Linux Load Averages: Solving the Mystery

08 Aug 2017

Load averages are an industry-critical metric – my company spends millions auto-scaling cloud instances based on them and other metrics – but on Linux there's some mystery around them. Linux load averages track not just runnable tasks, but also tasks in the uninterruptible sleep state. Why? I've never seen an explanation. In this post I'll solve this mystery, and summarize load averages as a reference for everyone trying to interpret them.

Linux load averages are "system load averages" that show the running thread (task) demand on the system as an average number of running plus waiting threads. This measures demand, which can be greater than what the system is currently processing. Most tools show three averages, for 1, 5, and 15 minutes:

```
$ uptime
 16:48:24 up  4:11,  1 user,  load average: 25.25, 23.40, 23.46

top - 16:48:42 up  4:12,  1 user,  load average: 25.25, 23.14, 23.37

$ cat /proc/loadavg
25.72 23.19 23.35 42/3411 43603
```

Some interpretations:

- If the averages are 0.0, then your system is idle.
- If the 1 minute average is higher than the 5 or 15 minute averages, then load is increasing.
- If the 1 minute average is lower than the 5 or 15 minute averages, then load is decreasing.
- If they are higher than your CPU count, then you might have a performance problem (it depends).

As a set of three, you can tell if load is increasing or decreasing, which is useful. They can be also useful when a single value of demand is desired, such as for a cloud auto scaling rule. But to understand them in more detail is difficult without the aid of other metrics. A single value of 23 - 25, by itself, doesn't mean anything, but might mean something if the CPU count is known, and if it's known to be a CPU-bound workload.

Instead of trying to debug load averages, I usually switch to other metrics. I'll discuss these in the "Better Metrics" section near the end.

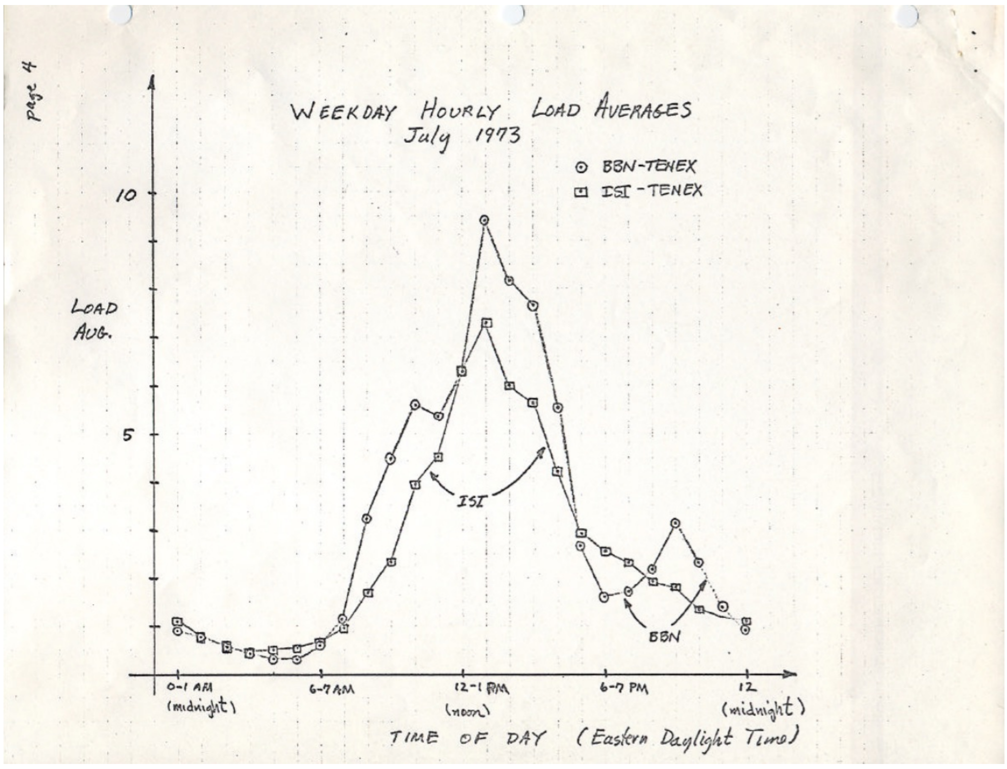
History

The original load averages show only CPU demand: the number of processes running plus those waiting to run. There's a nice description of this in RFC 546 titled "TENEX Load Averages", August 1973:

> [1] The TENEX load average is a measure of CPU demand. The load average is an average of the number of runnable processes over a given time period. For example, an hourly load average of 10 would mean that (for a single CPU system) at any time during that hour one

could expect to see 1 process running and 9 others ready to run (i.e., not blocked for I/O) waiting for the CPU.

The version of this on ietf.org links to a PDF scan of a hand drawn load average graph from July 1973, showing that this has been monitored for decades:



source: https://tools.ietf.org/html/rfc546

Nowadays, the source code to old operating systems can also be found online. Here's an except of DEC macro assembly from TENEX (early 1970's) SCHED.MAC:

```
NRJAVS==3                   ;NUMBER OF LOAD AVERAGES WE MAINTAIN
GS RJAV,NRJAVS              ;EXPONENTIAL AVERAGES OF NUMBER OF ACTIVE PROCESSES
[...]
;UPDATE RUNNABLE JOB AVERAGES

DORJAV: MOVEI 2,^D5000
        MOVEM 2,RJATIM              ;SET TIME OF NEXT UPDATE
        MOVE 4,RJTSUM               ;CURRENT INTEGRAL OF NBPROC+NGPROC
        SUBM 4,RJAVS1               ;DIFFERENCE FROM LAST UPDATE
        EXCH 4,RJAVS1
        FSC 4,233                   ;FLOAT IT
        FDVR 4,[5000.0]             ;AVERAGE OVER LAST 5000 MS
[...]
;TABLE OF EXP(-T/C) FOR T = 5 SEC.

EXPFF:  EXP 0.920043902 ;C = 1 MIN
        EXP 0.983471344 ;C = 5 MIN
        EXP 0.994459811 ;C = 15 MIN
```

And here's an excerpt from Linux today (include/linux/sched/loadavg.h):

```
#define EXP_1           1884            /* 1/exp(5sec/1min) as fixed-point */
#define EXP_5           2014            /* 1/exp(5sec/5min) */
#define EXP_15          2037            /* 1/exp(5sec/15min) */
```

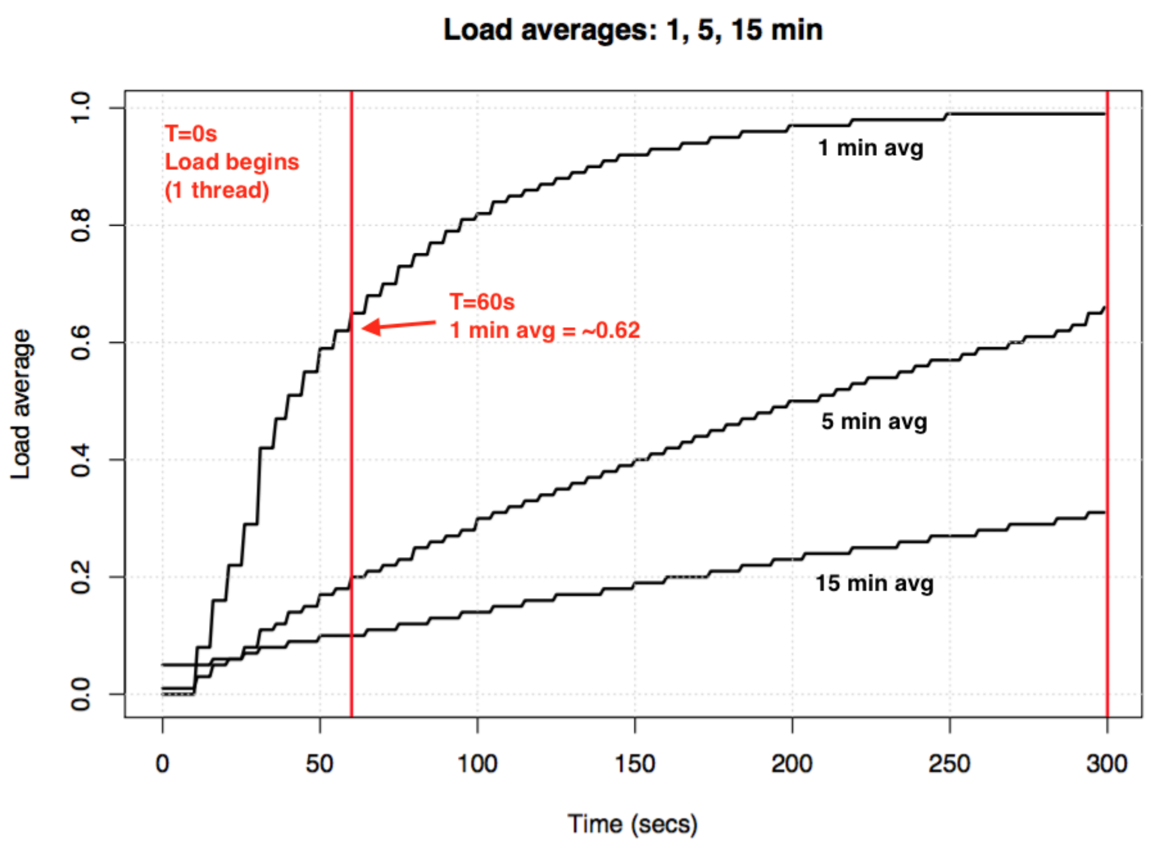
Linux is also hard coding the 1, 5, and 15 minute constants.

There have been similar load average metrics in older systems, including Multics, which had an exponential scheduling queue average.

The Three Numbers

These three numbers are the 1, 5, and 15 minute load averages. Except they aren't really averages, and they aren't 1, 5, and 15 minutes. As can be seen in the source above, 1, 5, and 15 minutes are constants used in an equation, which calculate exponentially-damped moving sums of a five second average. The resulting 1, 5, and 15 minute load averages reflect load well beyond 1, 5, and 15 minutes.

If you take an idle system, then begin a single-threaded CPU-bound workload (one thread in a loop), what would the one minute load average be after 60 seconds? If it was a plain average, it would be 1.0. Here is that experiment, graphed:



Load average experiment to visualize exponential damping

The so-called "one minute average" only reaches about 0.62 by the one minute mark. For more on the equation and similar experiments, Dr. Neil Gunther has written an article on load averages: How It Works, plus there are many Linux source block comments in loadavg.c.

Linux Uninterruptible Tasks

When load averages first appeared in Linux, they reflected CPU demand, as with other operating systems. But later on Linux changed them to include not only runnable tasks, but also tasks in the uninterruptible state (TASK_UNINTERRUPTIBLE or nr_uninterruptible). This state is used by code paths that want to avoid interruptions by signals, which includes tasks blocked on disk I/O and some locks. You may have seen this state before: it shows up as the "D" state in the output `ps` and `top`. The ps(1) man page calls it "uninterruptible sleep (usually IO)".

Adding the uninterruptible state means that Linux load averages can increase due to a disk (or NFS) I/O workload, not just CPU demand. For everyone familiar with other operating systems and their CPU load averages, including this state is at first deeply confusing.

Why? Why, exactly, did Linux do this?

There are countless articles on load averages, many of which point out the Linux nr_uninterruptible gotcha. But I've seen none that explain or even hazard a guess as to why it's included. My own guess would have been that it's meant to reflect demand in a more general sense, rather than just CPU demand.

Searching for an ancient Linux patch

Understanding why something changed in Linux is easy: you read the git commit history on the file in question and read the change description. I checked the history on loadavg.c, but the change that added the uninterruptible state predates that file, which was created with code from an earlier file. I checked the other file, but that trail ran cold as well: the code itself has hopped around different files. Hoping to take a shortcut, I dumped "git log -p" for the entire Linux github repository, which was 4 Gbytes of text, and began reading it backwards to see when the code first appeared. This, too, was a dead end. The oldest change in the entire Linux repo dates back to 2005, when Linus imported Linux 2.6.12-rc2, and this change predates that.

There are historical Linux repos (here and here), but this change description is missing from those as well. Trying to discover, at least, when this change occurred, I searched tarballs on kernel.org and found that it had changed by 0.99.15, and not by 0.99.13 – however, the tarball for 0.99.14 was missing. I found it elsewhere, and confirmed that the change was in Linux 0.99 patchlevel 14, Nov 1993. I was hoping that the release description for 0.99.14 by Linus would explain the change, but that too, was a dead end:

> "Changes to the last official release (p13) are too numerous to mention (or even to remember)..." – Linus

He mentions major changes, but not the load average change.

Based on the date, I looked up the kernel mailing list archives to find the actual patch, but the oldest email available is from June 1995, when the sysadmin writes:

> "While working on a system to make these mailing archives scale more effecitvely I accidently destroyed the current set of archives (ah whoops)."

My search was starting to feel cursed. Thankfully, I found some older linux-devel mailing list archives, rescued from server backups, often stored as tarballs of digests. I searched over 6,000 digests containing over 98,000 emails, 30,000 of which were from 1993. But it was somehow missing from all of them. It really looked as if the original patch description might be lost forever, and the "why" would remain a mystery.

The origin of uninterruptible

Fortunately, I did finally find the change, in a compressed mailbox file from 1993 on oldlinux.org. Here it is:

```
From: Matthias Urlichs <urlichs@smurf.sub.org>
Subject: Load average broken ?
Date: Fri, 29 Oct 1993 11:37:23 +0200


The kernel only counts "runnable" processes when computing the load average.
I don't like that; the problem is that processes which are swapping or
waiting on "fast", i.e. noninterruptible, I/O, also consume resources.

It seems somewhat nonintuitive that the load average goes down when you
replace your fast swap disk with a slow swap disk...

Anyway, the following patch seems to make the load average much more
consistent WRT the subjective speed of the system. And, most important, the
load is still zero when nobody is doing anything. ;-)

--- kernel/sched.c.orig Fri Oct 29 10:31:11 1993
+++ kernel/sched.c  Fri Oct 29 10:32:51 1993
@@ -414,7 +414,9 @@
    unsigned long nr = 0;

    for(p = &LAST_TASK; p > &FIRST_TASK; --p)
-       if (*p && (*p)->state == TASK_RUNNING)
+       if (*p && ((*p)->state == TASK_RUNNING) ||
+                  (*p)->state == TASK_UNINTERRUPTIBLE) ||
+                  (*p)->state == TASK_SWAPPING))
            nr += FIXED_1;
    return nr;
 }
--
Matthias Urlichs        \ XLink-POP N|rnberg   | EMail: urlichs@smurf.sub.org
Schleiermacherstra_e 12  \  Unix+Linux+Mac     | Phone: ...please use email.
90491 N|rnberg (Germany)  \   Consulting+Networking+Programming+etc'ing      42
```

It's amazing to read the thoughts behind this change from almost 24 years ago.

This confirms that the load averages were deliberately changed to reflect demand for other system resources, not just CPUs. Linux changed from "CPU load averages" to what one might call "system load averages".

His example of using a slower swap disk makes sense: by degrading the system's performance, the demand on the system (measured as running + queued) should increase. However, load averages decreased because they only tracked the CPU running states and not the swapping states. Matthias thought this was nonintuitive, which it is, so he fixed it.

Uninterruptible today

But don't Linux load averages sometimes go too high, more than can be explained by disk I/O? Yes, although my guess is that this is due to a new code path using TASK_UNINTERRUPTIBLE that didn't exist in 1993. In Linux 0.99.14, there were 13 codepaths that directly set TASK_UNINTERRUPTIBLE or TASK_SWAPPING (the swapping state was later removed from Linux). Nowadays, in Linux 4.12, there are nearly 400 codepaths that set TASK_UNINTERRUPTIBLE, including some lock primitives. It's possible that one of these codepaths should not be included in the load averages. Next time I have load averages that seem too high, I'll see if that is the case, and if it can be fixed.

I emailed Matthias (for the first time) to ask what he thought about his load average change almost 24 years later. He responded in one hour (as I mentioned on Twitter), and wrote:

> "The point of "load average" is to arrive at a number relating how busy the system is from a human point of view. TASK_UNINTERRUPTIBLE means (meant?) that the process is waiting for something like a disk read which contributes to system load. A heavily disk-bound system might be extremely sluggish but only have a TASK_RUNNING average of 0.1, which doesn't help anybody."

(Getting a response so quickly, or even a response at all, really made my day. Thanks!)

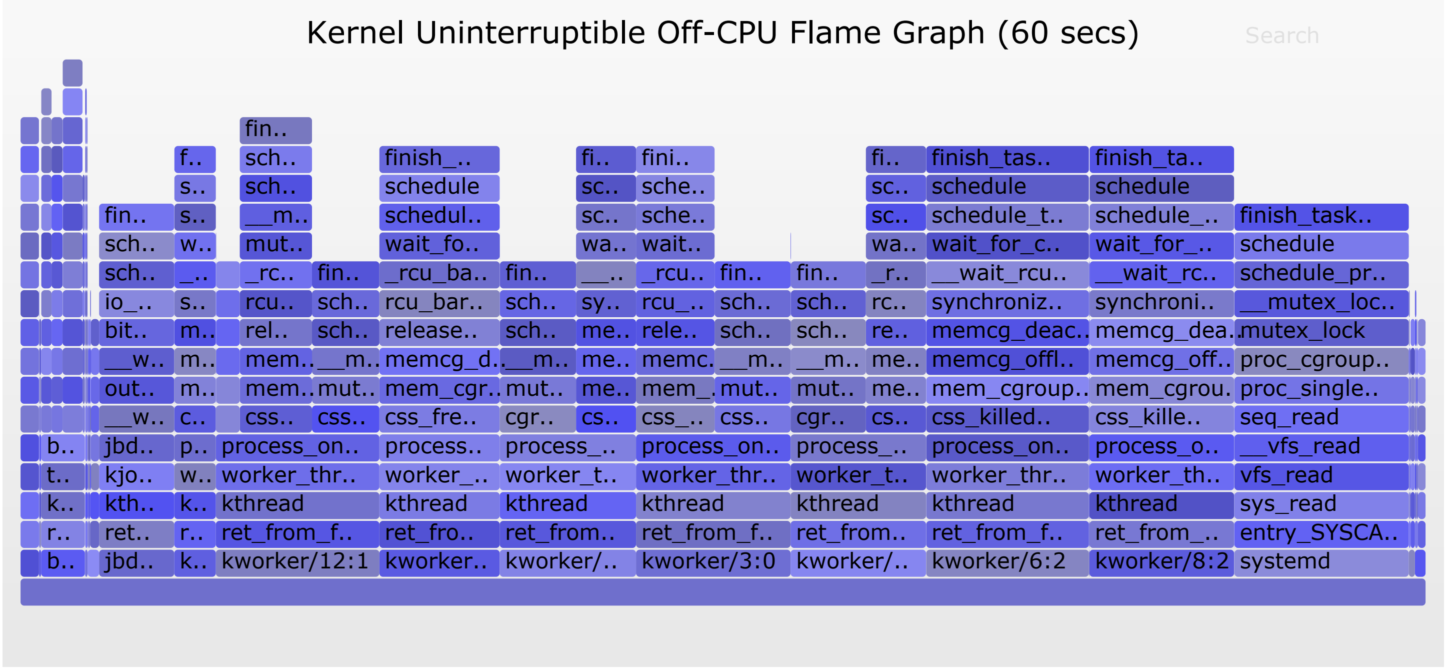
So Matthias still thinks it makes sense, at least given what TASK_UNINTERRUPTIBLE used to mean.

But TASK_UNITERRUPTIBLE matches more things today. Should we change load averages to be just CPU and disk demand? Scheduler maintainer Peter Zijstra has already sent me one clever option to explore for doing this: include `task_struct->in_iowait` in load averages instead of TASK_UNINTERRUPTIBLE, so that it more closely matches disk I/O. It begs another question, however, which is what do we really want? Do we want to measure demand on the system in terms of threads, or just demand for physical resources? If it's the former, then waiting on uninterruptible locks should be included as those threads are demand on the system. They aren't idle. So perhaps Linux load averages already work the way we want them to.

To better understand uninterruptible code paths, I'd like a way to measure them in action. Then we can examine different examples, quantify time spent in them, and see if it all makes sense.

Measuring uninterruptible tasks

The following is an Off-CPU flame graph from a production server, spanning 60 seconds and showing kernel stacks only, where I'm filtering to only include those in the TASK_UNINTERRUPTIBLE state (SVG). It provides many examples of uninterruptible code paths:



If you are new to off-CPU flame graphs: you can click on frames to zoom in, examining the full stacks which appear as a tower of frames. The x-axis size is proportional to the time spent blocked off-CPU, and the sort order (left to right) has no real meaning. The color is blue for off-CPU stacks (I use warm colors for on-CPU stacks), and the saturation has random variance to differentiate frames.

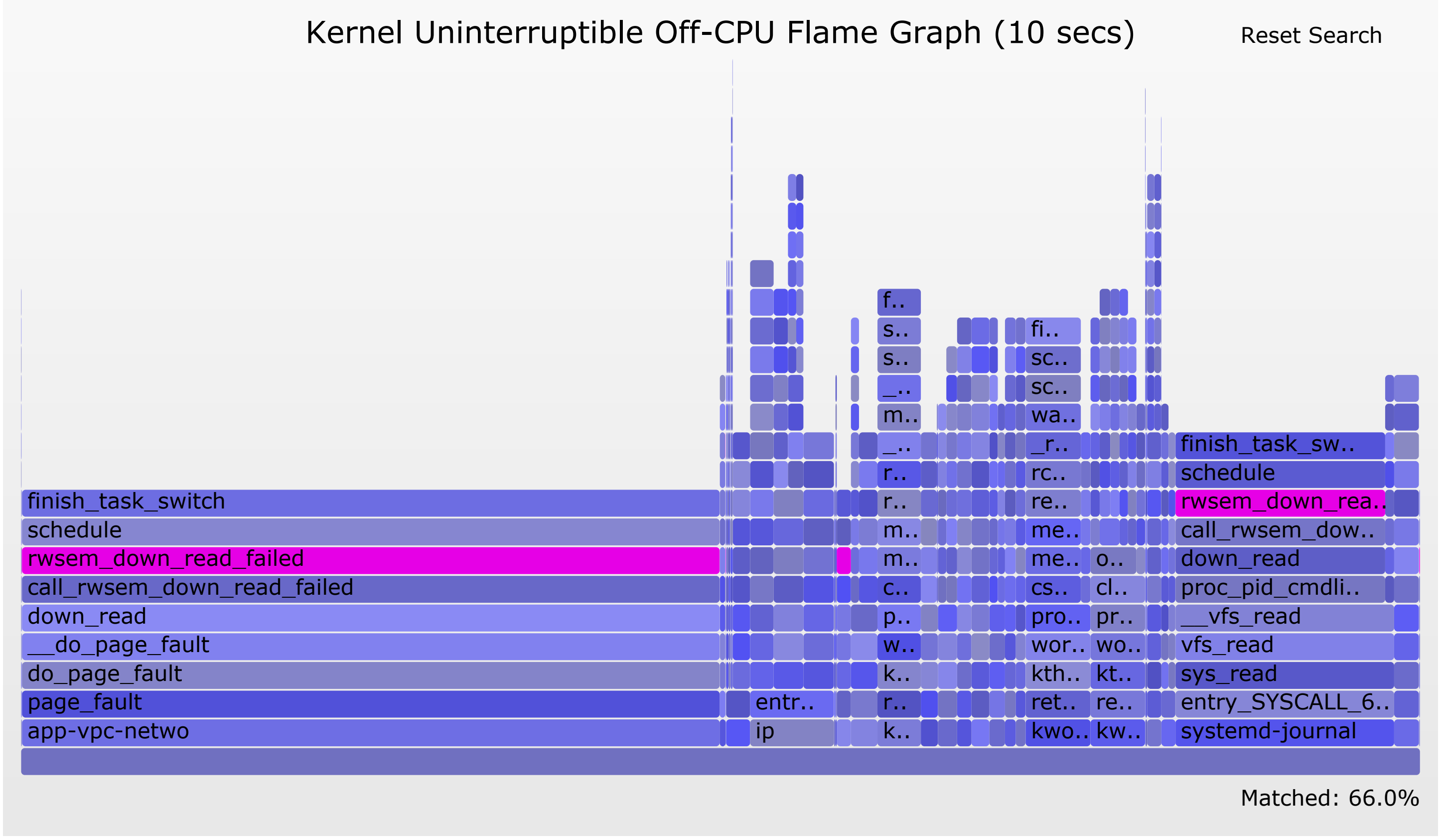
I generated this using my offcputime tool from bcc (this tool needs eBPF features from Linux 4.8+), and my flame graph software:

```
# ./bcc/tools/offcputime.py -K --state 2 -f 60 > out.stacks
# awk '{ print $1, $2 / 1000 }' out.stacks | ./FlameGraph/flamegraph.pl --color=io --countname=ms
```

I'm using awk to change the output from microseconds to milliseconds. The offcputime "--state 2" matches on TASK_UNINTERRUPTIBLE (see sched.h), and is an option I just added for this post. Facebook's Josef Bacik first did this with his kernelscope tool, which also uses bcc and flame graphs. In my examples, I'm just showing the kernel stacks, but offcputime.py supports showing the user stacks as well.

As for the flame graph above: it shows that only 926 ms out of 60 seconds were spent in uninterruptible sleep. That's only adding 0.015 to our load averages. It's time in some cgroup paths, but this server is not doing much disk I/O.

Here is a more interesting one, this time only spanning 10 seconds (SVG):



The wide tower on the right is showing `systemd-journal` in proc_pid_cmdline_read() (reading /proc/PID/cmdline), getting blocked, and contributing 0.07 to the load average. And there is a wider page fault tower on the left, that also ends up in rwsem_down_read_failed() (adding 0.23 to the load average). I've highlighted those functions in magenta using the flame graph search feature. Here's an excerpt from rwsem_down_read_failed():

```
    /* wait to be given the lock */
    while (true) {
        set_task_state(tsk, TASK_UNINTERRUPTIBLE);
        if (!waiter.task)
            break;
        schedule();
    }
```

This is lock acquisition code that's using TASK_UNINTERRUPTIBLE. Linux has uninterruptible and interruptible versions of mutex acquire functions (eg, mutex_lock() vs mutex_lock_interruptible(), and down() and down_interruptible() for semaphores). The interruptible versions allow the task to be interrupted by a signal, and then wake up to process it before the lock is acquired. Time in uninterruptible lock sleeps usually don't add much to the load averages, but in this case they are adding 0.30. If this was much higher, it would be worth analyzing to see if lock contention could be reduced (eg, I'd start digging on systemd-journal and proc_pid_cmdline_read()!), which should improve performance and lower the load average.

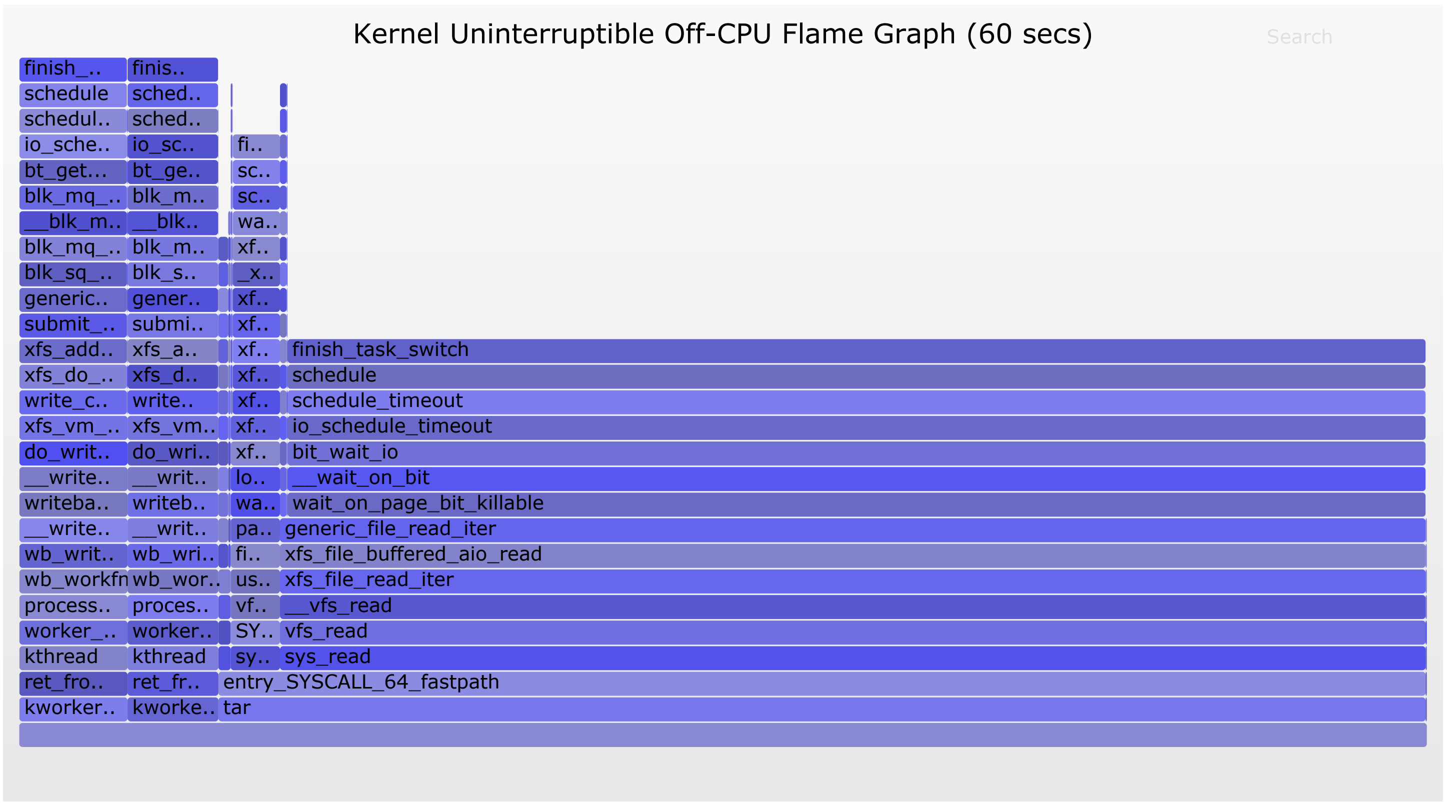
Does it make sense for these code paths to be included in the load average? Yes, I'd say so. Those threads are in the middle of doing work, and happen to block on a lock. They aren't idle. They are demand on the system, albeit for software resources rather than hardware resources.

Decomposing Linux load averages

Can the Linux load average value be fully decomposed into components? Here's an example: on an idle 8 CPU system, I launched `tar` to archive some uncached files. It spends several minutes mostly blocked on disk reads. Here are the stats, collected from three different terminal windows:

```
terma$ pidstat -p `pgrep -x tar` 60
Linux 4.9.0-rc5-virtual (bgregg-xenial-bpf-i-0b7296777a2585be1)     08/01/2017  _x86_64_    (8 CP

10:15:51 PM   UID       PID    %usr %system  %guest    %CPU   CPU  Command
10:16:51 PM     0     18468    2.85   29.77    0.00   32.62     3  tar

termb$ iostat -x 60
[...]
avg-cpu:  %user   %nice %system %iowait  %steal   %idle
           0.54    0.00    4.03    8.24    0.09   87.10

Device:         rrqm/s   wrqm/s     r/s     w/s    rkB/s    wkB/s avgrq-sz avgqu-sz   await r_awa
xvdap1            0.00     0.05   30.83    0.18   638.33     0.93    41.22     0.06    1.84    1.
xvdb            958.18  1333.83 2045.30  499.38 60965.27 63721.67    98.00     3.97    1.56    0.
xvdc            957.63  1333.78 2054.55  499.38 61018.87 63722.13    97.69     4.21    1.65    0.
md0               0.00     0.00 4383.73 1991.63 121984.13 127443.80    78.25     0.00    0.00

termc$ uptime
 22:15:50 up 154 days, 23:20,  5 users,  load average: 1.25, 1.19, 1.05
[...]
termc$ uptime
 22:17:14 up 154 days, 23:21,  5 users,  load average: 1.19, 1.17, 1.06
```

I also collected an Off-CPU flame graph just for the uninterruptible state (SVG):



The final one minute load average is 1.19. Let me decompose that:

- 0.33 is from tar's CPU time (pidstat)
- 0.67 is from tar's uninterruptible disk reads, inferred (offcpu flame graph has this at 0.69, I suspect as it began collecting a little later and spans a slightly different time range)
- 0.04 is from other CPU consumers (iostat user + system, minus tar's CPU from pidstat)
- 0.11 is from kernel workers uninterruptible disk I/O time, flushing disk writes (offcpu flame graph, the two towers on the left)

That adds up to 1.15. I'm still missing 0.04, some of which may be rounding and measurement interval offset errors, but a lot may be due to the load average being an exponentially-damped moving sum, whereas the other averages I'm using (pidstat, iostat) are normal averages. Prior to 1.19, the one minute average was 1.25, so some of that will still be dragging us high. How much? From my earlier graphs, at the one minute mark, 62% of the metric was from that minute, and the rest was older. So 0.62 x 1.15 + 0.38 x 1.25 = 1.18. That's pretty close to the 1.19 reported.

This is a system where one thread (tar) plus a little more (some time in kernel worker threads) are doing work, and Linux reports the load average as 1.19, which makes sense. If it was measuring "CPU load averages", the system would have reported 0.37 (inferred from mpstat's summary), which is correct for CPU resources only, but hides the fact that there is demand for over one thread's worth of work.

I hope this example shows that the numbers really do mean something deliberate (CPU + uninterruptible), and you can decompose them and figure it out.

Making sense of Linux load averages

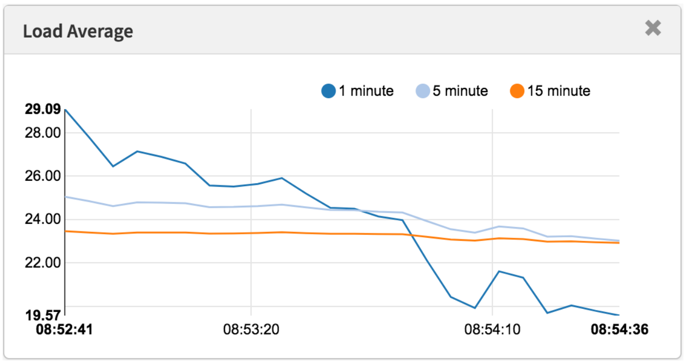
I grew up with OSes where load averages meant CPU load averages, so the Linux version has always bothered me. Perhaps the real problem all along is that the words "load averages" are about as ambiguous as "I/O". Which type of I/O? Disk I/O? File system I/O? Network I/O? ... Likewise, which load averages? CPU load averages? System load averages? Clarifying it this way lets me make sense of it like this:

- On Linux, load averages are (or try to be) "**system load averages**", for the system as a whole, measuring the number of threads that are working and waiting to work (CPU, disk, uninterruptible locks). Put differently, it measures the number of threads that aren't completely idle. Advantage: includes demand for different resources.
- On other OSes, load averages are "**CPU load averages**", measuring the number of CPU running + CPU runnable threads. Advantage: can be easier to understand and reason about (for CPUs only).

Note that there's another possible type: "**physical resource load averages**", which would include load for physical resources only (CPU + disk).

Perhaps one day we'll add additional load averages to Linux, and let the user choose what they want to use: a separate "CPU load averages", "disk load averages", "network load averages", etc. Or just use different metrics altogether.

What is a "good" or "bad" load average?



Load averages measured in a modern tool

Some people have found values that seem to work for their systems and workloads: they know that when load goes over X, application latency is high and customers start complaining. But there aren't really rules for this.

With CPU load averages, one could divide the value by the CPU count, then say that if that ratio is over 1.0 you are running at saturation, which may cause performance problems. It's somewhat ambiguous, as it's a long-term average (at least one minute) which can hide variation. One system with a ratio of 1.5 might be running fine, whereas another at 1.5 that was bursty within the minute might be performing badly.

I once administered a two-CPU email server that during the day ran with a CPU load average of between 11 and 16 (a ratio of between 5.5 and 8). Latency was acceptable and no one complained. That's an extreme example: most systems will be suffering with a load/CPU ratio of just 2.

As for Linux's system load averages: these are even more ambiguous as they cover different resource types, so you can't just divide by the CPU count. It's more useful for *relative* comparisons: if you know the system runs fine at a load of 20, and it's now at 40, then it's time to dig in with other metrics to see what's going on.

Better Metrics

When Linux load averages increase, you know you have higher demand for resources (CPUs, disks, and some locks), but you aren't sure which. You can use other metrics for clarification. For example, for CPUs:

- **per-CPU utilization**: eg, using `mpstat -P ALL 1`
- **per-process CPU utilization**: eg, `top`, `pidstat 1`, etc.

- **per-thread run queue (scheduler) latency**: eg, in /proc/PID/schedstats, delaystats, `perf sched`
- **CPU run queue latency**: eg, in /proc/schedstat, `perf sched`, my runqlat bcc tool.
- **CPU run queue length**: eg, using `vmstat 1` and the 'r' column, or my runqlen bcc tool.

The first two are utilization metrics, the last three are saturation metrics. Utilization metrics are useful for workload characterization, and saturation metrics useful for identifying a performance problem. The best CPU saturation metrics are measures of run queue (or scheduler) latency: the time a task/thread was in a runnable state, but had to wait its turn. These allow you to calculate the magnitude of a performance problem, eg, the percent of time a thread spent in scheduler latency. Measuring the run queue length instead can suggest that there is a problem, but it's more difficult to estimate the magnitude.

The schedstats facility was made a kernel tunable in Linux 4.6 (sysctl kernel.sched_schedstats) and changed to be off by default. Delay accounting exposes the same scheduler latency metric, which is in cpustat and I just suggested adding it to htop too, as that would make it easier for people to use. Easier than, say, scraping the wait-time (scheduler latency) metric from the (undocumented) /proc/sched_debug output:

```
$ awk 'NF > 7 { if ($1 == "task") { if (h == 0) { print; h=1 } } else { print } }' /proc/sched_de
            task   PID         tree-key  switches  prio     wait-time             sum-exec
         systemd     1      5028.684564    306666   120     43.133899     48840.448980   21068
     ksoftirqd/0     3 99071232057.573051   1109494   120        5.682347     21846.967164   209
    kworker/0:0H     5 99062732253.878471         9   100        0.014976         0.037737
     migration/0     9         0.000000   1995690     0      0.000000     25020.580993
   lru-add-drain    10        28.548203         2   100      0.000000         0.002620
      watchdog/0    11         0.000000   3368570     0      0.000000     23989.957382
         cpuhp/0    12      1216.569504         6   120      0.000000         0.010958
          xenbus    58  72026342.961752       343   120      0.000000         1.471102
      khungtaskd    59 99071124375.968195    111514   120        0.048912      5708.875023   205
[...]
         dockerd 16014    247832.821522   2020884   120     95.016057    131987.990617   22988
         dockerd 16015    106611.777737   2961407   120      0.000000    160704.014444
         dockerd 16024       101.600644        16   120      0.000000         0.915798
[...]
```

Apart from CPU metrics, you can also look for utilization and saturation metrics for disk devices. I focus on such metrics in the USE method, and have a Linux checklist of these.

While there are more explicit metrics, that doesn't mean that load averages are useless. They are used successfully in scale-up policies for cloud computing microservices, along with other metrics. This helps microservices respond to different types of load increases, CPU or disk I/O. With these policies it's safer to err on scaling up (costing money) than not to scale up (costing customers), so including more signals is desirable. If we scale up too much, we'll debug why the next day.

The one thing I keep using load averages for is their historical information. If I'm asked to check out a poor-performing instance on the cloud, then login and find that the one minute average is much lower than the fifteen minute average, it's a big clue that I might be too late to see the performance issue live. But I only spend a few seconds contemplating load averages, before turning to other metrics.

Conclusion

In 1993, a Linux engineer found a nonintuitive case with load averages, and with a three-line patch changed them forever from "CPU load averages" to what one might call "system load averages." His change included tasks in the uninterruptible state, so that load averages reflected demand for disk resources and not just CPUs. These system load averages count the number of threads working and waiting to work, and are summarized as a triplet of exponentially-damped moving sum averages that use 1, 5, and 15 minutes as constants in an equation. This triplet of numbers lets you see if load is increasing or decreasing, and their greatest value may be for relative comparisons with themselves.

The use of the uninterruptible state has since grown in the Linux kernel, and nowadays includes uninterruptible lock primitives. If the load average is a measure of demand in terms of running and waiting threads (and not strictly threads wanting hardware resources), then they are still working the way we want them to.

In this post, I dug up the Linux load average patch from 1993 – which was surprisingly difficult to find – containing the original explanation by the author. I also measured stack traces and time in the uninterruptible state using bcc/eBPF on a modern Linux system, and visualized this time as an off-CPU flame graph. This visualization provides many examples of uninterruptible sleeps, and can be generated whenever needed to explain unusually high load averages. I also proposed other metrics you can use to understand system load in more detail, instead of load averages.

I'll finish by quoting from a comment at the top of kernel/sched/loadavg.c in the Linux source, by scheduler maintainer Peter Zijlstra:

> * This file contains the magic bits required to compute the global loadavg
> * figure. **Its a silly number but people think its important.** We go through
> * great pains to make it work on big machines and tickless kernels.

References

- Saltzer, J., and J. Gintell. "The Instrumentation of Multics," CACM, August 1970 (explains exponentials).
- Multics system_performance_graph command reference (mentions the 1 minute average).
- TENEX source code (load average code is in SCHED.MAC).
- RFC 546 "TENEX Load Averages for July 1973" (explains measuring CPU demand).
- Bobrow, D., et al. "TENEX: A Paged Time Sharing System for the PDP-10," Communications of the ACM, March 1972 (explains the load average triplet).
- Gunther, N. "UNIX Load Average Part 1: How It Works" PDF (explains the exponential calculations).
- Linus's email about Linux 0.99 patchlevel 14.
- The load average change email is on oldlinux.org (in alan-old-funet-lists/kernel.1993.gz, and not in the linux directories, which I searched first).
- The Linux kernel/sched.c source before and after the load average change: 0.99.13, 0.99.14.
- Tarballs for Linux 0.99 releases are on kernel.org.
- The current Linux load average code: loadavg.c, loadavg.h
- The bcc analysis tools includes my offcputime, used for tracing TASK_UNINTERRUPTIBLE.
- Flame Graphs were used for visualizing uninterruptible paths.

Thanks to Deirdre Straughan for edits.

Comments for this thread are now closed ×

34 Comments **Brendan Gregg's Blog** 1 **Login**

Recommend 40 Tweet Share **Sort by Best**

Juan Pablo Reyes Sepúlveda • a year ago

Great investigation work and very educative post.

Thanks for sharing!!!

6 ^ | v • Share ›

Ory Band • a year ago

Yet another great post by Brendan Gregg. Keep up the good work, educating developers worldwide.

2 ^ | v • Share ›

Jon Currey • a year ago

Great stuff. Thank you!
Some people might enjoy Neil Gunther's follow up articles, where he digs in deeper and relates the exponential decay approach to queuing theory (https://www.teamquest.com/f... and analog circuits (https://www.teamquest.com/f.... The Multics paper acknowledges taking the lightweight method for

computing the exponential average from signal processing. Specifically, 1950s work from Bell Labs, co-authored by JW Tukey, who also gave the world the Fast Fourier Transform and boxplots.

1 ^ | ∨ • Share ›

hmijail ➦ Jon Currey • a year ago

Interesting links. Note that they have an extra closing parens, which causes the link to fail!

^ | ∨ • Share ›

Steve Mushero • a year ago

I'm confused by the latency that you mentioned - I just did lots of research lately as part of articles I wrote on Golden Signals / tools (runqstat) and I'm very confused by the CPU run queue latency in /proc/schedstat - this does not seem to really measure what you describe.

You wrote & I expect a sum of runnable process time waiting for a CPU, but in my measurements it vastly exceeds this number even on very lightly loaded systems.

Instead it seems to measure tasks in ANY non-running state, i.e. how long since a task has run, even if it has no work to do - it appears to be dozens of seconds for every second its sampled (and of course subtracted from the prior count value) - it simple cannot be higher than 1 second per second on an non-saturated system, but was dozens or hundreds on my tests (I can easily be doing something wrong, of course; and this doesn't really seem to be in Jiffies, either, or the results are even higher).

It appears this is used as part of the scheduling criteria to avoid starvation in the CFQ scheduler, i.e. the sum of all tasks not-running, so if there are 100 non-running tasks/processes, this will go up by about 100 seconds per second.

I hope I'm missing something, as I'd love to find a way to measure this, ideally in /proc and without BPF.

^ | ∨ • Share ›

finnich • a year ago

Thanks for adding something new to my knowledge...really loved the post.

^ | ∨ • Share ›

Hayden James • a year ago

Your level of detail, while yet being able to deliver uncomplicated guidance on often misunderstood topics, is simply amazing. Thanks!

^ | ∨ • Share ›

Thomas Phifer • a year ago

This is good stuff. Thanks.

^ | ∨ • Share ›

Noah Friedman • a year ago

Load average has always included processes in iowait, at least in BSD. Both the 4.3BSD and 4.4BSD books by McKusick et al were explicit about this.

The addition of other uninterruptible conditions may be new, but not disk io.

^ | ∨ • Share ›

ZhangChao • a year ago

Really nice article, thanks for sharing! Now I understand what the load average is, it's really make me confused!

I have a question:
From my earlier graphs, at the one minute mark, 62% of the metric was from that minute, and the rest was older. So 0.62 x 1.15 + 0.38 x 1.25 = 1.18. That's pretty close to the 1.19 reported.

which is your earlier graphs?
what is the 0.62 and 0.38 mean? the time?

oh, I get it:
The so-called "one minute average" only reaches about 0.62 by the one minute mark.

^ | v • Share ›

vb2 • a year ago

I'm impressed by the persistence you displayed in tracking down the root cause. It is a skill that is lacking so much in IT. Thank you for educating us.
In regards to better metrics for CPU run queue length you mention the vmstat r column. There are different interpretations of the meaning of this column, with man vmstat stating "r: The number of processes waiting for run time." while others state something like "cpu + wait on cpu"
If man is correct, then r >0 implies cpu saturation. Is that interpretation correct?

^ | v • Share ›

Rituraj • a year ago

great work on this. While I agree with Matthias' POV
i.e:

quote - The point of "load average"[in Linux] is to arrive at a number relating how busy the system is from a human point of view. - unquote

..
I must add that its more like "waiting for godot" (ref uninterruptible), which basically IMO is not a positive and practical way to live a 'human' life. :)

^ | v • Share ›

Vijay Ram • a year ago

Another great post

^ | v • Share ›

Matt Fleming • a year ago

Fantastic article Brendan. You kept digging through the kernel source history long after most of us would have given up! This is a great detective story.

^ | v • Share ›

Sergey Senozhatsky • a year ago

yeah, one of the reasons why I want to rework `console_sem' sempahore is that TASK_UNINTERRUPTIBLE thing, which also adds up to LA.

-ss

^ | v • Share ›

Hagai Kariti • a year ago

Great post!

Shouldn't the time tar spent reading from disk be the one reported by iostat's r_await metric? Or at least dominated by it? Looking at the output, it seems that r_await*reads is a really small amount of

^ | v • Share ›

Jason Cai • a year ago

It's so informative and useful! I've investigated Linux's "load average" but I'm not able to figure out the mystery of TASK_UNINTERRUPTIBLE.
Thank you so much!

^ | v • Share ›

Stefan Parvu • a year ago

Nice blog entry.

Some comments: LA is not really an "industry-critical metric". People use them just because they been there for decades and better have them around anyway. In fact it is a very confusing metric in system performance measurements and sizing. Run queue length and other metrics are much useful and practical with a real value.

At Kronometrix we are researching and developing new ways to add useful metrics to our data recorders which can help us better understand systems overall or component level.

https://github.com/kronomet...

^ | v • Share ›

Bhaskar Chowdhury • a year ago

Magnificent digging Brendan! Learnt a lot and thanks a bunch for the pain taken by you to make it count.

^ | v • Share ›

Valentine Sinitsyn • a year ago

Great article, thanks!

It's a shame to say, but I don't fully get the math behind tar's LA decomposition:
* 0.32 from pidstat seems evident (%CPU is 32.3)
* 0.69 is supposedly 0.8576 * 0.8139 (tar share * vfs_read share). But why do one need to multiple these shares? These values are global, not relative to the parent.
* 0.04 is hard to get as there is no mpstat in the preceding figure, but there is the formula in the text.
* 0.11: the two leftmost towers on the off-cpu flame graph sum up to 0.14, not 0.11 - where do I get that number?

Many thanks

^ | v • Share ›

brendangregg Mod ➦ Valentine Sinitsyn • a year ago

tar: the off-CPU flame graph has 41,464 ms, and that's a sum over a 60 second trace. Normalizing that to 1 second = 41.464 / 60 = 0.69. The pidstat output has tar taking 32.62% average CPU (not a sum), and I know all its off-CPU time is in uninterruptible (by generating off-CPU graphs for the other states), so I can infer that 67.38% of its time is in uninterruptible. 0.67. I used that number instead, as the pidstat interval closely matched the other tools I was running.

The kworker threads have 3,684 and 3,102 ms. Normalizing to 1 second is 6.786 / 60 = 0.11.

^ | v • Share ›

fuyou ➦ brendangregg • a year ago

0.04 where come from ? thank you very much!

10 ^ | v • Share ›

brendangregg Mod ➦ fuyou • a year ago

by mpstat I meant iostat sorry (I updated the text), but it's the same CPU summary. It's 0.54 + 4.03% for user + sys. That's 4.57% average across 8 CPUs, 4.57 x 8 = 36.56% in terms of one CPU. pidstat says that tar consumed 32.62%, so the remander is 36.56% - 32.62% = 3.94% of one CPU, which was used by things that weren't tar (other processes). That's the 0.04 added to load average.

^ | v • Share ›

Valentine Sinitsyn ➦ brendangregg • a year ago

Thanks a lot, Brendan. It's crystal clear now. Shame on me again :)

^ | v • Share ›

Les Stroud • a year ago

Don't forget that, in a virtualized world, load average can also represent supply. The time to get on CPU, underlying io bus contention, etc can all show up as higher than normal loads.

I ran into this, more than once, when server load averages were changing over time with no change to the task executions themselves.

^ | v • Share ›

Vince Poore ➦ Les Stroud • a year ago

I think I might have run into this. Are there any articles or blogs you are aware of that would show the methodology to pin the problem to a hypervisor supply issue?

^ | v • Share ›

Matt Saladna ➦ Les Stroud • a year ago

That supply/demand response is conferred through steal% so long as the kernel supports it as a compile-time option. "iostat" will tell you what's going on, but as a whole unless you have 2 identical workloads on two different nodes, steal% is nothing conclusive apart from "hey, x% of the workload isn't getting serviced by the hv." and not necessarily a sign of oversubscription.

^ | v • Share ›

Michael Pinnegar • a year ago

Really nice very deep article!

^ | v • Share ›

MPW • a year ago

Thanks for this awesome article and the dive through Linux's history! Very interesting and fun to read.

^ | v • Share ›

AllenB • a year ago

Another great post, Brendan! I've always "known" that Linux load average included "stuff waiting on IO" but never had the details before. Hoorah!

^ | v • Share ›

David VomLehn • a year ago

Uninterruptible waits predate Linux. In UNIX they were used when waiting for a disk block to be read. Since the disk read was something that happened really fast (well, it seemed like it at the time) the process would start again very soon and so should still be considered runnable. In the Linux era, people didn't necessarily think about the consequences of unkillable processes and used uninterruptible waits as an easy wait to avoid accommodating signals in their implementations. This skewed the load average as well as causing reboots to get rid of unkillable processes. Over the past year or so, I think Linus Torvalds has become a bit more aware of the issue, but there is a lot of education needed.

In terms of actual programming, you should only use an uninterruptible wait if you *know* an operation will complete quickly. Otherwise, handle the signal in an interruptible wait or use a timeout.

• Share ›

MM • a year ago

Fascinating article. Thank you for sharing.

I noticed that something seems awry with the terminal output in "Decomposing Linux load averages". The 'termc' output for the second `uptime` command shows an earlier time of day but a longer uptime than the first command. Not critical but maybe some of the other output got mangled somehow also?

• Share ›

brendangregg Mod MM • a year ago

Thanks, fixed, was supposed to be 22:17:14 -- I'd manually flipped them to 10:17:14 to match the timezone from the other command, then changed my mind and flipped them back (with a typo).

• Share ›

John Piers Cilliers • a year ago

Very nice! Informative to say the least!

• Share ›

You can comment here, but I can't guarantee your comment will remain here forever: I might switch comment systems at some point (eg, if disqus add advertisements).