps getting worse!
- **E.g., task_struct:** 163 fields in Linux 3.0 (07/2011), 215 fields in 4.6 (05/2016)
- **20,000 lines of C!**
WHERE DO WE GO FROM HERE?

- **Idea 5:** switch to simpler schedulers, easier to reason about!
WHERE DO WE GO FROM HERE?

- **Idea 5:** switch to simpler schedulers, easier to reason about!

- **Proving the scheduler implementation correct: not doable!**
  - Way too much code for current technology
  - We’d need to detect high-level abstractions from low-level C: a challenge!
  - Even if we managed that, how do we keep up with updates?
    - Code keeps evolving with new architectures and application needs...

- We need another approach...
WHERE DO WE GO FROM HERE?

- **Idea 5:** switch to simpler schedulers, easier to reason about!

- **Write simple, schedulers with proven properties!**
  - A scheduler is tailored to a (class of) parallel application(s)
  - Specific thread election criterion, load balancing criterion, state machine with events...
  - **Machine partitioned into sets of cores that run ≠ schedulers**
  - Scheduler deployed together with (an) application(s) on a partition

- **Through a DSL, for two reasons:**
  - Much easier, safer and less bug-prone than writing low-level C kernel code!
  - Clear abstractions, possible to reason about them and prove properties
    - Work conservation, load balancing live and in finite # or rounds, valid hierarchy...
WHERE DO WE GO FROM HERE?

- **Idea 6**: ???
- Any other ideas?
CONCLUSION

- Scheduling (as in dividing CPU cycles among threads) was thought to be a solved problem.
- **Analysis:** fundamental issues in the load metric, scheduling domains, scheduling choices...
- Very bug-prone implementation following years of adapting to hardware
- Can’t ensure simple “invariant”: no idle cores while overloaded cores
- Proposed fixes: not always satisfactory
- What can we do? Many things to explore!

**Our takeaway:** more research must be directed towards implementing efficient and reliable schedulers for multicore architectures!

**Your turn!**

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