

Performance Profiling Tools Tutorial

CS-255 Systems Programming Lab

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Motivation

Let's say you've written a program

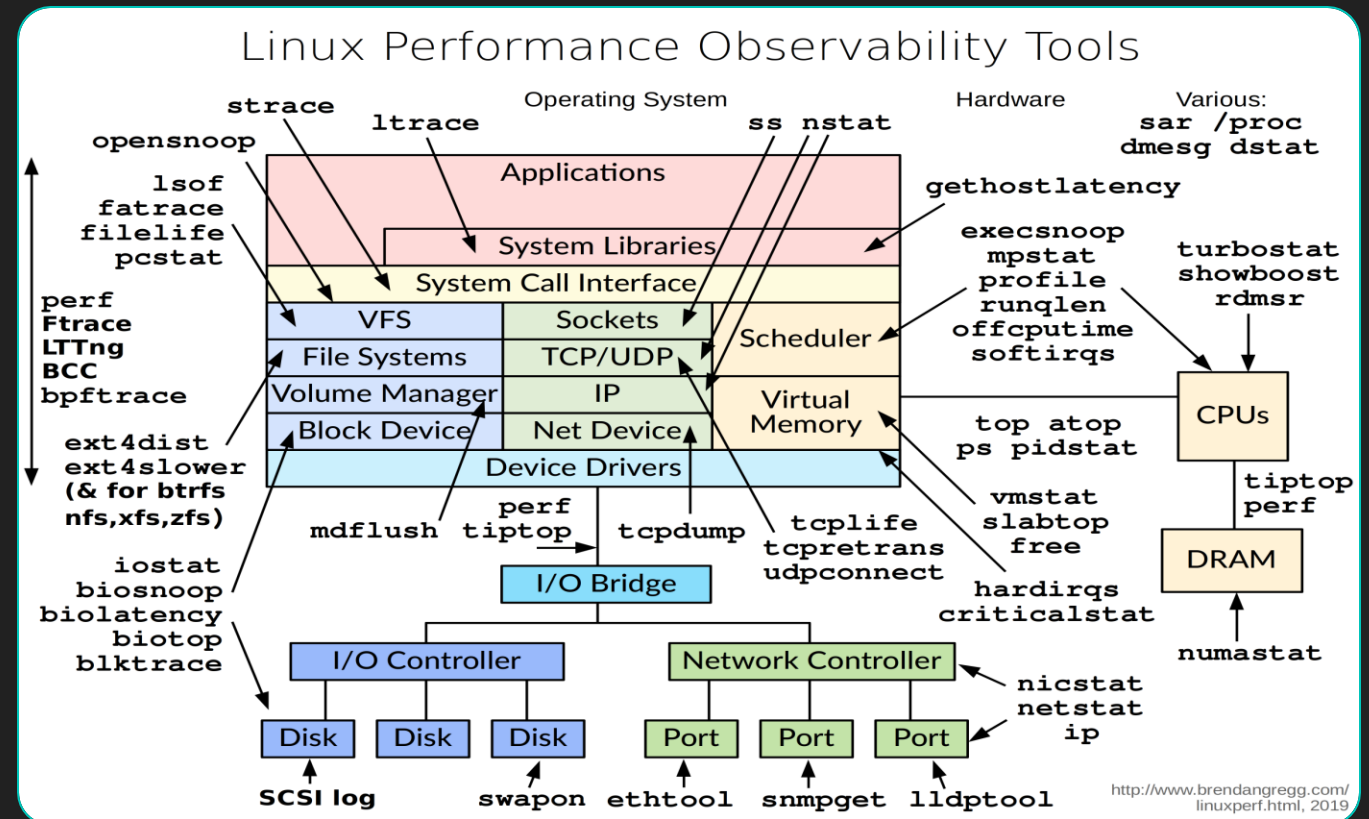
- It looks to be working
- But the performance is bad
- You want to find the underlying cause **efficiently**
- How do you do it?

Another example:

- Your server/machine is underperforming
- You want to check resource usage and running programs
- How do you do it? (in **Linux**)

A roadmap of available tools

Many tools available, for different system components

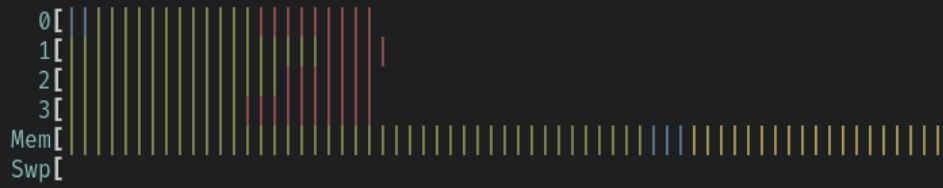


top

- Display Linux processes
- Continuous output, until pressing 'q'
- **Lots** of functionality, press 'h' to display help

```
top - 11:29:08 up 90 days, 38 min, 1 user, load average: 0.03, 0.08, 0.04
Tasks: 135 total, 1 running, 134 sleeping, 0 stopped, 0 zombie
%Cpu(s):  0.0 us,  0.2 sy,  0.0 ni, 99.5 id,  0.3 wa,  0.0 hi,  0.0 si,  0.0 st
KiB Mem:  4033100 total,  2060884 used,  1972216 free,  271464 buffers
KiB Swap: 3905532 total,    2680 used,  3902852 free. 1224392 cached Mem
```

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
22628	jmal	20	0	5388	2464	2076	R	0.3	0.1	0:00.02	top
1	root	20	0	5788	3780	2652	S	0.0	0.1	1:11.14	systemd
2	root	20	0	0	0	0	S	0.0	0.0	0:03.66	kthreadd
3	root	20	0	0	0	0	S	0.0	0.0	6:35.70	ksoftirqd/0
5	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	kworker/0:0H
7	root	20	0	0	0	0	S	0.0	0.0	25:38.90	rcu_sched
8	root	20	0	0	0	0	S	0.0	0.0	0:00.00	rcu_bh
9	root	rt	0	0	0	0	S	0.0	0.0	0:27.61	migration/0
10	root	rt	0	0	0	0	S	0.0	0.0	0:29.18	watchdog/0
11	root	rt	0	0	0	0	S	0.0	0.0	0:28.57	watchdog/1
12	root	rt	0	0	0	0	S	0.0	0.0	0:17.48	migration/1
13	root	20	0	0	0	0	S	0.0	0.0	3:54.60	ksoftirqd/1
15	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	kworker/1:0H
16	root	rt	0	0	0	0	S	0.0	0.0	0:23.89	watchdog/2
17	root	rt	0	0	0	0	S	0.0	0.0	0:33.54	migration/2
18	root	20	0	0	0	0	S	0.0	0.0	3:16.16	ksoftirqd/2
20	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	kworker/2:0H
21	root	rt	0	0	0	0	S	0.0	0.0	0:22.05	watchdog/3
22	root	rt	0	0	0	0	S	0.0	0.0	0:26.82	migration/3
23	root	20	0	0	0	0	S	0.0	0.0	3:27.36	ksoftirqd/3
25	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	kworker/3:0H
26	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	khelper
27	root	20	0	0	0	0	S	0.0	0.0	0:00.00	kdevtmpfs
28	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	netns
29	root	20	0	0	0	0	S	0.0	0.0	0:02.43	khungtaskd
30	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	writeback
31	root	25	5	0	0	0	S	0.0	0.0	0:00.00	ksmd
32	root	39	19	0	0	0	S	0.0	0.0	0:00.00	khugepaged
33	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	crypto
34	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	integrityd
35	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	bioaset
36	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	kblockd
41	root	20	0	0	0	0	S	0.0	0.0	1:22.81	kswapd0
42	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	vmstat
43	root	20	0	0	0	0	S	0.0	0.0	0:00.01	fsnotify_mark
49	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	kthrotld
50	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	ipv6_addrconf
52	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	deferwq
92	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	acpi_thermal_pm
93	root	20	0	0	0	0	S	0.0	0.0	0:00.00	khubd
94	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	kpsmoused
95	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	ata_sff
97	root	20	0	0	0	0	S	0.0	0.0	0:00.00	scsi_eh_0



24.3%] Tasks: 67, 669 thr; 4 running
 27.6%] Load average: 1.60 2.26 2.33
 26.6%] Uptime: 02:38:04
 25.5%]
 3.86G/7.71G
 0K/4.00G]

PID	USER	PRI	NI	VIRT	RES	SHR	S	CPU%	MEM%	TIME+	Command
5916	mallias	20	0	3424M	761M	211M	S	4.6	9.6	12:04.36	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5920	mallias	20	0	3424M	761M	211M	S	1.3	9.6	1:02.40	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5921	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:03.67	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5922	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.16	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5923	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:07.32	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5924	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:07.37	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5925	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:07.05	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5926	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:07.49	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5927	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:08.68	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5929	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.00	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5930	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.00	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5931	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.04	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5932	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.00	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5933	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.00	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
5934	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.00	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6044	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.00	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6050	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:02.33	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6051	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:01.83	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6052	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:01.49	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6060	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.14	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6086	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.71	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6087	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.74	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6088	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.68	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6108	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.04	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6125	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.01	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6126	mallias	20	0	3424M	761M	211M	S	0.0	9.6	0:00.09	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6127	mallias	39	19	3424M	761M	211M	S	0.0	9.6	0:00.01	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419
6128	mallias	39	19	3424M	761M	211M	S	0.0	9.6	0:00.00	/usr/lib/firefox/firefox -contentproc -childID 18 -isForBrowser -prefsLen 10391 -prefMapSize 252953 -parentBuildID 20210419

htop

- An interactive Linux process viewer
- Similar to top, but with better UI, some extra features (mouse support!)

```
jmal@thanatos ~ % vmstat 1
```

```
procs -----memory----- ---swap-- -----io----- -system-- -----cpu-----
r  b   swpd   free   buff  cache   si   so    bi    bo    in    cs  us  sy  id  wa  st
0  0   7156 1514700 447452 1673396    0    0     1     1     0     0   1   0   99   0   0
0  0   7156 1514568 447452 1673396    0    0     0     0    40    81   0   0  100   0   0
0  0   7156 1514568 447452 1673396    0    0     0     0    36    84   0   0  100   0   0
0  0   7156 1514784 447460 1673388    0    0     0    16   187   532   4   1   94   1   0
0  0   7156 1514784 447460 1673388    0    0     0     8    27    63   0   0  100   0   0
0  0   7156 1514520 447460 1673396    0    0     0     0    30    78   0   0  100   0   0
```

vmstat

- Virtual Memory Stat
- View system memory and processor statistics
- Configurable output frequency, count

```
jmal@thanatos ~ % free -m
```

	total	used	free	shared	buffers	cached
Mem:	3938	2462	1476	87	437	1635
-/+ buffers/cache:		388	3550			
Swap:	3813	6	3807			

```
jmal@thanatos ~ % █
```

free

- Display system memory statistics
- Configurable output unit, report duration

mpstat

- Processor statistics
- Various processor time metrics
- Configurable CPU set to display stats

```
mallias@ArchCorsair ~ % mpstat -P ALL 1 1
Linux 5.11.16-arch1-1 (ArchCorsair)    05/18/2021    _x86_64_    (4 CPU)

01:08:43 PM  CPU    %usr  %nice    %sys %iowait    %irq  %soft  %steal  %guest  %gnice   %idle
01:08:44 PM  all    7.97   0.00    1.80   0.00    0.77   0.00   0.00   0.00   0.00   89.46
01:08:44 PM   0     4.17   0.00    1.04   0.00    1.04   0.00   0.00   0.00   0.00   93.75
01:08:44 PM   1     5.21   0.00    3.12   0.00    0.00   0.00   0.00   0.00   0.00   91.67
01:08:44 PM   2    15.31   0.00    1.02   0.00    1.02   0.00   0.00   0.00   0.00   82.65
01:08:44 PM   3     7.07   0.00    2.02   0.00    1.01   0.00   0.00   0.00   0.00   89.90

Average:      CPU    %usr  %nice    %sys %iowait    %irq  %soft  %steal  %guest  %gnice   %idle
Average:      all    7.97   0.00    1.80   0.00    0.77   0.00   0.00   0.00   0.00   89.46
Average:       0     4.17   0.00    1.04   0.00    1.04   0.00   0.00   0.00   0.00   93.75
Average:       1     5.21   0.00    3.12   0.00    0.00   0.00   0.00   0.00   0.00   91.67
Average:       2    15.31   0.00    1.02   0.00    1.02   0.00   0.00   0.00   0.00   82.65
Average:       3     7.07   0.00    2.02   0.00    1.01   0.00   0.00   0.00   0.00   89.90
mallias@ArchCorsair ~ %
```


iostat

- I/O related statistics
- Displayed per device
- Configurable report frequency/duration

```
jmal@sith5 ~ % iostat -xm 1
Linux 3.10.0-514.16.1.el7.x86_64 (sith5.cluster.ics.forth.gr) 05/18/2021 _x86_64_ (32 CPU)

avg-cpu:  %user   %nice %system %iowait  %steal   %idle
           0.35    0.00   0.04   0.01   0.00   99.60

Device:            rrqm/s   wrqm/s     r/s     w/s    rMB/s   wMB/s avgrq-sz avgqu-sz   await  r_await  w_await  svctm  %util
nvme0n1             0.00     0.00    0.00    0.00     0.00    0.00   77.96     0.00    0.10   0.10     0.00   0.10   0.00
sda                  0.00     0.01    0.24    0.21     0.00    0.00   27.08     0.01   11.22   7.09   16.08   6.35   0.28
sdb                   0.00     0.00    1.27    0.01     0.16    0.00  252.28     0.01    4.76   4.35   66.81   2.22   0.28

avg-cpu:  %user   %nice %system %iowait  %steal   %idle
           0.00    0.00   0.00   0.00   0.00  100.00

Device:            rrqm/s   wrqm/s     r/s     w/s    rMB/s   wMB/s avgrq-sz avgqu-sz   await  r_await  w_await  svctm  %util
nvme0n1             0.00     0.00    0.00    0.00     0.00    0.00    0.00     0.00    0.00   0.00     0.00   0.00   0.00
sda                  0.00     0.00    0.00    0.00     0.00    0.00    0.00     0.00    0.00   0.00     0.00   0.00   0.00
sdb                   0.00     0.00    0.00    0.00     0.00    0.00    0.00     0.00    0.00   0.00     0.00   0.00   0.00

^C
```

Profiling

- Program = Algorithms + Data Structures
- Both can be debugged to avoid errors
- But how to optimize efficiently?
- Profiling: dynamic program performance analysis
- Program analysis can examine many things:
 1. Time spent in functions (stalls/delays)
 2. Call paths and function call frequencies
 3. Memory Consumption

gprof

- GNU Profiler (Not a debugger!)
- Compile (and link) your program with `-pg`
- Run your program as you would normally
- Once your program exits there should be a `gmon.out` file
- Run `gprof <gprof options> <your executable> gmon.out` to perform profiling
- Common gprof options:
 1. `-p`: flat profile, shows the time your program spent executing each function
 2. `-q`: call graph analysis, view function calls in a tree-like manner

gprof output

```

mallias@ArchCorsair ~/Documents/HY255/EX04 % gprof -p -b sudoku gmon.out
Flat profile:

Each sample counts as 0.01 seconds.
%   cumulative   self           self         total
time  seconds    seconds    calls  ms/call  ms/call  name
66.73   0.18      0.18      4841     0.04     0.05  sudoku_init_choices
 7.41   0.20      0.02    2087055     0.00     0.00  grid_clear_choice
 7.41   0.22      0.02    456892     0.00     0.00  grid_choice_is_valid
 7.41   0.24      0.02     4841     0.00     0.00  sudoku_try_next
 7.41   0.26      0.02     4780     0.00     0.00  sudoku_is_solvable
 3.71   0.27      0.01     4842     0.00     0.00  sudoku_is_correct
 0.00   0.27      0.00    1647725     0.00     0.00  grid_read_choice
 0.00   0.27      0.00    1209593     0.00     0.00  grid_read_value
 0.00   0.27      0.00     742673     0.00     0.00  grid_read_count
 0.00   0.27      0.00    229593     0.00     0.00  grid_clear_count
 0.00   0.27      0.00    123310     0.00     0.00  grid_remove_choice
 0.00   0.27      0.00     4471     0.00     0.00  grid_update_value
 0.00   0.27      0.00     4390     0.00     0.00  sudoku_eliminate_choice
 0.00   0.27      0.00     4390     0.00     0.00  sudoku_update_choice
 0.00   0.27      0.00     729     0.00     0.00  grid_set_choice
 0.00   0.27      0.00     454     0.00     0.00  grid_clear_unique
 0.00   0.27      0.00      81     0.00     0.00  grid_set_count
 0.00   0.27      0.00      2     0.00     0.00  sudoku_print
 0.00   0.27      0.00      1     0.00     0.00  grid_read_unique
 0.00   0.27      0.00      1     0.00     0.00  grid_set_unique
 0.00   0.27      0.00      1     0.00     0.00  sudoku_read
 0.00   0.27      0.00      1     0.00     0.00  sudoku_solution_is_unique
 0.00   0.27      0.00      1     0.00    270.27  sudoku_solve

```

```

mallias@ArchCorsair ~/Documents/HY255/EX04 % gprof -b -q sudoku gmon.out
Call graph

```

granularity: each sample hit covers 2 byte(s) for 3.70% of 0.27 seconds

```

index % time    self  children   called   name
-----
[1]  100.0    0.00   0.27      1/1      <spontaneous>
      0.00   0.27      1/4842   main [1]
      0.00   0.00      1/4842   sudoku_solve [2]
      0.00   0.00      2/2      sudoku_is_correct [8]
      0.00   0.00      1/1      sudoku_print [20]
      0.00   0.00      1/1      sudoku_read [23]
      0.00   0.00      1/1      sudoku_solution_is_unique [24]
-----
                                4840
                                1/1      sudoku_solve [2]
[2]  100.0    0.00   0.27      1+4840   main [1]
      0.18   0.04    4841/4841  sudoku_solve [2]
      0.02   0.00    4841/4841  sudoku_init_choices [3]
      0.02   0.00    4841/4841  sudoku_try_next [6]
      0.01   0.00    4780/4780  sudoku_is_solvable [7]
      0.01   0.00    4841/4842  sudoku_is_correct [8]
      0.00   0.00    4390/4390  sudoku_update_choice [9]
      0.00   0.00    4390/4390  sudoku_eliminate_choice [11]
      0.00   0.00    4780/123310  grid_remove_choice [10]
      0.00   0.00     454/454  grid_clear_unique [18]
                                4840
                                4841/4841  sudoku_solve [2]
[3]  81.3     0.18   0.04     4841     sudoku_init_choices [3]
      0.02   0.00    456892/456892  grid_choice_is_valid [5]
      0.02   0.00    2029123/2087055  grid_clear_choice [4]
      0.00   0.00    1502262/1647725  grid_read_choice [12]
      0.00   0.00    392121/1209593  grid_read_value [13]
      0.00   0.00    225203/229593  grid_clear_count [15]
-----
                                18422/2087055  grid_remove_choice [10]
                                39510/2087055  sudoku_update_choice [9]
                                2029123/2087055  sudoku_init_choices [3]
[4]  7.4      0.02   0.00    2087055  grid_clear_choice [4]
-----
                                456892/456892  sudoku_init_choices [3]
[5]  7.4      0.02   0.00    456892  grid_choice_is_valid [5]
-----
                                4841/4841  sudoku_solve [2]
[6]  7.4      0.02   0.00     4841   sudoku_try_next [6]
      0.00   0.00    662645/742673  grid_read_count [14]

```

Going a level deeper: perf

- *perf* is a **robust** Linux profiler
- Can monitor **lots** of system events (use *perf list* to check them out)
- Configurable monitoring frequency
- Useful mainly for the Linux kernel (`perf_events`), but can also be used in userspace
- Userspace command interface, use *perf <perf_command> <perf_options> <your command>*

Some useful perf commands

- *perf stat* : obtain event counts
- *perf record* : record events for later reporting
- *perf report* : event breakdown
- *perf top* : live event count

Sample perf stat output

```
mallias@ArchCorsair ~/Documents/HY255/EX04 % perf stat ./sudoku < puzzles/hard.txt
```

```
8 0 0 0 0 0 0 0 0
0 0 3 6 0 0 0 0 0
0 7 0 0 9 0 2 0 0
0 5 0 0 0 7 0 0 0
0 0 0 0 4 5 7 0 0
0 0 0 1 0 0 0 3 0
0 0 1 0 0 0 0 6 8
0 0 8 5 0 0 0 1 0
0 9 0 0 0 0 4 0 0
```

```
8 1 2 7 5 3 6 4 9
9 4 3 6 8 2 1 7 5
6 7 5 4 9 1 2 8 3
1 5 4 2 3 7 8 9 6
3 6 9 8 4 5 7 2 1
2 8 7 1 6 9 5 3 4
5 2 1 9 7 4 3 6 8
4 3 8 5 2 6 9 1 7
7 9 6 3 1 8 4 5 2
```

```
Has a unique solution: 0
```

```
Performance counter stats for './sudoku':
```

630.81 msec	task-clock:u	#	0.998 CPUs utilized
0	context-switches:u	#	0.000 K/sec
0	cpu-migrations:u	#	0.000 K/sec
245	page-faults:u	#	0.388 K/sec
2,240,681,990	cycles:u	#	3.552 GHz
1,854,715,553	instructions:u	#	0.83 insn per cycle
321,735,923	branches:u	#	510.034 M/sec
2,293,988	branch-misses:u	#	0.71% of all branches

```
0.631850229 seconds time elapsed
```

```
0.630962000 seconds user
```

```
0.000000000 seconds sys
```

perf record and report

```
mallias@ArchCorsair ~/Documents/HY255/EX04 % perf record -F 99 -g ./sudoku < puzzles/hard.txt
```

```
8 0 0 0 0 0 0 0 0
0 0 3 6 0 0 0 0 0
0 7 0 0 9 0 2 0 0
0 5 0 0 0 7 0 0 0
0 0 0 0 4 5 7 0 0
0 0 0 1 0 0 0 3 0
0 0 1 0 0 0 0 6 8
0 0 8 5 0 0 0 1 0
0 9 0 0 0 0 4 0 0
```

```
8 1 2 7 5 3 6 4 9
9 4 3 6 8 2 1 7 5
6 7 5 4 9 1 2 8 3
1 5 4 2 3 7 8 9 6
3 6 9 8 4 5 7 2 1
2 8 7 1 6 9 5 3 4
5 2 1 9 7 4 3 6 8
4 3 8 5 2 6 9 1 7
7 9 6 3 1 8 4 5 2
```

```
Has a unique solution: 0
```

```
[ perf record: Woken up 1 times to write data ]
```

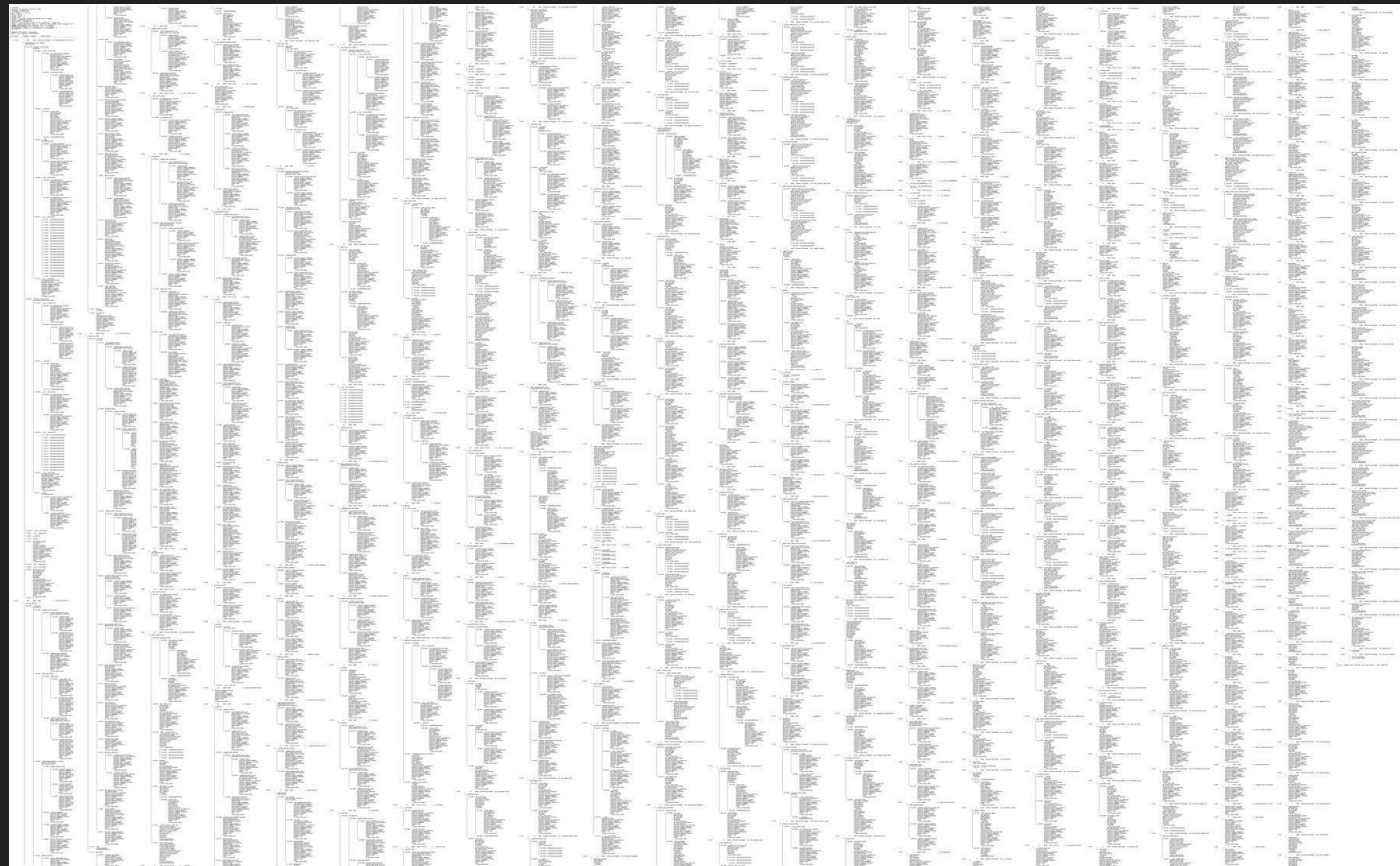
```
[ perf record: Captured and wrote 0.029 MB perf.data (97 samples) ]
```

```
Samples: 97 of event 'cycles:u', Event count (approx.): 3931367321
Children Self Command Shared Object Symbol
+ 97.49% 0.00% sudoku libc-2.33.so [.] __libc_start_main
+ 97.49% 0.00% sudoku sudoku [.] main
- 97.49% 0.91% sudoku sudoku [.] sudoku_solve
- 96.58% sudoku_solve
  sudoku_solve
  sudoku_solve
  sudoku_solve
  sudoku_solve
  sudoku_solve
  sudoku_solve
  sudoku_solve
  sudoku_solve
  sudoku_solve
  + sudoku_solve
+ 0.91% __libc_start_main
+ 62.15% 47.25% sudoku sudoku [.] sudoku_init_choices
+ 15.72% 12.06% sudoku sudoku [.] sudoku_try_next
+ 13.17% 13.17% sudoku sudoku [.] sudoku_is_solvable
+ 9.34% 9.34% sudoku libc-2.33.so [.] _mcount_internal
+ 6.40% 6.40% sudoku sudoku [.] grid_choice_is_valid
+ 3.69% 0.00% sudoku sudoku [.] sudoku_eliminate_choice
+ 2.81% 1.88% sudoku sudoku [.] grid_clear_choice
+ 2.78% 2.78% sudoku sudoku [.] grid_remove_choice
+ 1.84% 1.84% sudoku sudoku [.] sudoku_is_correct
+ 1.58% 1.58% sudoku libc-2.33.so [.] _int_malloc
+ 0.93% 0.93% sudoku sudoku [.] grid_read_count
+ 0.93% 0.93% sudoku libc-2.33.so [.] malloc
+ 0.92% 0.92% sudoku libc-2.33.so [.] _mcount
0.01% 0.01% sudoku [unknown] [k] 0xfffffffffab601067
0.01% 0.00% sudoku ld-2.33.so [.] _start
```

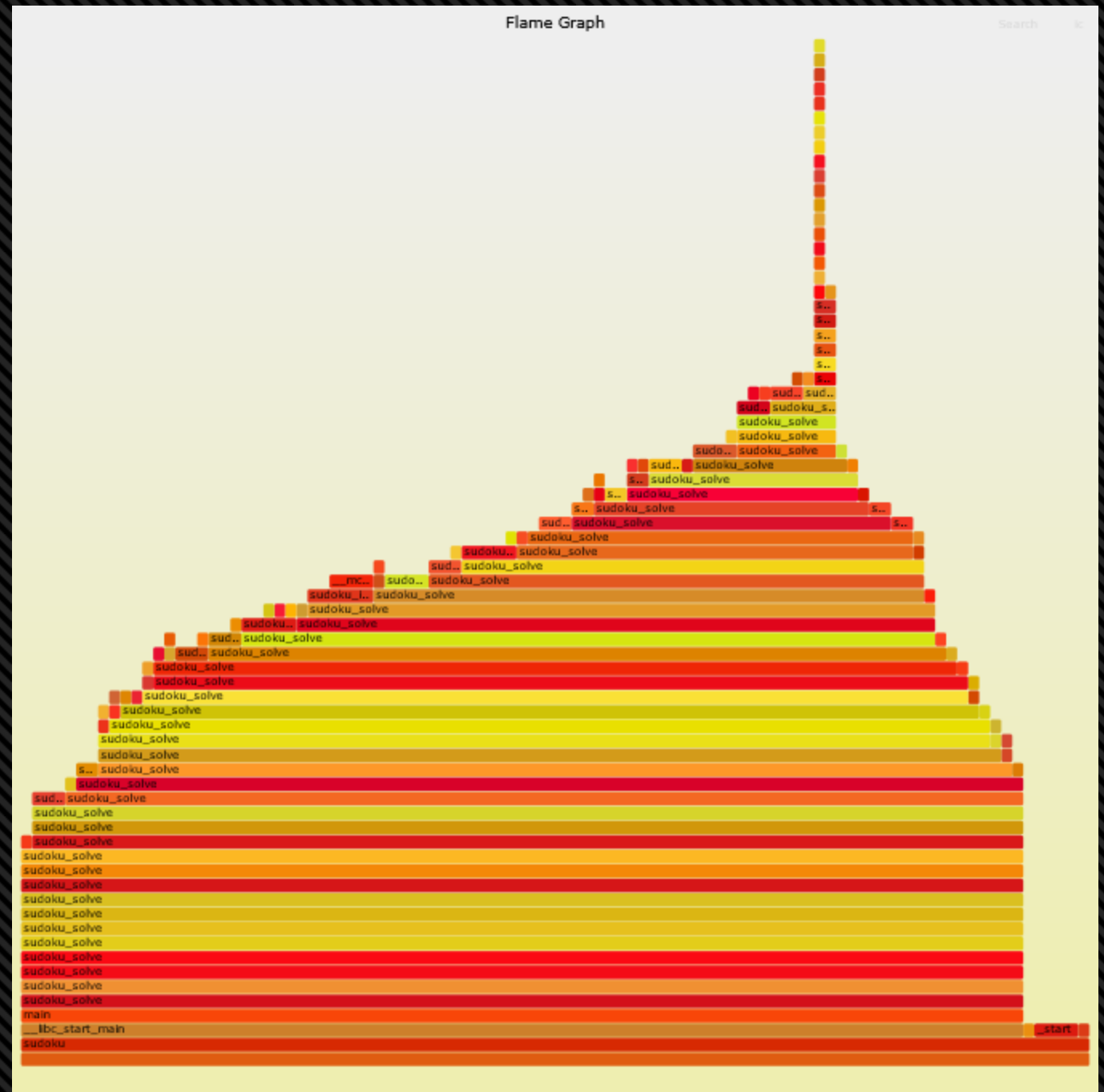
Tip: For memory address profiling, try: perf mem record / perf mem report

Flame Graphs

- Perf output can be **very long** (especially for large programs)
- This is where flame graphs come in
- Visualize function call stacks (and other data) efficiently
- Interactive svg output



Sudoku solve sample CPU flame graph



References

- Check the man pages for tool details/options (top, htop, vmstat, free, iostat, mpstat, perf)
- Performance analysis in 60 seconds: <https://netflixtechblog.com/linux-performance-analysis-in-60-000-milliseconds-acc10403c55>
- gprof documentation: <https://sourceware.org/binutils/docs/gprof/>
- gprof tutorial: <https://linoxide.com/gprof-performance-analysis-programs/>
- perf wiki: https://perf.wiki.kernel.org/index.php/Main_Page
- Brendan Gregg's perf examples: <http://brendangregg.com/perf.html>
- Flame Graphs: <http://brendangregg.com/flamegraphs.html>