Velocity
Build resilient systems at scale
May 27–29, 2015 • Santa Clara, CA

Linux Performance Tools

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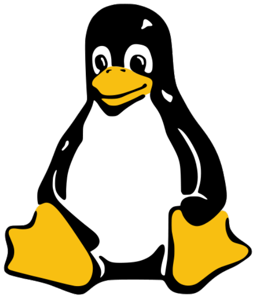
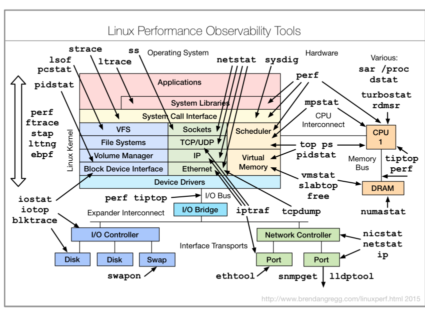


NETFLIX

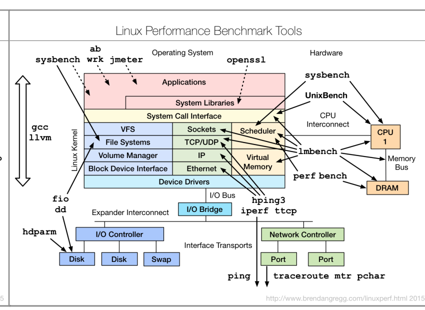
This Tutorial

- A tour of many Linux performance tools
  - To show you what can be done
  - With guidance for how to do it
- This includes objectives, discussion, live demos
  - See the video of this tutorial

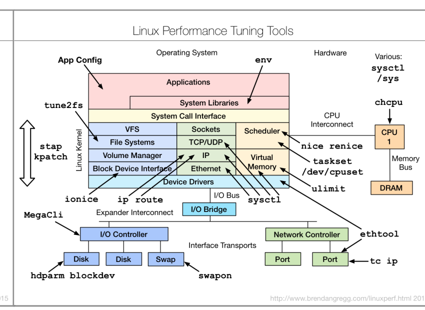
Observability



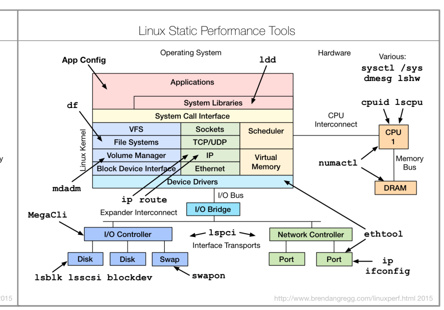
Benchmarking



Tuning

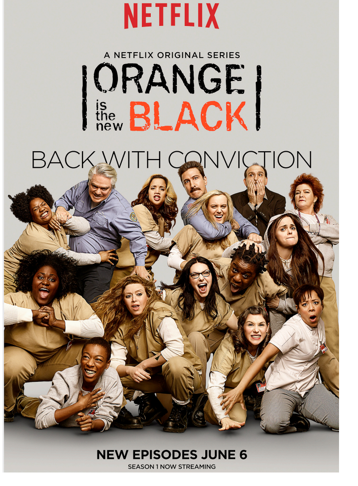


Static Tuning



NETFLIX

- Massive AWS EC2 Linux cloud
  - 10s of thousands of cloud instances
- FreeBSD for content delivery
  - ~33% of US Internet traffic at night
- Over 50M subscribers
  - Recently launched in ANZ
- Use Linux server tools as needed
  - After cloud monitoring (Atlas, etc.) and instance monitoring (Vector) tools



Agenda

- Methodologies
- Tools
- Tool Types:
  - Observability
  - Benchmarking
  - Tuning
  - Static
- Profiling
- Tracing

Methodologies

Methodologies

- Objectives:
  - Recognize the Streetlight Anti-Method
  - Perform the Workload Characterization Method
  - Perform the USE Method
  - Learn how to start with the questions, before using tools
  - Be aware of other methodologies

My system is slow…

DEMO

&

DISCUSSION

Methodologies

- There are dozens of performance tools for Linux
  - Packages: sysstat, procps, coreutils, …
  - Commercial products
- Methodologies can provide guidance for choosing and using tools effectively
- A starting point, a process, and an ending point

Anti-Methodologies

- The lack of a deliberate methodology…

Street Light Anti-Method

1. Pick observability tools that are:
   – Familiar
   – Found on the Internet
   – Found at random
2. Run tools
3. Look for obvious issues

Drunk Man Anti-Method

- Tune things at random until the problem goes away

Blame Someone Else Anti-Method

1. Find a system or environment component you are not responsible for
2. Hypothesize that the issue is with that component
3. Redirect the issue to the responsible team
4. When proven wrong, go to 1

Actual Methodologies

- Problem Statement Method
- Workload Characterization Method
- USE Method
- Off-CPU Analysis
- CPU Profile Method
- RTFM Method
- Active Benchmarking *(covered later)*
- Static Performance Tuning *(covered later)*
- …

Problem Statement Method

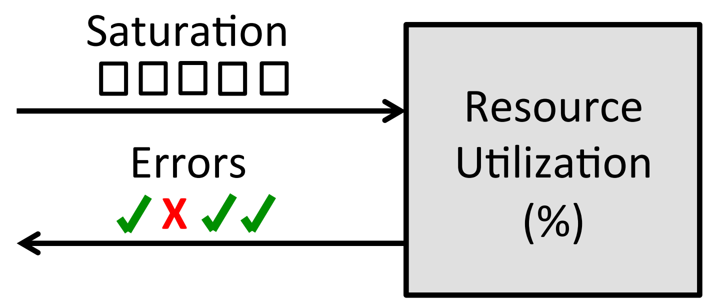
1. What makes you **think** there is a performance problem?
2. Has this system **ever** performed well?
3. What has **changed** recently? (Software? Hardware? Load?)
4. Can the performance degradation be expressed in terms of **latency** or run time?
5. Does the problem affect **other** people or applications (or is it just you)?
6. What is the **environment**? Software, hardware, instance types? Versions? Configuration?

Workload Characterization Method

1. **Who** is causing the load? PID, UID, IP addr, ...
2. **Why** is the load called? code path, stack trace
3. **What** is the load? IOPS, tput, type, r/w
4. **How** is the load changing over time?

The USE Method

- For every resource, check:
  1. **Utilization**
  2. **Saturation**
  3. **Errors**

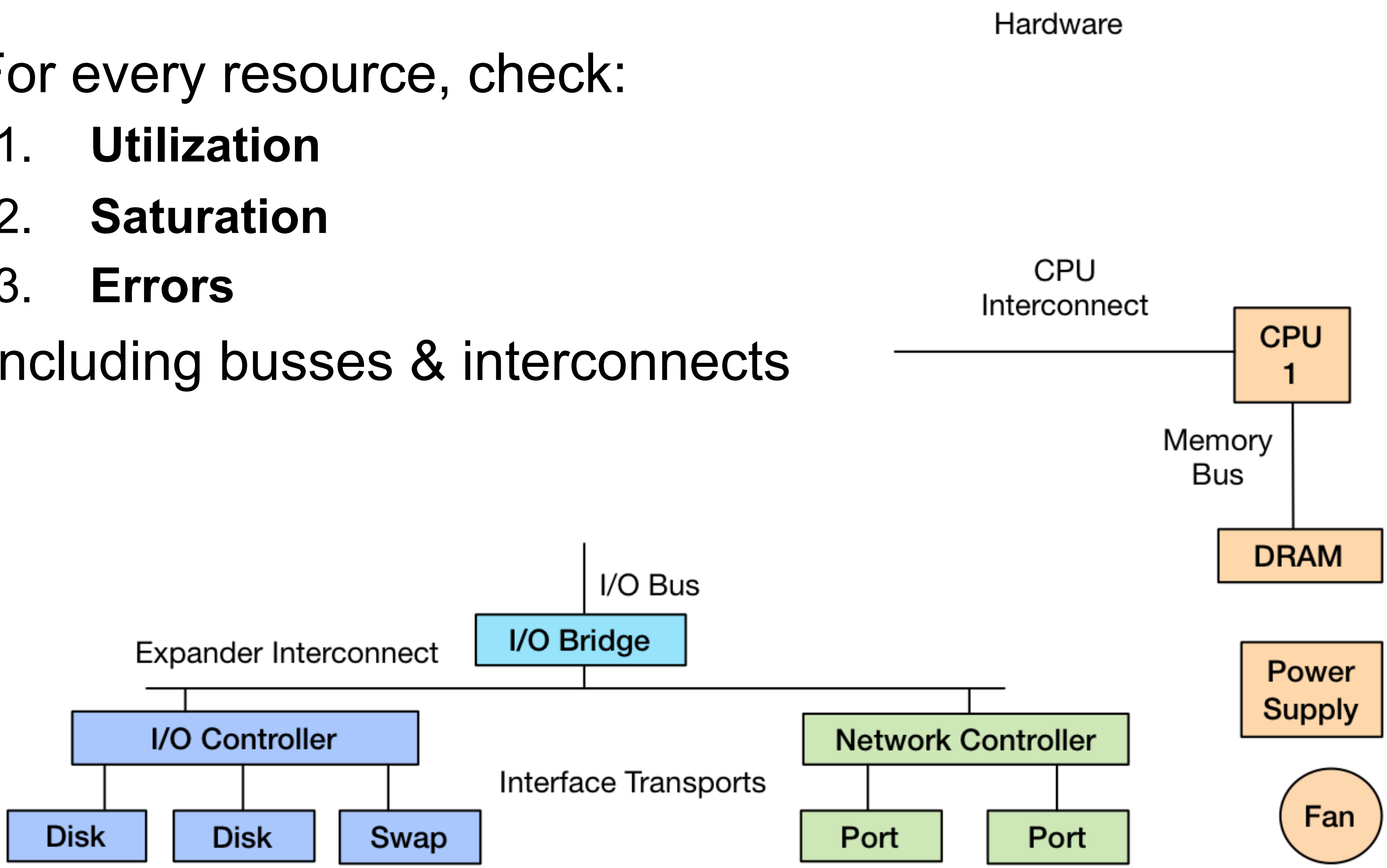


- Definitions:
  – Utilization: busy time
  – Saturation: queue length or queued time
  – Errors: easy to interpret (objective)
- Helps if you have a functional (block) diagram of your system / software / environment, showing all resources

Start with the questions, then find the tools

USE Method for Hardware

- For every resource, check:
  1. **Utilization**
  2. **Saturation**
  3. **Errors**
- Including busses & interconnects



Linux USE Method Example

USE Method: Linux Performance Checklist

The USE Method provides a strategy for performing a complete check of system health, identifying common bottlenecks and errors. For each system resource, metrics for utilization, saturation and errors are identified and checked. Any issues discovered are then investigated using further strategies.

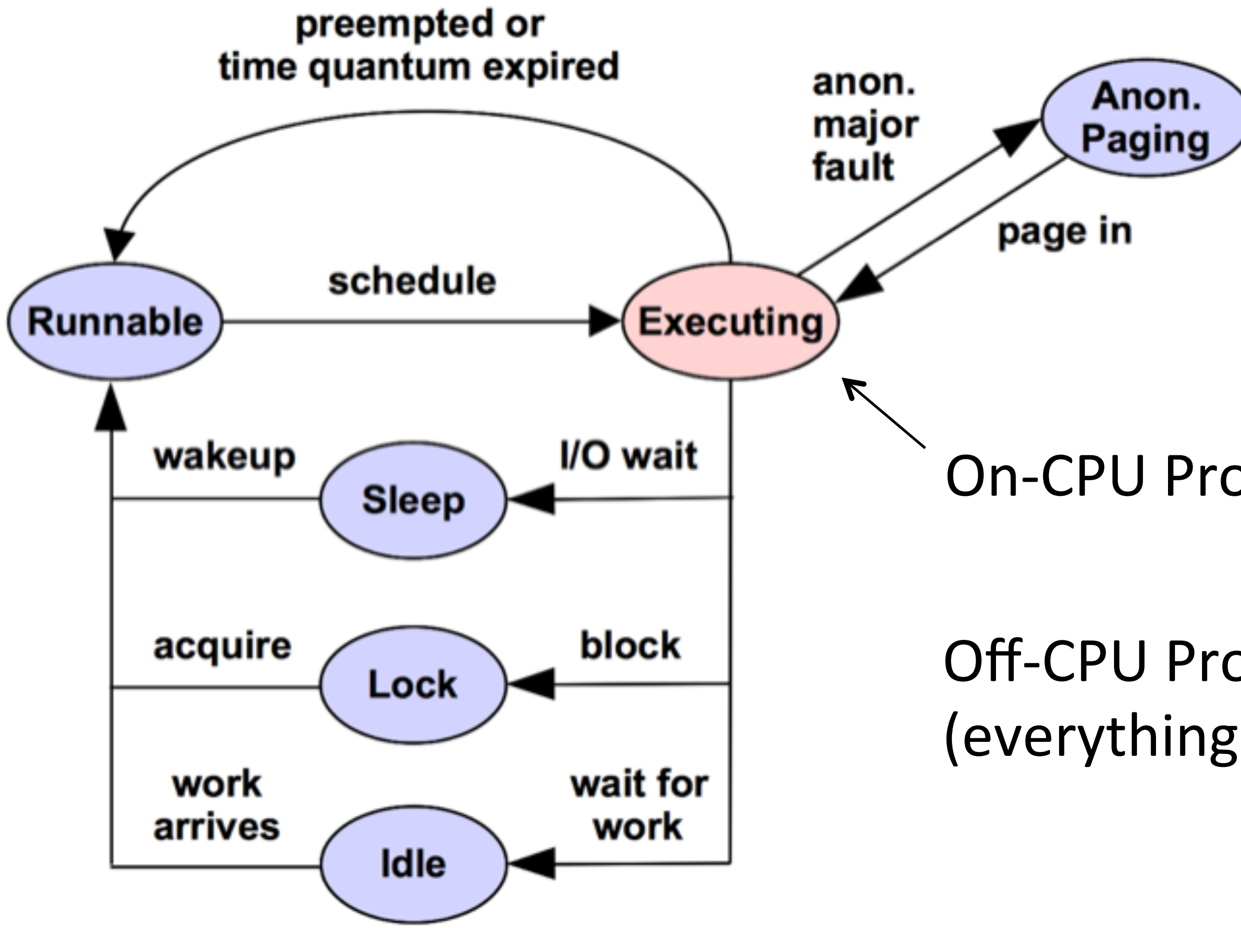
This is an example USE-based metric list for Linux operating systems (eg, Ubuntu, CentOS, Fedora). This is primarily intended for system administrators of the physical systems, who are using command line tools. Some of these metrics can be found in remote monitoring tools.

Physical Resources

http://www.brendangregg.com/USEmethod/use-linux.html

component	type	metric
CPU	utilization	system-wide: `vmstat 1`, "us" + "sy" + "st"; `sar -u`, sum fields except "%idle" and "%iowait"; `dstat -c`, sum fields except "idl" and "wai"; per-cpu: `mpstat -P ALL 1`, sum fields except "%idle" and "%iowait"; `sar -P ALL`, same as `mpstat`; per-process: `top`, "%CPU"; `htop`, "CPU%"; `ps -o pcpu`; `pidstat 1`, "%CPU"; per-kernel-thread: `top/htop` ("K" to toggle), where VIRT == 0 (heuristic). [1]
CPU	saturation	system-wide: `vmstat 1`, "r" > CPU count [2]; `sar -q`, "runq-sz" > CPU count; `dstat -p`, "run" > CPU count; per-process: /proc/PID/schedstat 2nd field (sched_info.run_delay); `perf sched latency` (shows "Average" and "Maximum" delay per-schedule); dynamic tracing, eg, SystemTap schedtimes.stp "queued(us)" [3]
CPU	errors	`perf` (LPE) if processor specific error events (CPC) are available; eg, AMD64's "04Ah Single-bit ECC Errors Recorded by Scrubber" [4]
Memory capacity	utilization	system-wide: `free -m`, "Mem:" (main memory), "Swap:" (virtual memory); `vmstat 1`, "free" (main memory), "swap" (virtual memory); `sar -r`, "%memused"; `dstat -m`, "free"; `slabtop -s c` for kmem slab usage; per-process: `top/htop`, "RES" (resident main memory), "VIRT" (virtual memory), "Mem" for system-wide summary
Memory capacity	saturation	system-wide: `vmstat 1`, "si"/"so" (swapping); `sar -B`, "pgscank" + "pgscand" (scanning); `sar -W`; per-process: 10th field (min_flt) from /proc/PID/stat for minor-fault rate, or dynamic tracing [5]; OOM killer: `dmesg | grep killed`
Memory	errors	`dmesg` for physical failures; dynamic tracing, eg, SystemTap uprobes for failed malloc()s

Off-CPU Analysis



On-CPU Profiling

Off-CPU Profiling
(everything else)

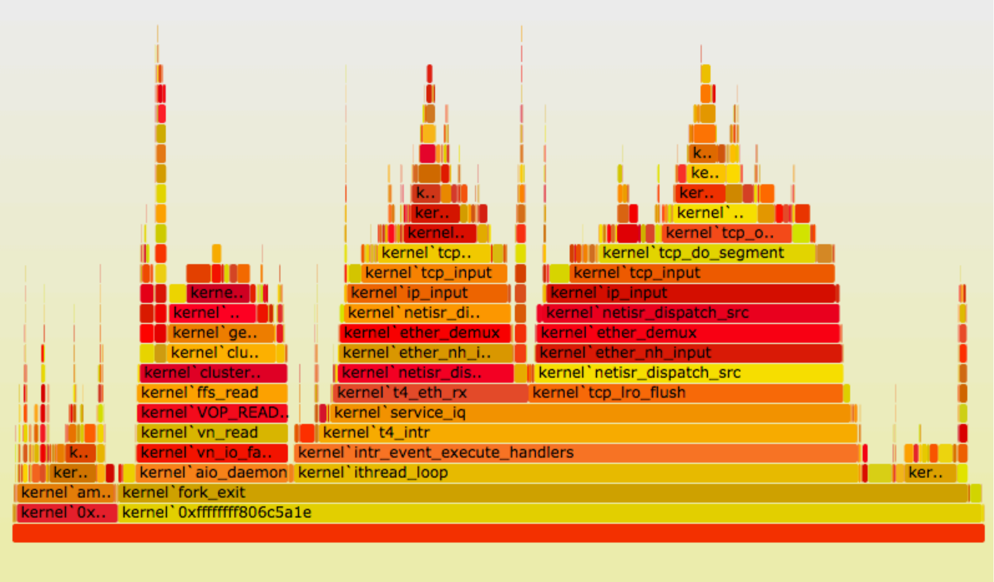
Thread State Transition Diagram

CPU Profile Method

1. Take a CPU profile
2. Understand all software in profile > 1%

- Discovers a wide range of performance issues by their CPU usage
- Narrows software to study

Flame Graph



RTFM Method

- How to understand performance tools or metrics:
  1. Man pages
  2. Books
  3. Web search
  4. Co-workers
  5. Prior talk slides/video (this one!)
  6. Support services
  7. Source code
  8. Experimentation
  9. Social

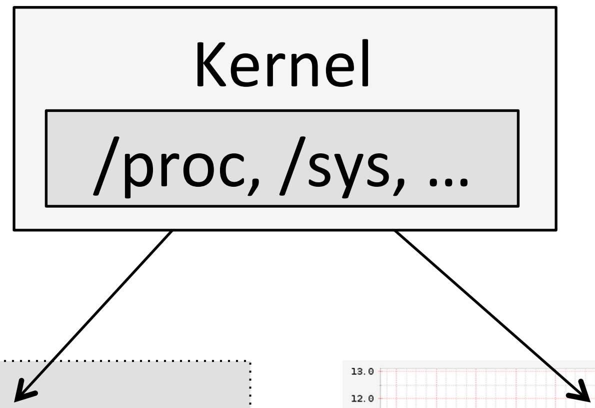
Tools

Tools

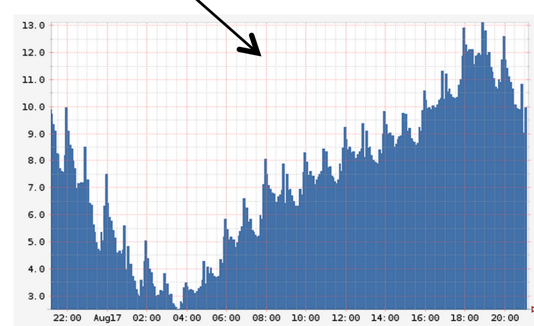
- Objectives:
  - Perform the USE Method for resource utilization
  - Perform Workload Characterization for disks, network
  - Perform the CPU Profile Method using flame graphs
  - Have exposure to various observability tools:
    - Basic: vmstat, iostat, mpstat, ps, top, …
    - Intermediate: tcpdump, netstat, nicstat, pidstat, sar, …
    - Advanced: ss, slaptop, perf_events, …
  - Perform Active Benchmarking
  - Understand tuning risks
  - Perform Static Performance Tuning

Command Line Tools

- Useful to study even if you never use them: GUIs and commercial products often use the same interfaces




```
$ vmstat 1
procs -----------memory---------- ---swap-- …
 r  b   swpd   free   buff  cache   si   so …
 9  0      0 29549320  29252 9299060    0    …
 2  0      0 29547876  29252 9299332    0    …
 4  0      0 29548124  29252 9299460    0    …
 5  0      0 29548840  29252 9299592    0    …
```

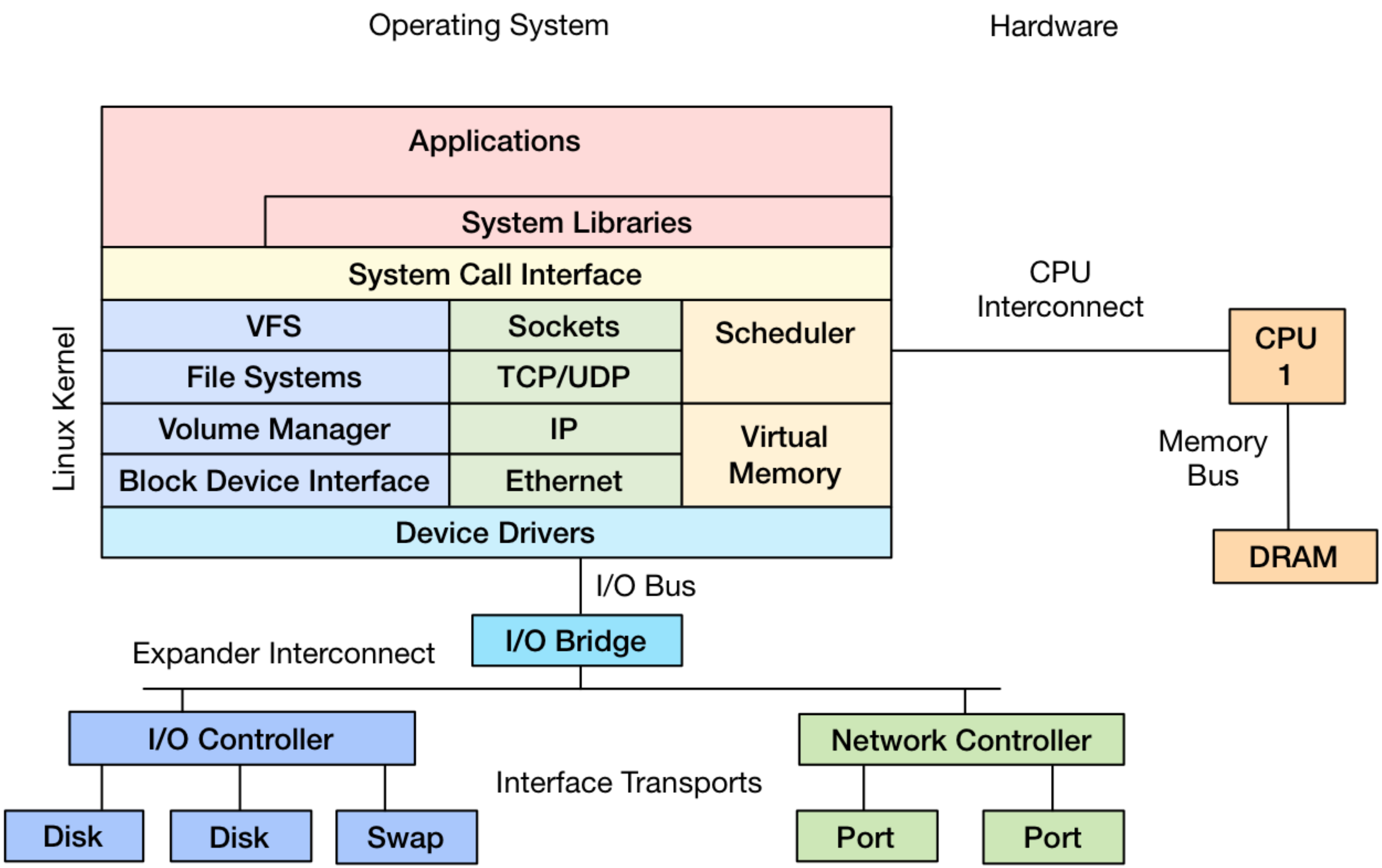


Tool Types

Type	Characteristic
Observability	Watch activity. Safe, usually, depending on resource overhead.
Benchmarking	Load test. Caution: production tests can cause issues due to contention.
Tuning	Change. Danger: changes could hurt performance, now or later with load.
Static	Check configuration. Should be safe.

Observability Tools

How do you measure these?



http://www.brendangregg.com/linuxperf.html 2015

Observability Tools: Basic

- uptime
- top (or htop)
- ps
- vmstat
- iostat
- mpstat
- free

uptime

- One way to print *load averages*:

```
$ uptime
 07:42:06 up  8:16,  1 user,  load average: 2.27, 2.84, 2.91
```

- A measure of resource demand: CPUs + disks
  - Other OSes only show CPUs: easier to interpret
- Exponentially-damped moving averages
- Time constants of 1, 5, and 15 minutes
  - Historic trend without the line graph
- Load > # of CPUs, may mean CPU saturation
  - Don’t spend more than 5 seconds studying these

top (or htop)

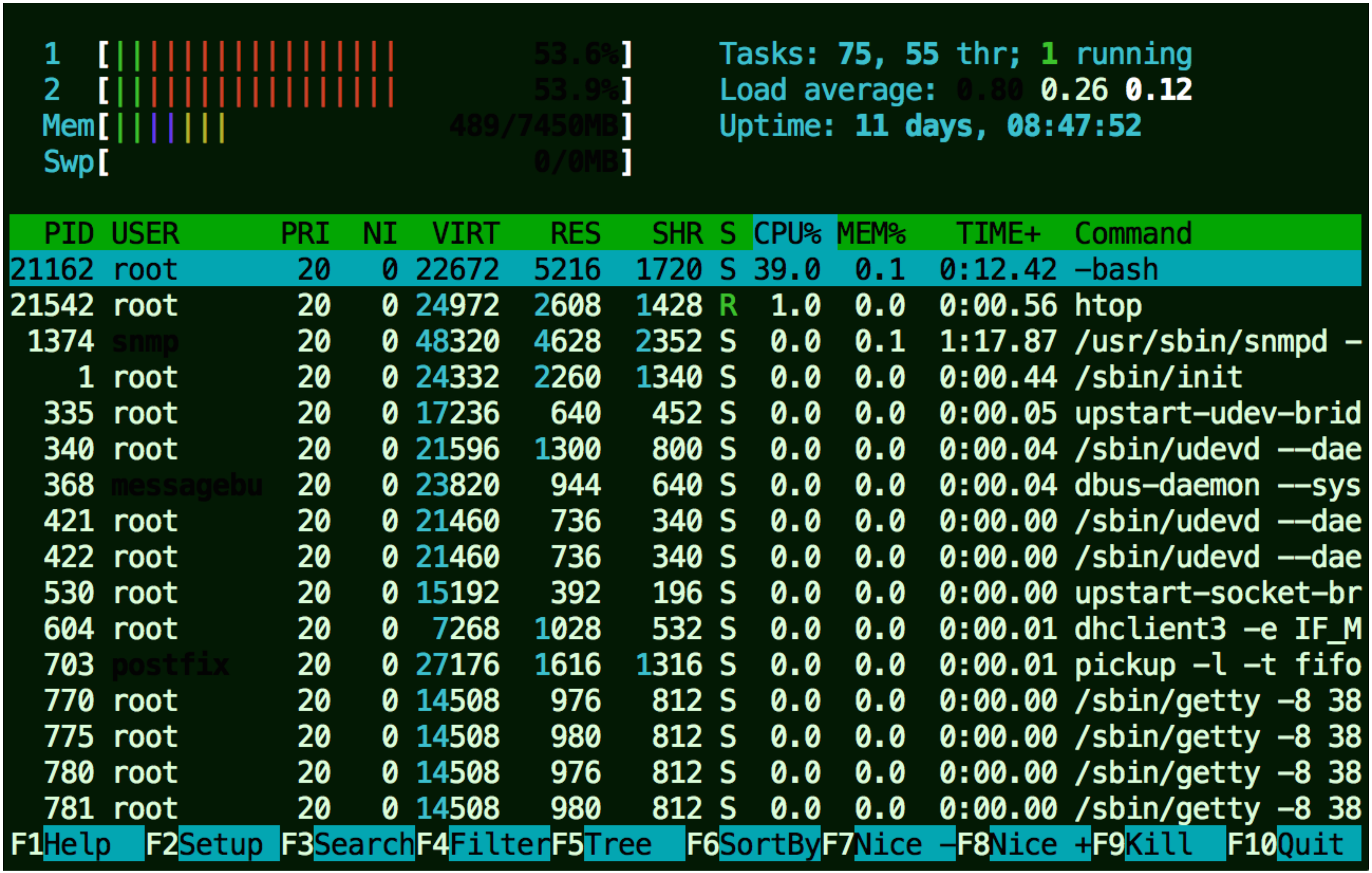
- System and per-process interval summary:

```
$ top - 18:50:26 up  7:43,  1 user,  load average: 4.11, 4.91, 5.22
Tasks: 209 total,   1 running, 206 sleeping,   0 stopped,   2 zombie
Cpu(s): 47.1%us, 4.0%sy, 0.0%ni, 48.4%id, 0.0%wa, 0.0%hi, 0.3%si, 0.2%st
Mem:  70197156k total, 44831072k used, 25366084k free,    36360k buffers
Swap:        0k total,        0k used,        0k free, 11873356k cached

  PID USER      PR  NI  VIRT  RES  SHR S %CPU %MEM    TIME+  COMMAND
 5738 apiprod   20   0 62.6g  29g 352m S  417 44.2   2144:15 java
 1386 apiprod   20   0 17452 1388  964 R    0  0.0   0:00.02 top
    1 root      20   0 24340 2272 1340 S    0  0.0   0:01.51 init
    2 root      20   0     0    0    0 S    0  0.0   0:00.00 kthreadd
[…]
```

- %CPU is summed across all CPUs
- Can miss short-lived processes (atop won't)
- Can consume noticeable CPU to read /proc

htop


1 [||||||||||||||||| 53.6%]
2 [||||||||||||||||| 53.9%]
Mem[||||||| 489/7450MB]
Swp[0/0MB]
Tasks: 75, 55 thr; 1 running
Load average: 0.80 0.26 0.12
Uptime: 11 days, 08:47:52
PID USER PRI NI VIRT RES SHR S CPU% MEM% TIME+ Command
21162 root 20 0 22672 5216 1720 S 39.0 0.1 0:12.42 -bash
21542 root 20 0 24972 2608 1428 R 1.0 0.0 0:00.56 htop
1374 snmp 20 0 48320 4628 2352 S 0.0 0.1 1:17.87 /usr/sbin/snmpd -
1 root 20 0 24332 2260 1340 S 0.0 0.0 0:00.44 /sbin/init
335 root 20 0 17236 640 452 S 0.0 0.0 0:00.05 upstart-udev-brid
340 root 20 0 21596 1300 800 S 0.0 0.0 0:00.04 /sbin/udevd --dae
368 messagebu 20 0 23820 944 640 S 0.0 0.0 0:00.04 dbus-daemon --sys
421 root 20 0 21460 736 340 S 0.0 0.0 0:00.00 /sbin/udevd --dae
422 root 20 0 21460 736 340 S 0.0 0.0 0:00.00 /sbin/udevd --dae
530 root 20 0 15192 392 196 S 0.0 0.0 0:00.00 upstart-socket-br
604 root 20 0 7268 1028 532 S 0.0 0.0 0:00.01 dhclient3 -e IF_M
703 postfix 20 0 27176 1616 1316 S 0.0 0.0 0:00.01 pickup -l -t fifo
770 root 20 0 14508 976 812 S 0.0 0.0 0:00.00 /sbin/getty -8 38
775 root 20 0 14508 980 812 S 0.0 0.0 0:00.00 /sbin/getty -8 38
780 root 20 0 14508 976 812 S 0.0 0.0 0:00.00 /sbin/getty -8 38
781 root 20 0 14508 980 812 S 0.0 0.0 0:00.00 /sbin/getty -8 38
F1Help F2Setup F3Search F4Filter F5Tree F6SortBy F7Nice -F8Nice +F9Kill F10Quit

ps

- Process status listing (eg, “ASCII art forest”):

```
$ ps -ef f
UID        PID  PPID  C STIME TTY      STAT   TIME CMD
[…]
root      4546     1  0 11:08 ?        Ss     0:00 /usr/sbin/sshd -D
root     28261  4546  0 17:24 ?        Ss     0:00  \_ sshd: prod [priv]
prod     28287 28261  0 17:24 ?        S      0:00      \_ sshd: prod@pts/0
prod     28288 28287  0 17:24 pts/0    Ss     0:00          \_ -bash
prod      3156 28288  0 19:15 pts/0    R+     0:00              \_ ps -ef f
root      4965     1  0 11:08 ?        Ss     0:00 /bin/sh /usr/bin/svscanboot
root      4969  4965  0 11:08 ?        S      0:00  \_ svscan /etc/service
[…]
```

- Custom fields:

```
$ ps -eo user,sz,rss,minflt,majflt,pcpu,args
USER         SZ   RSS MINFLT MAJFLT %CPU COMMAND
root       6085  2272  11928     24  0.0 /sbin/init
[…]
```

vmstat

- Virtual memory statistics and more:

```
$ vmstat –Sm 1
procs -----------memory---------- ---swap-- -----io---- -system-- ----cpu----
 r  b   swpd   free   buff  cache   si   so    bi    bo   in   cs us sy id wa
 8  0      0   1620    149    552    0    0     1   179   77   12 25 34  0  0
 7  0      0   1598    149    552    0    0     0     0  205  186 46 13  0  0
 8  0      0   1617    149    552    0    0     0     8  210  435 39 21  0  0
 8  0      0   1589    149    552    0    0     0     0  218  219 42 17  0  0
[…]
```

- USAGE: vmstat [interval [count]]
- First output line has *some* summary since boot values
  - Should be all; partial is confusing
- High level CPU summary
  - “r” is runnable tasks

iostat

- Block I/O (disk) stats. 1st output is since boot.

```
$ iostat -xmdz 1

Linux 3.13.0-29 (db001-eb883efa)   08/18/2014   _x86_64_   (16 CPU)

Device:         rrqm/s   wrqm/s     r/s     w/s    rMB/s    wMB/s \ ...
xvda              0.00     0.00     0.00    0.00     0.00     0.00 / ...
xvdb            213.00     0.00 15299.00    0.00   338.17     0.00 \ ...
xvdc            129.00     0.00 15271.00    3.00   336.65     0.01 / ...
md0               0.00     0.00 31082.00    3.00   678.45     0.01 \ ...
```

Workload →

- Very useful set of stats

```
 ... \ avgqu-sz   await r_await w_await  svctm  %util
 ... /     0.00    0.00    0.00    0.00   0.00   0.00
 ... \   126.09    8.22    8.22    0.00   0.06  86.40
 ... /    99.31    6.47    6.47    0.00   0.06  86.00
 ... \     0.00    0.00    0.00    0.00   0.00   0.00
```

Resulting Performance →

mpstat

- Multi-processor statistics, per-CPU:

```
$ mpstat –P ALL 1
[…]
08:06:43 PM  CPU   %usr  %nice   %sys %iowait   %irq  %soft %steal %guest  %idle
08:06:44 PM  all  53.45   0.00   3.77    0.00   0.00   0.39   0.13   0.00  42.26
08:06:44 PM    0  49.49   0.00   3.03    0.00   0.00   1.01   1.01   0.00  45.45
08:06:44 PM    1  51.61   0.00   4.30    0.00   0.00   2.15   0.00   0.00  41.94
08:06:44 PM    2  58.16   0.00   7.14    0.00   0.00   0.00   1.02   0.00  33.67
08:06:44 PM    3  54.55   0.00   5.05    0.00   0.00   0.00   0.00   0.00  40.40
08:06:44 PM    4  47.42   0.00   3.09    0.00   0.00   0.00   0.00   0.00  49.48
08:06:44 PM    5  65.66   0.00   3.03    0.00   0.00   0.00   0.00   0.00  31.31
08:06:44 PM    6  50.00   0.00   2.08    0.00   0.00   0.00   0.00   0.00  47.92
[…]
```

- Look for unbalanced workloads, hot CPUs.

free

- Main memory usage:

```
$ free -m
             total       used       free     shared    buffers     cached
Mem:          3750       1111       2639          0        147        527
-/+ buffers/cache:        436       3313
Swap:            0          0          0
```

- buffers: block device I/O cache
- cached: virtual page cache

Latency is now much higher…

DEMO

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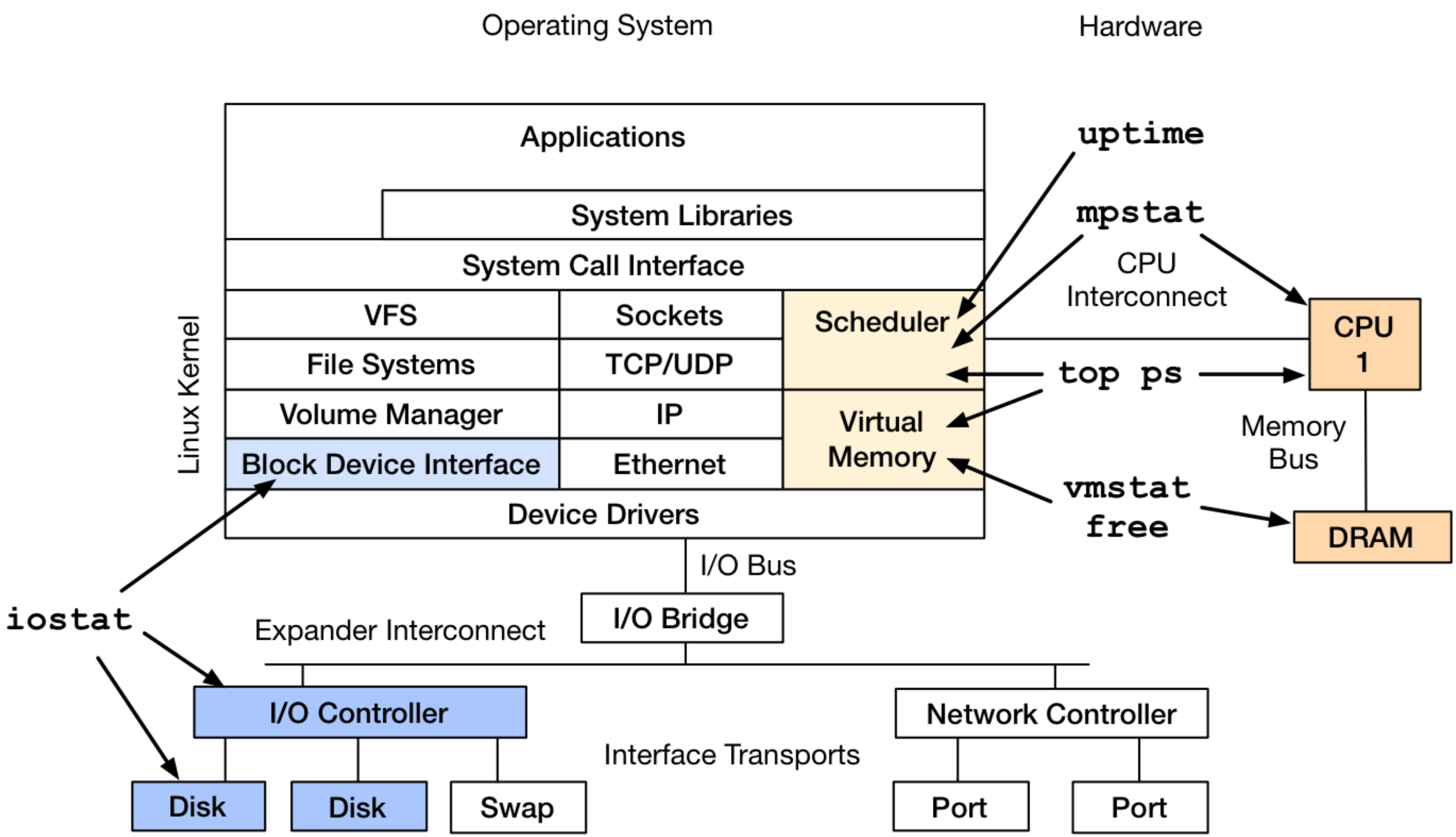
DISCUSSION

Observability Tools: Basic



Observability Tools: Intermediate

- strace
- tcpdump
- netstat
- nicstat
- pidstat
- swapon
- lsof
- sar (and collectl, dstat, etc.)

strace

- System call tracer:

```
$ strace –tttT –p 313
1408393285.779746 getgroups(0, NULL)     = 1 <0.000016>
1408393285.779873 getgroups(1, [0])      = 1 <0.000015>
1408393285.780797 close(3)               = 0 <0.000016>
1408393285.781338 write(1, "LinuxCon 2014!\n", 15LinuxCon 2014!
) = 15 <0.000048>
```

- Eg, -ttt: time (us) since epoch; -T: syscall time (s)
- Translates syscall args
  - Very helpful for solving system usage issues
- Currently has massive overhead (ptrace based)
  - Can slow the target by > 100x. Use extreme caution.

tcpdump

- Sniff network packets for post analysis:

```
$ tcpdump -i eth0 -w /tmp/out.tcpdump
tcpdump: listening on eth0, link-type EN10MB (Ethernet), capture size 65535 bytes
^C7985 packets captured
8996 packets received by filter
1010 packets dropped by kernel
# tcpdump -nr /tmp/out.tcpdump | head
reading from file /tmp/out.tcpdump, link-type EN10MB (Ethernet)
20:41:05.038437 IP 10.44.107.151.22 > 10.53.237.72.46425: Flags [P.], seq 18...
20:41:05.038533 IP 10.44.107.151.22 > 10.53.237.72.46425: Flags [P.], seq 48...
20:41:05.038584 IP 10.44.107.151.22 > 10.53.237.72.46425: Flags [P.], seq 96...
[…]
```

- Study packet sequences with timestamps (us)
- CPU overhead optimized (socket ring buffers), but can still be significant. Use caution.

netstat

- Various network protocol statistics using -s:
- A multi-tool:
  - -i: interface stats
  - -r: route table
  - default: list conns
- netstat -p: shows process details!
- Per-second interval with -c

```
$ netstat –s
[…]
Tcp:
    736455 active connections openings
    176887 passive connection openings
    33 failed connection attempts
    1466 connection resets received
    3311 connections established
    91975192 segments received
    180415763 segments send out
    223685 segments retransmited
    2 bad segments received.
    39481 resets sent
[…]
TcpExt:
    12377 invalid SYN cookies received
    2982 delayed acks sent
[…]
```

nicstat

- Network interface stats, iostat-like output:

```
$ ./nicstat 1
    Time      Int   rKB/s   wKB/s   rPk/s   wPk/s    rAvs    wAvs %Util    Sat
21:21:43       lo   823.0   823.0   171.5   171.5  4915.4  4915.4  0.00   0.00
21:21:43     eth0    5.53    1.74   15.11   12.72   374.5   139.8  0.00   0.00
    Time      Int   rKB/s   wKB/s   rPk/s   wPk/s    rAvs    wAvs %Util    Sat
21:21:44       lo    0.00    0.00    0.00    0.00    0.00    0.00  0.00   0.00
21:21:44     eth0   20.42  3394.1   355.8   85.94   58.76 40441.3  0.00   0.00
    Time      Int   rKB/s   wKB/s   rPk/s   wPk/s    rAvs    wAvs %Util    Sat
21:21:45       lo  1409.1  1409.1   327.9   327.9  4400.8  4400.8  0.00   0.00
21:21:45     eth0   75.12  4402.3  1398.9  1513.2   54.99  2979.1  0.00   0.00
[…]
```

- Check network throughput and interface %util
- I wrote this years ago; Tim Cook ported to Linux

pidstat

- Very useful process stats. eg, by-thread, disk I/O:

```
$ pidstat -t 1
Linux 3.2.0-54 (db002-91befe03)  08/18/2014    _x86_64_ (8 CPU)

08:57:52 PM      TGID       TID    %usr %system  %guest    %CPU   CPU  Command
08:57:54 PM      5738         -  484.75   39.83    0.00  524.58     1  java
08:57:54 PM         -      5817    0.85    0.00    0.00    0.85     2  |__java
08:57:54 PM         -      5931    1.69    1.69    0.00    3.39     4  |__java
08:57:54 PM         -      5981    0.85    0.00    0.00    0.85     7  |__java
08:57:54 PM         -      5990    0.85    0.00    0.00    0.85     4  |__java
[…]
$ pidstat -d 1
[…]
08:58:27 PM       PID   kB_rd/s   kB_wr/s kB_ccwr/s  Command
08:58:28 PM      5738      0.00    815.69      0.00  java
[…]
```

swapon

- Show swap device usage:

```
$ swapon -s
Filename                        Type        Size      Used    Priority
/dev/sda3                       partition   5245212   284     -1
```

- If you have swap enabled…

lsof

- More a debug tool, lsof(8) shows file descriptor usage, which for some apps, equals current active network connections:

```
# lsof -iTCP -sTCP:ESTABLISHED
COMMAND    PID  USER   FD   TYPE   DEVICE SIZE/OFF NODE NAME
sshd       755  root   3r  IPv4 13576887      0t0  TCP bgregg-test-i-f106:ssh->prod100.netflix.com:
15241 (ESTABLISHED)
platforms 2614  app1   8u  IPv4    14618      0t0  TCP localhost:33868->localhost:5433 (ESTABLISHED)
postgres  2648  app1   7u  IPv4    14619      0t0  TCP localhost:5433->localhost:33868 (ESTABLISHED)
epic_plug 2857  app1   7u  IPv4    15678      0t0  TCP localhost:33885->localhost:5433 (ESTABLISHED)
postgres  2892  app1   7u  IPv4    15679      0t0  TCP localhost:5433->localhost:33885 (ESTABLISHED)
[…]
```

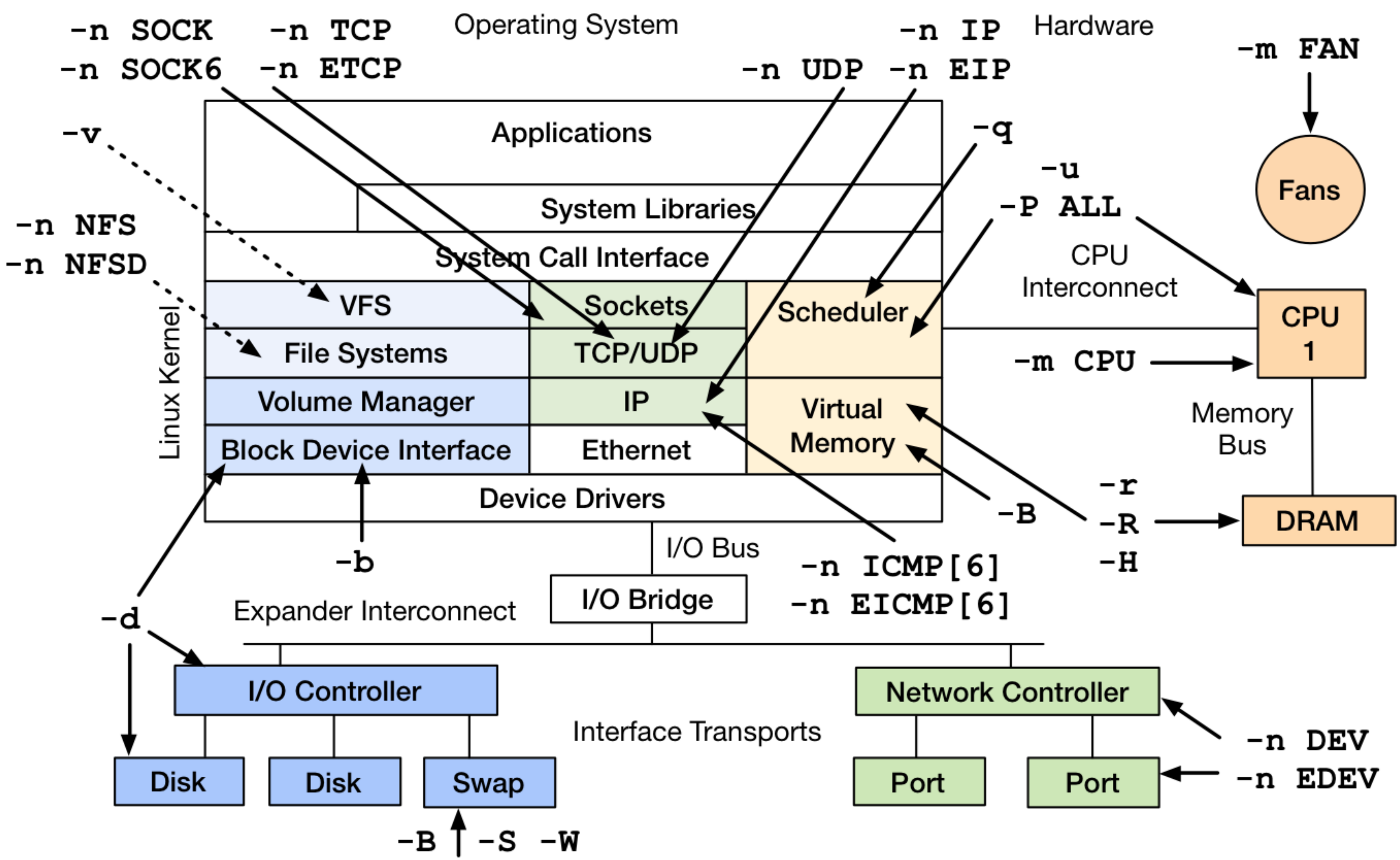
sar

- System Activity Reporter. Many stats, eg:

```
$ sar -n TCP,ETCP,DEV 1
Linux 3.2.55 (test-e4f1a80b)    08/18/2014    _x86_64_ (8 CPU)

09:10:43 PM  IFACE  rxpck/s  txpck/s   rxkB/s   txkB/s rxcmp/s txcmp/s  rxmcst/s
09:10:44 PM     lo    14.00    14.00     1.34     1.34    0.00    0.00      0.00
09:10:44 PM   eth0  4114.00  4186.00  4537.46 28513.24    0.00    0.00      0.00

09:10:43 PM  active/s passive/s    iseg/s    oseg/s
09:10:44 PM     21.00      4.00   4107.00  22511.00

09:10:43 PM  atmptf/s  estres/s retrans/s isegerr/s   orsts/s
09:10:44 PM      0.00      0.00     36.00      0.00      1.00
[…]
```

- Archive or live mode: (interval [count])
- Well designed. Header naming convention, logical groups: TCP, ETCP, DEV, EDEV, …

Observability: sar



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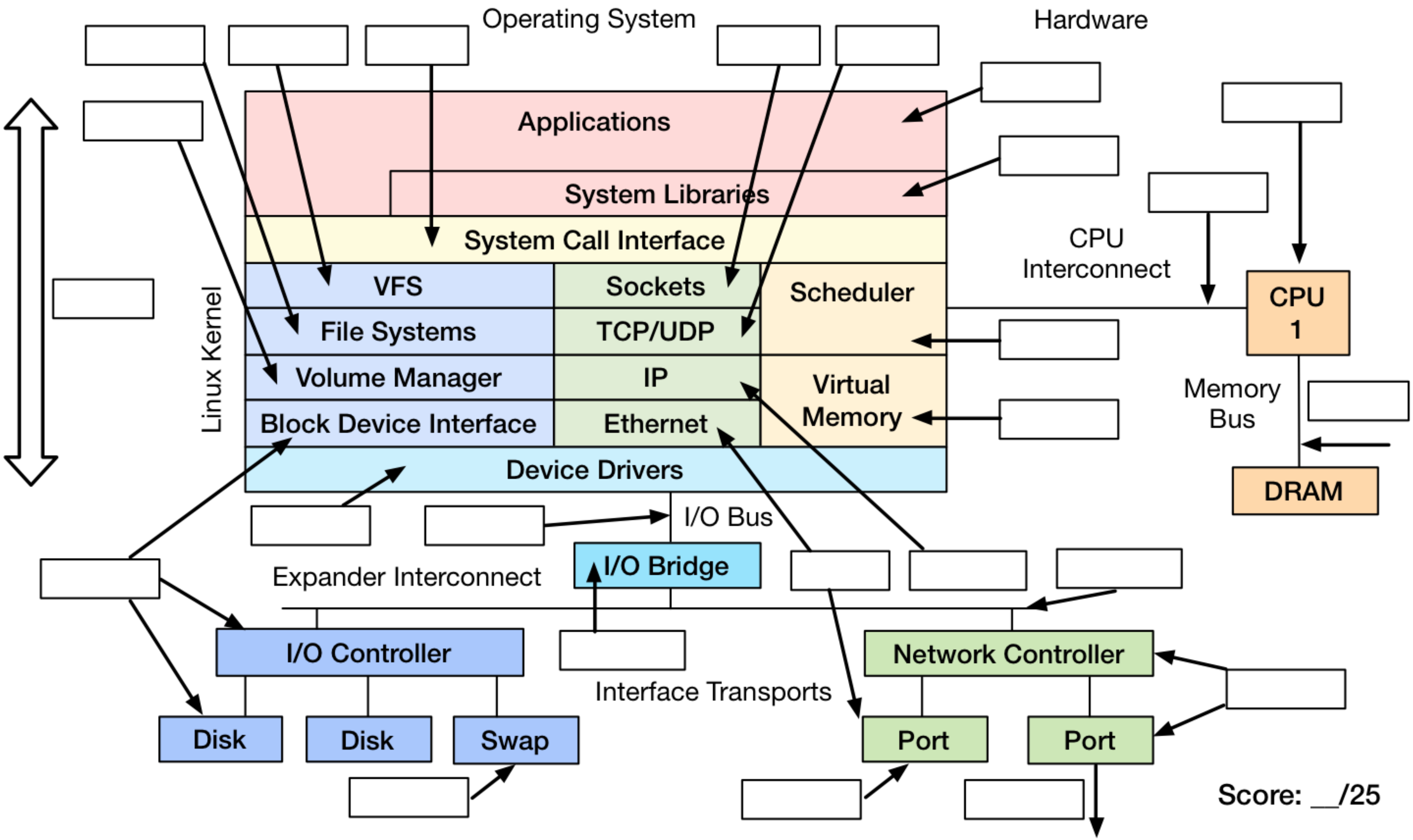
Other Tools

- You may also use collectl, atop, dstat, or another measure-all tool
- The tool isn't important – it's important to have *a* way to measure everything
- In cloud environments, you are probably using a monitoring product, developed in-house or commercial.
  - We develop Atlas for cloud-wide monitoring, and Vector for instance-level analysis (both NetflixOSS)
  - Same method applies…

How does your monitoring tool measure these?



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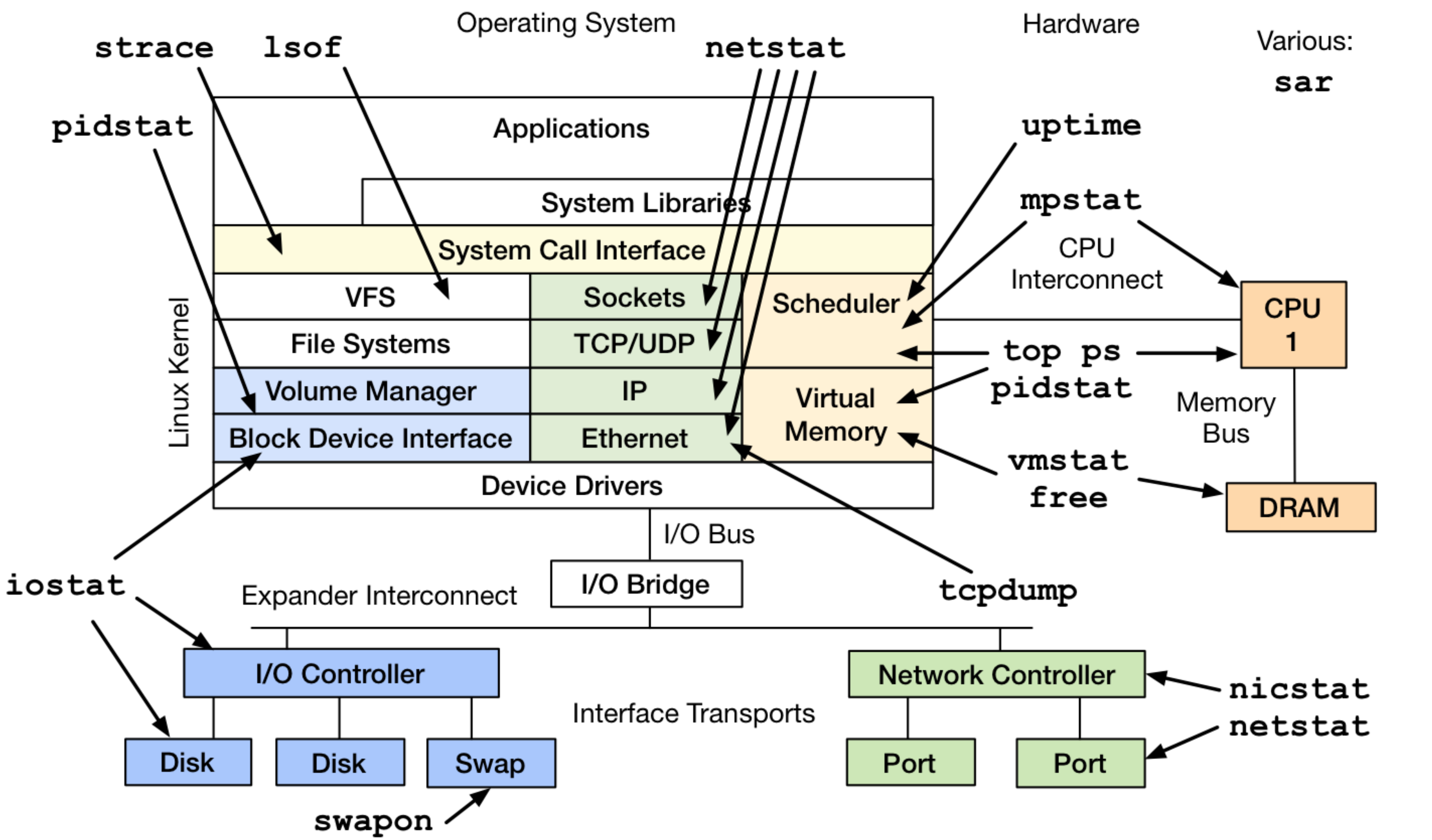
App is taking forever…

DEMO

&

DISCUSSION

Observability Tools: Intermediate



Advanced Observability Tools

- Misc:
  - ltrace, ss, iptraf, ethtool, snmpget, lldptool, iotop, blktrace, slabtop, /proc, pcstat
- CPU Performance Counters:
  - perf_events, tiptop, rdmsr
- Advanced Tracers:
  - perf_events, ftrace, eBPF, SystemTap, ktap, LTTng, dtrace4linux, sysdig
- Some selected demos…

ss

- More socket statistics:

```
$ ss -mop
State      Recv-Q Send-Q      Local Address:Port          Peer Address:Port
CLOSE-WAIT 1      0               127.0.0.1:42295            127.0.0.1:28527
users:(("apacheLogParser",2702,3))
      mem:(r1280,w0,f2816,t0)
ESTAB      0      0               127.0.0.1:5433             127.0.0.1:41312
timer:(keepalive,36min,0) users:(("postgres",2333,7))
      mem:(r0,w0,f0,t0)
[…]
$ ss –i
State      Recv-Q Send-Q      Local Address:Port          Peer Address:Port
CLOSE-WAIT 1      0               127.0.0.1:42295            127.0.0.1:28527
 cubic wscale:6,6 rto:208 rtt:9/6 ato:40 cwnd:10 send 145.6Mbps rcv_space:32792
ESTAB      0      0          10.144.107.101:ssh           10.53.237.72:4532
 cubic wscale:4,6 rto:268 rtt:71.5/3 ato:40 cwnd:10 send 1.5Mbps rcv_rtt:72
rcv_space:14480
[…]
```

iptraf

```
IPTraf
 Packet Distribution by Size

 Packet size brackets for interface eth0


 Packet Size (bytes)      Count     Packet Size (bytes)     Count
     1 to   75:           62148      751 to  825:              84
    76 to  150:            5734      826 to  900:              61
   151 to  225:           25519      901 to  975:              45
   226 to  300:           20246      976 to 1050:              63
   301 to  375:            5011     1051 to 1125:              49
   376 to  450:             802     1126 to 1200:              47
   451 to  525:             677     1201 to 1275:              65
   526 to  600:             274     1276 to 1350:              52
   601 to  675:             135     1351 to 1425:             339
   676 to  750:             105     1426 to 1500+:           3696


 Interface MTU is 1500 bytes, not counting the data-link header
 Maximum packet size is the MTU plus the data-link header length
 Packet size computations include data-link headers, if any
```

iotop

- Block device I/O (disk) by process:

```
$ iotop
 Total DISK READ:       50.47 M/s | Total DISK WRITE:      59.21 M/s
  TID  PRIO  USER     DISK READ  DISK WRITE  SWAPIN     IO>    COMMAND
  959 be/4 root        0.00 B/s    0.00 B/s  0.00 % 99.99 % [flush-202:1]
 6641 be/4 root       50.47 M/s   82.60 M/s  0.00 % 32.51 % java –Dnop –X
    1 be/4 root        0.00 B/s    0.00 B/s  0.00 %  0.00 % init
    2 be/4 root        0.00 B/s    0.00 B/s  0.00 %  0.00 % [kthreadd]
    3 be/4 root        0.00 B/s    0.00 B/s  0.00 %  0.00 % [ksoftirqd/0]
    4 be/4 root        0.00 B/s    0.00 B/s  0.00 %  0.00 % [kworker/0:0]
    5 be/4 root        0.00 B/s    0.00 B/s  0.00 %  0.00 % [kworker/u:0]
    6 rt/4 root        0.00 B/s    0.00 B/s  0.00 %  0.00 % [migration/0]
[…]
```

- Needs kernel support enabled
  - CONFIG_TASK_IO_ACCOUNTING

slabtop

- Kernel slab allocator memory usage:

```
$ slabtop
 Active / Total Objects (% used)    : 4692768 / 4751161 (98.8%)
 Active / Total Slabs (% used)      : 129083 / 129083 (100.0%)
 Active / Total Caches (% used)     : 71 / 109 (65.1%)
 Active / Total Size (% used)       : 729966.22K / 738277.47K (98.9%)
 Minimum / Average / Maximum Object : 0.01K / 0.16K / 8.00K

  OBJS ACTIVE  USE OBJ SIZE  SLABS OBJ/SLAB CACHE SIZE NAME
3565575 3565575 100%    0.10K  91425       39    365700K buffer_head
314916 314066  99%    0.19K  14996       21     59984K dentry
184192 183751  99%    0.06K   2878       64     11512K kmalloc-64
138618 138618 100%    0.94K   4077       34    130464K xfs_inode
138602 138602 100%    0.21K   3746       37     29968K xfs_ili
102116  99012  96%    0.55K   3647       28     58352K radix_tree_node
 97482  49093  50%    0.09K   2321       42      9284K kmalloc-96
 22695  20777  91%    0.05K    267       85      1068K shared_policy_node
 21312  21312 100%    0.86K    576       37     18432K ext4_inode_cache
 16288  14601  89%    0.25K    509       32      4072K kmalloc-256
[…]
```

pcstat

- Show page cache residency by file:

```
# ./pcstat data0*
|----------+----------------+------------+-----------+---------|
| Name     | Size           | Pages      | Cached    | Percent |
|----------+----------------+------------+-----------+---------|
| data00   | 104857600      | 25600      | 25600     | 100.000 |
| data01   | 104857600      | 25600      | 25600     | 100.000 |
| data02   | 104857600      | 25600      | 4080      | 015.938 |
| data03   | 104857600      | 25600      | 25600     | 100.000 |
| data04   | 104857600      | 25600      | 16010     | 062.539 |
| data05   | 104857600      | 25600      | 0         | 000.000 |
|----------+----------------+------------+-----------+---------|
```

- Uses the mincore(2) syscall. Useful for database performance analysis.

perf_events

- Provides the "perf" command
- In Linux source code: tools/perf
  - Usually pkg added by linux-tools-common, etc.
- **Multi-tool** with many capabilities
  - CPU profiling
  - PMC profiling
  - Static & dynamic tracing
- *Covered later in Profiling & Tracing*

tiptop

```
tiptop -
Tasks: 378 total,  15 displayed                                     screen  0: default

  PID [ %CPU] %SYS      P   Mcycle    Minstr    IPC  %MISS  %BMIS  %BUS COMMAND
 5910+  13.4   0.5      0   603.72    461.80   0.76   0.29   0.67     ? plugin-con
 3249+  11.4   3.5      1   394.35    551.39   1.40   0.10   0.19     ? gnome-term
17838    9.4   0.0      0   472.37    547.62   1.16   0.24   0.52     ? python
24782    8.4   7.9      0    47.99     39.76   0.83   0.09   1.02     ? find
 2889+   4.0   0.5      5   114.78     30.42   0.27   2.38   1.81     ? enlightenm
 3311+   4.0   0.5      3   186.75     96.11   0.51   0.71   0.85     ? firefox
 3534+   4.0   1.0      1   157.75     69.34   0.44   1.23   0.74     ? chromium-b
 3518+   1.5   0.0      7        ?         ?      ?      ?      ?     ? chromium-b
 3307+   1.0   0.0      0    15.31      3.30   0.22   1.86   1.98     ? chromium-b
24717    1.0   1.0      3    13.29     13.60   1.02   0.05   0.65     ? tiptop
 3635+   0.5   0.0      0        ?         ?      ?      ?      ?     ? chromium-b
```

- IPC by process, %MISS, %BUS
- Needs some love. perfmon2 library integration?
- Still can’t use it in clouds yet (needs PMCs enabled)

rdmsr

- Model Specific Registers (MSRs), unlike PMCs, can be read by default in Xen guests
  - Timestamp clock, temp, power, …
  - Use rdmsr(1) from the msr-tools package to read them
  - From https://github.com/brendangregg/msr-cloud-tools:

```
ec2-guest# ./showboost
[...]
TIME        C0_MCYC        C0_ACYC          UTIL   RATIO    MHz
06:11:35    6428553166     7457384521        51%    116%   2900
06:11:40    6349881107     7365764152        50%    115%   2899
06:11:45    6240610655     7239046277        49%    115%   2899
[...]
ec2-guest# ./cputemp 1
CPU1 CPU2 CPU3 CPU4
61 61 60 59
60 61 60 60
[...]
```

Real CPU MHz

CPU Temperature

More Advanced Tools…

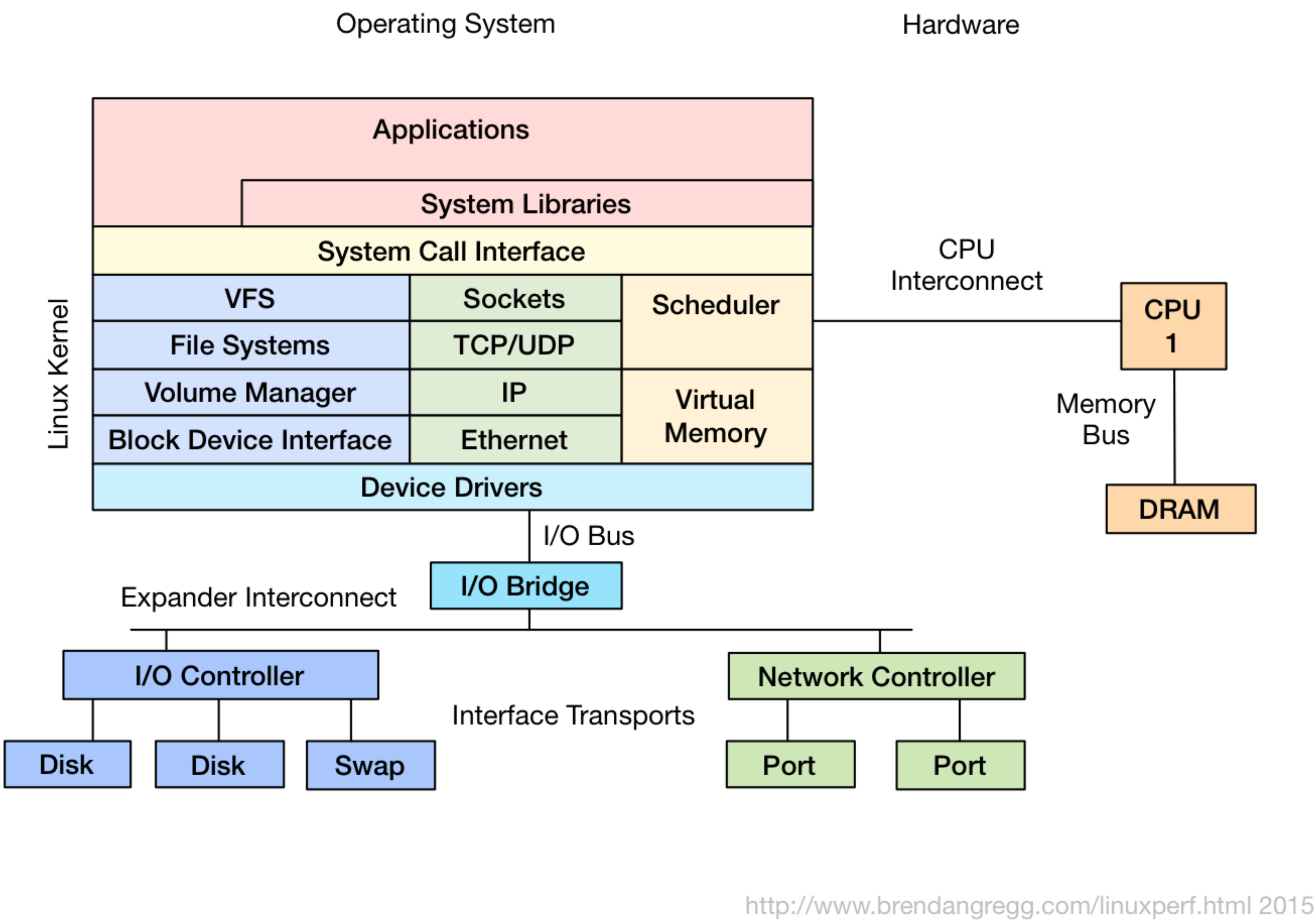
- Some others worth mentioning:

Tool	Description
ltrace	Library call tracer
ethtool	Mostly interface tuning; some stats
snmpget	SNMP network host statistics
lldptool	Can get LLDP broadcast stats
blktrace	Block I/O event tracer
/proc	Many raw kernel counters
pmu-tools	On- and off-core CPU counter tools

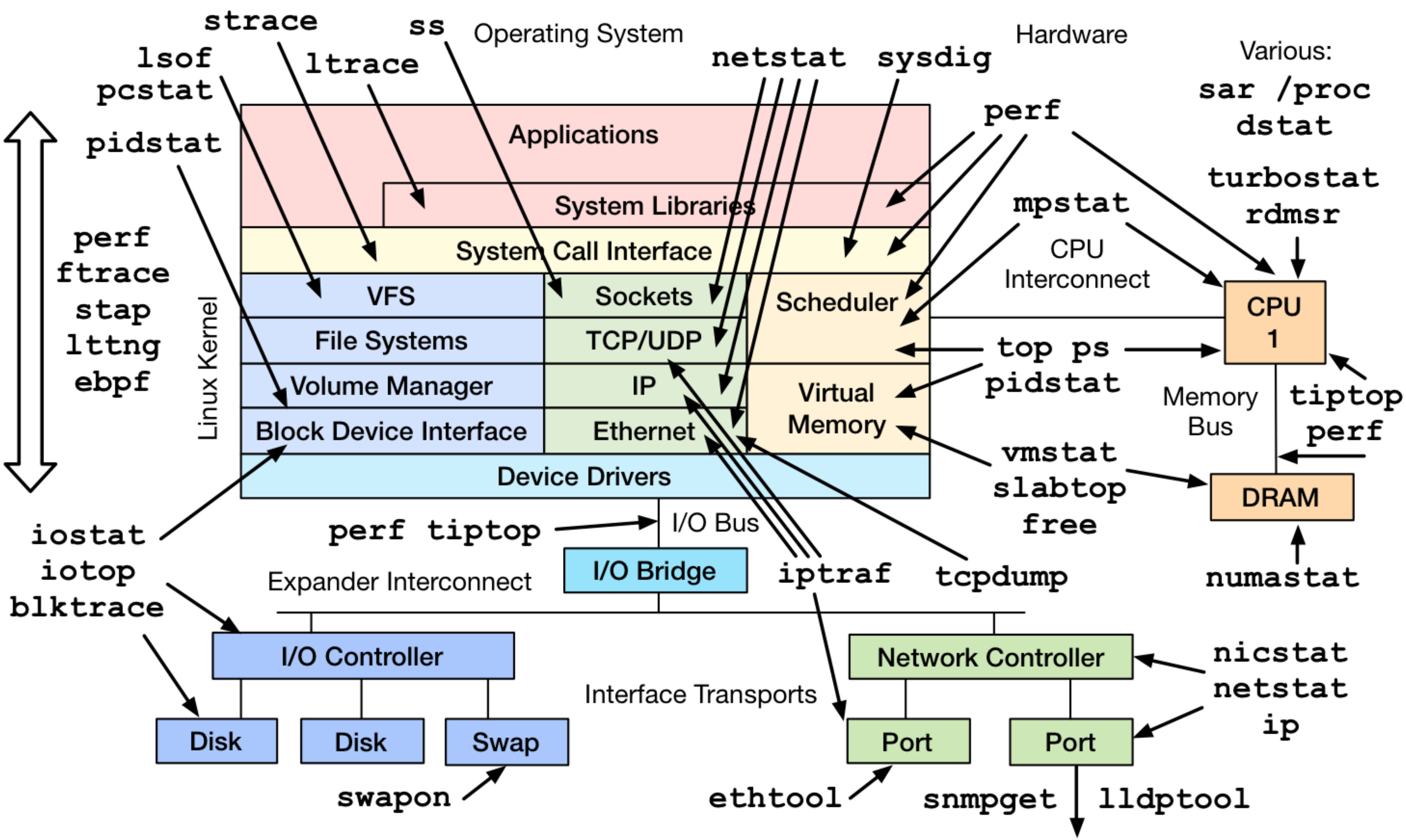
Advanced Tracers

- Many options on Linux:
  - perf_events, ftrace, eBPF, SystemTap, ktap, LTTng, dtrace4linux, sysdig
- Most can do static and dynamic tracing
  - Static: pre-defined events (tracepoints)
  - Dynamic: instrument any software (kprobes, uprobes). Custom metrics on-demand. *Catch all*.
- Many are in-development

Linux Observability Tools



Linux Observability Tools



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Benchmarking Tools

Benchmarking Tools

- Multi:
  - UnixBench, lmbench, sysbench, perf bench
- FS/disk:
  - dd, hdparm, fio
- App/lib:
  - ab, wrk, jmeter, openssl
- Networking:
  - ping, hping3, iperf, ttcp, traceroute, mtr, pchar

Benchmarking

- ~100% of benchmarks are wrong
- Results are usually misleading:
  you benchmark A, but actually measure B, and conclude you measured C
- Common mistakes:
  - Testing the wrong target: eg, FS cache instead of disk
  - Choosing the wrong target: eg, disk instead of FS cache
    … doesn't resemble real world usage
  - Invalid results: eg, bugs
- The energy needed to refute benchmarks is multiple orders of magnitude bigger than to run them

Active Benchmarking (Method)

1. Run the benchmark for hours
2. While running, analyze and confirm the performance limiter using *observability tools*
   - Disk benchmark: run iostat, …
   - CPU benchmark: run pidstat, perf, flame graphs, …
   - …

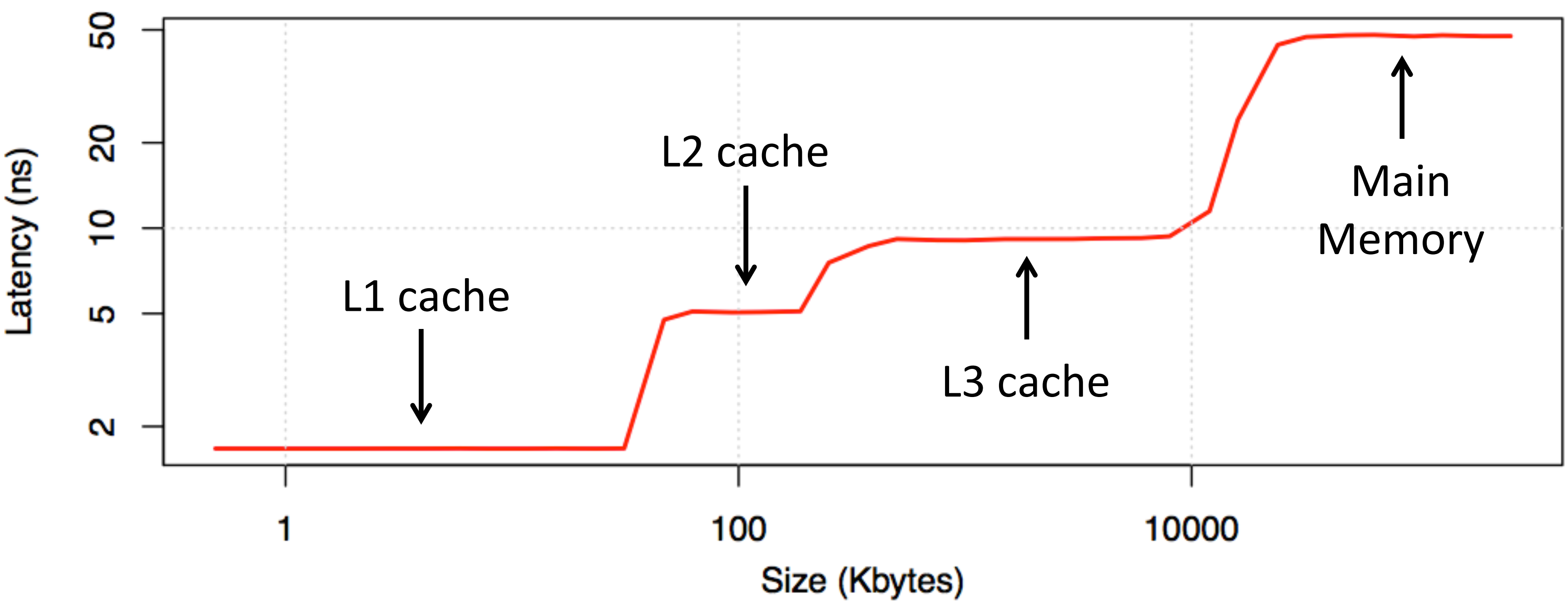
- Answer the question: why isn't the result 10x?

We just covered the observability tools – use them!

lmbench

- CPU, memory, and kernel micro-benchmarks
- Eg, memory latency by stride size:

```
$ lat_mem_rd 100m 128 > out.latencies
some R processing…
```



fio

- FS or disk I/O micro-benchmarks

```
$ fio --name=seqwrite --rw=write --bs=128k --size=122374m
[…]
seqwrite: (groupid=0, jobs=1): err= 0: pid=22321
  write: io=122374MB, bw=840951KB/s, iops=6569 , runt=149011msec
    clat (usec): min=41 , max=133186 , avg=148.26, stdev=1287.17
     lat (usec): min=44 , max=133188 , avg=151.11, stdev=1287.21
    bw (KB/s) : min=10746, max=1983488, per=100.18%, avg=842503.94,
stdev=262774.35
  cpu          : usr=2.67%, sys=43.46%, ctx=14284, majf=1, minf=24
  IO depths    : 1=100.0%, 2=0.0%, 4=0.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
     submit    : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
     complete  : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
     issued r/w/d: total=0/978992/0, short=0/0/0
     lat (usec): 50=0.02%, 100=98.30%, 250=1.06%, 500=0.01%, 750=0.01%
     lat (usec): 1000=0.01%
     lat (msec): 2=0.01%, 4=0.01%, 10=0.25%, 20=0.29%, 50=0.06%
     lat (msec): 100=0.01%, 250=0.01%
```

- Results include basic latency distribution

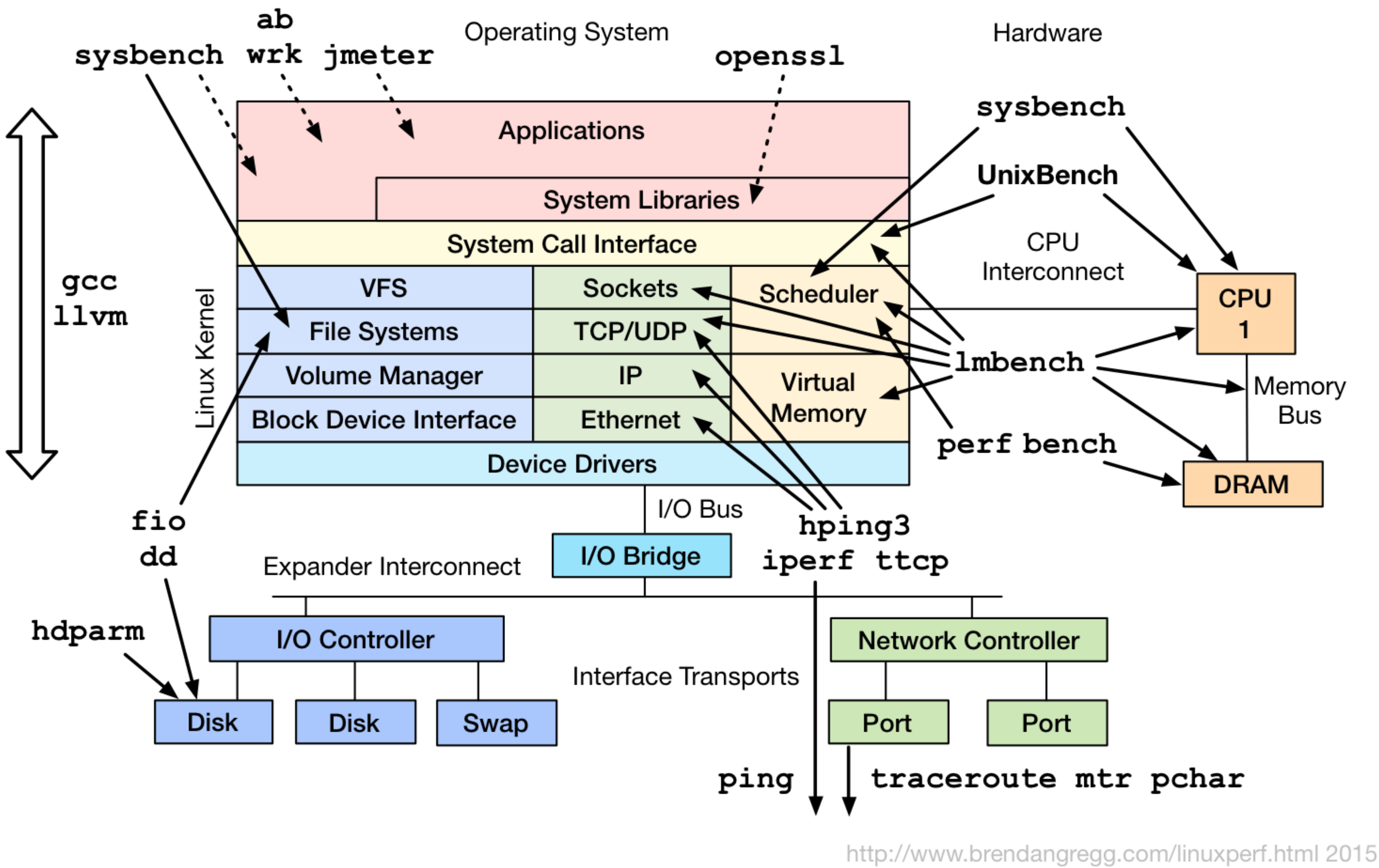
pchar

- Traceroute with bandwidth per hop!

```
$ pchar 10.71.83.1
[…]
 4: 10.110.80.1 (10.110.80.1)
    Partial loss:      0 / 5 (0%)
    Partial char:      rtt = 9.351109 ms, (b = 0.004961 ms/B), r2 = 0.184105
                       stddev rtt = 4.967992, stddev b = 0.006029
    Partial queueing:  avg = 0.000000 ms (0 bytes)
    Hop char:          rtt = --.--- ms, bw = 1268.975773 Kbps
    Hop queueing:      avg = 0.000000 ms (0 bytes)
 5: 10.193.43.181 (10.193.43.181)
    Partial loss:      0 / 5 (0%)
    Partial char:      rtt = 25.461597 ms, (b = 0.011934 ms/B), r2 = 0.228707
                       stddev rtt = 10.426112, stddev b = 0.012653
    Partial queueing:  avg = 0.000000 ms (0 bytes)
    Hop char:          rtt = 16.110487 ms, bw = 1147.210397 Kbps
    Hop queueing:      avg = 0.000000 ms (0 bytes)
[…]
```

- Needs love. Based on pathchar (Linux 2.0.30).

Benchmarking Tools



Tuning Tools

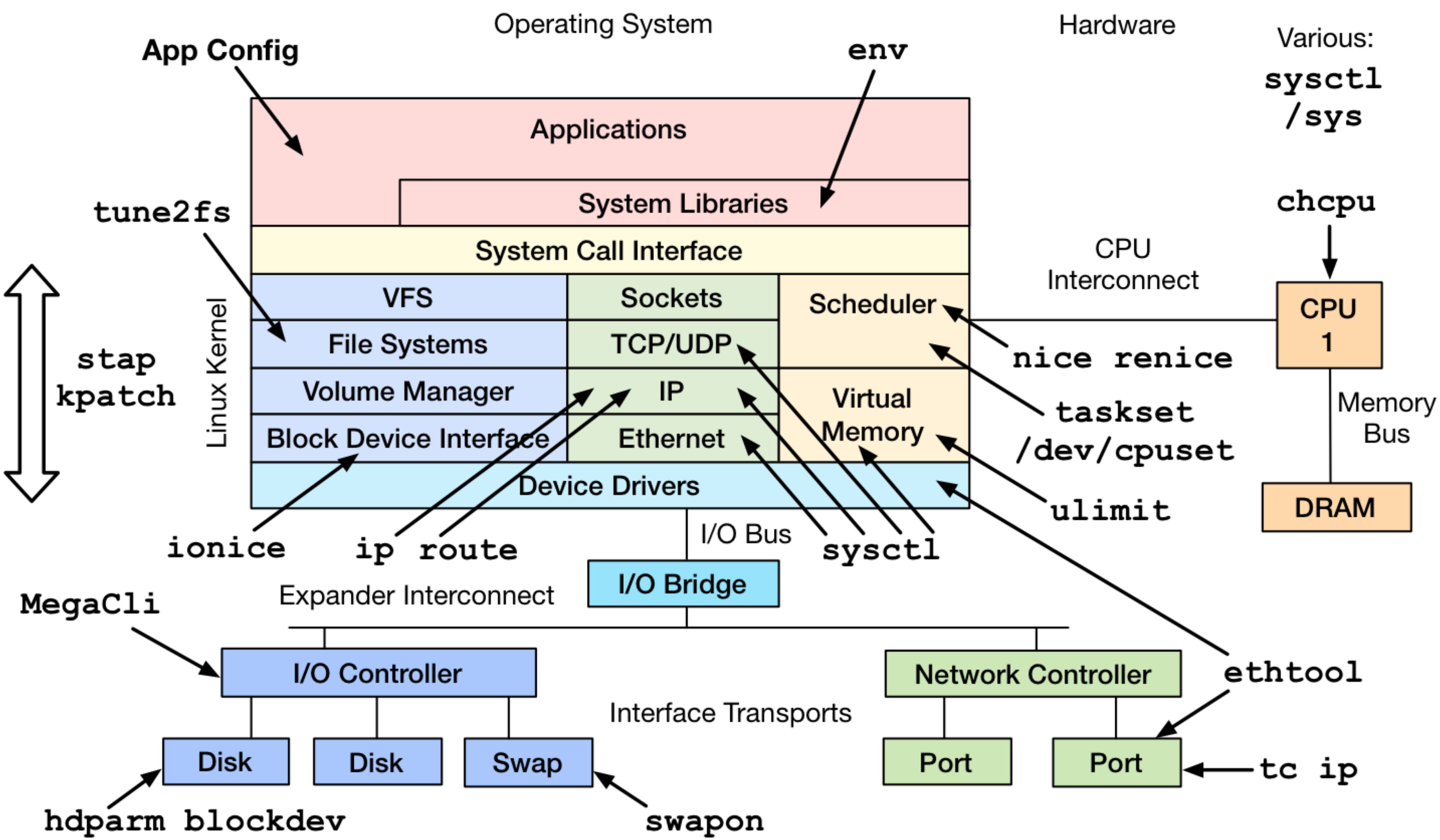
Tuning Tools

- Generic interfaces:
  - sysctl, /sys
- Many areas have custom tuning tools:
  - Applications: their own config
  - CPU/scheduler: nice, renice, taskset, ulimit, chcpu
  - Storage I/O: tune2fs, ionice, hdparm, blockdev, …
  - Network: ethtool, tc, ip, route
  - Dynamic patching: stap, kpatch

Tuning Methods

- Scientific Method:
  1. Question
  2. Hypothesis
  3. Prediction
  4. Test
  5. Analysis
- Any observational or benchmarking tests you can try before tuning?
- Consider risks, and see previous tools

Tuning Tools



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Static Tools

Static Tools

- Static Performance Tuning: check the static state and configuration of the system
  - CPU types & flags
  - CPU frequency scaling config
  - Storage devices
  - File system capacity
  - File system and volume configuration
  - Route table
  - State of hardware
  - etc.
- What can be checked on a system without load
- Methodology by Richard Elling (2000)

CPU Types & Flags

```
$ more /proc/cpuinfo
processor       : 0
vendor_id       : GenuineIntel
cpu family      : 6
model           : 42
model name      : Intel(R) Core(TM) i5-2400 CPU @ 3.10GHz
stepping        : 7
microcode       : 0x1a
cpu MHz         : 1600.000
cache size      : 6144 KB
physical id     : 0
siblings        : 4
core id         : 0
cpu cores       : 4
apicid          : 0
initial apicid  : 0
fpu             : yes
fpu_exception   : yes
cpuid level     : 13
wp              : yes
flags           : fpu vme de pse tsc msr pae mce cx8 apic sep mtrr pge mca cmov pat pse36
clflush dts acpi mmx fxsr sse sse2 ss ht tm pbe syscall nx rdtscp lm constant_tsc ar
ch_perfmon pebs bts rep_good nopl xtopology nonstop_tsc aperfmperf eagerfpu pni
pclmulqdq dtes64 monitor ds_cpl vmx smx est tm2 ssse3 cx16 xtpr pdcm pcid sse4_1 sse4_2
x2apic popcnt tsc_deadline_timer aes xsave avx lahf_lm ida arat epb xsaveopt pln pts
dtherm tpr_shadow vnmi flexpriority ept vpid
[…]
```

CPU speed still matters

CPU Frequency Scaling

- Kernel may be configured to dynamically modify CPU frequency:

```
# cat /sys/devices/system/cpu/cpu0/cpufreq/scaling_available_frequencies
3101000 3100000 2900000 2700000 2500000 2300000 2100000 1900000 1700000 1600000
# cat /sys/devices/system/cpu/cpu0/cpufreq/scaling_governor
ondemand
```

  - See Documentation/cpu-freq/governors.txt, and scaling_governor == performance
- Not to be confused with Intel Turbo Boost (which is H/W)

Storage Devices

```
# cat /proc/scsi/scsi
Attached devices:
Host: scsi0 Channel: 00 Id: 00 Lun: 00
  Vendor: ATA      Model: ST3320413AS      Rev: JC65
  Type:   Direct-Access                    ANSI  SCSI revision: 05
Host: scsi1 Channel: 00 Id: 00 Lun: 00
  Vendor: PLDS     Model: DVD-RW DH16ABSH  Rev: YL32
  Type:   CD-ROM                           ANSI  SCSI revision: 05

# lsscsi
[0:0:0:0]    disk    ATA      ST3320413AS      JC65  /dev/sda
[1:0:0:0]    cd/dvd  PLDS     DVD-RW DH16ABSH  YL32  /dev/sr0
```

- Micro-benchmarking disks (not file systems!) is also useful for understanding their characteristics

Routing Table

- Use "ip route get" to test a given IP:

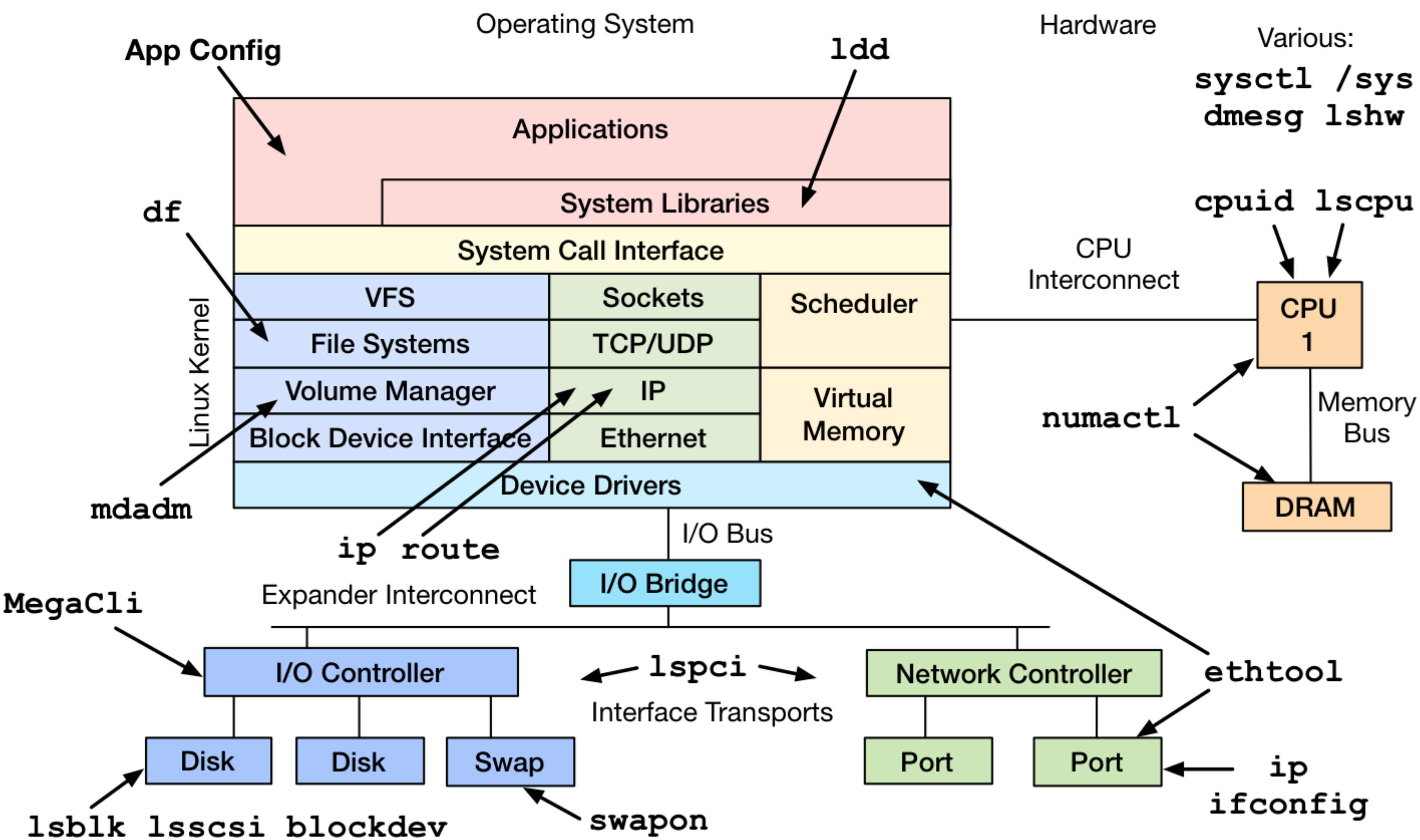
```
$ netstat -rn
Kernel IP routing table
Destination     Gateway         Genmask         Flags   MSS Window  irtt Iface
0.0.0.0         192.11.0.1      0.0.0.0         UG        0 0          0 eth0
169.254.169.254 0.0.0.0         255.255.255.255 UH        0 0          0 eth0
192.11.0.0      0.0.0.0         255.255.240.0   U         0 0          0 eth0

$ ip route get 54.214.28.210
54.214.28.210 via 192.11.0.1 dev eth0  src 192.11.7.201
    cache
```

etc…

- System messages: `dmesg`
- Network interface config: `ifconfig –a; ip link`
- File system capacity: `df -h`
- Volume config: `mdadm --misc -D /dev/md0`
- Storage device info: `smartctl`
- NUMA config: `numactl -s; numactl -H`
- PCI info: `lspci`
- Installed kernel modules: `lsmod`
- Root crontab config: `crontab –l`
- Services: `service --status-all`
- …

Static Tools



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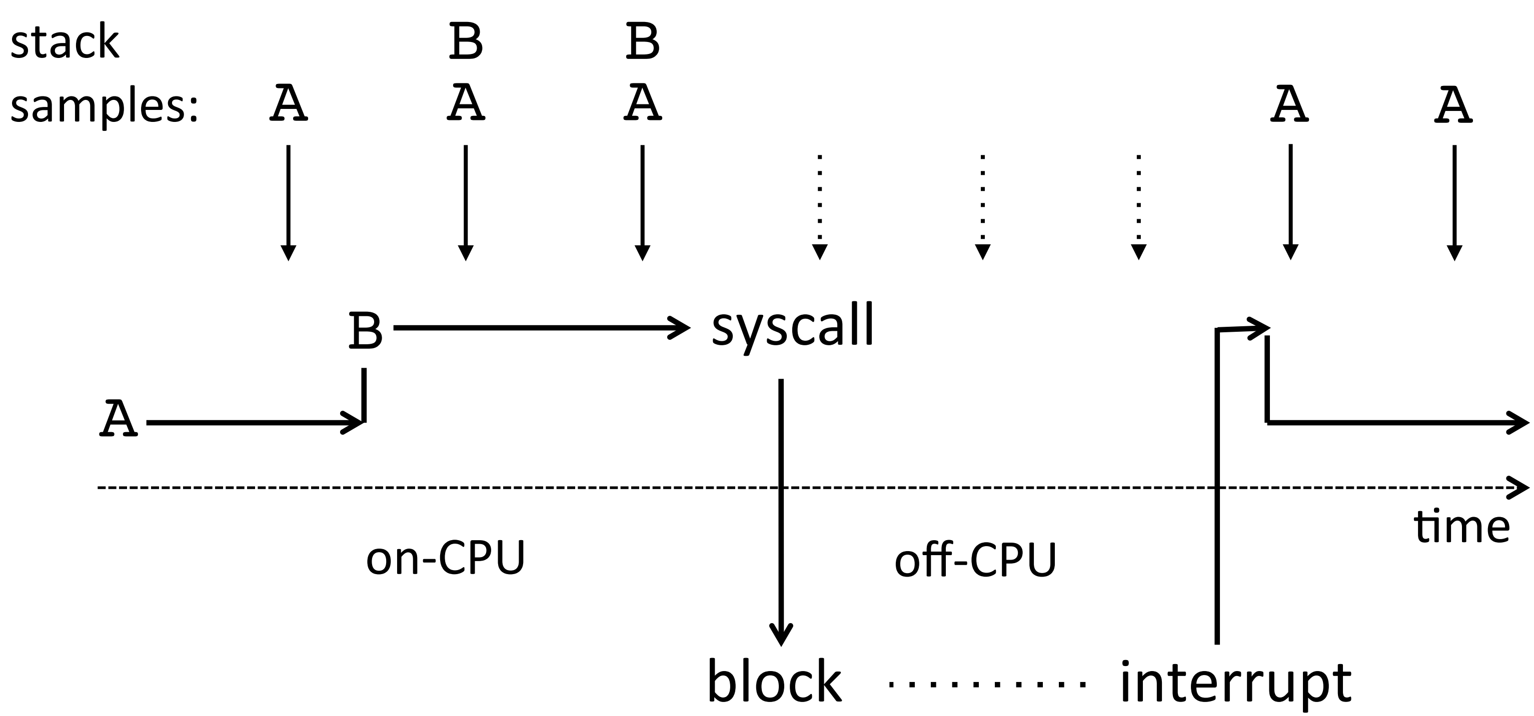
Profiling

Profiling

- Objectives:
  - Profile CPU usage by stack sampling
  - Generate CPU flame graphs
  - Understand gotchas with stacks & symbols

CPU Profiling

- Record stacks at a timed interval: simple and effective
  - Pros: Low (deterministic) overhead
  - Cons: Coarse accuracy, but usually sufficient



perf_events

- Introduced earlier: multi-tool, profiler. Provides "perf".

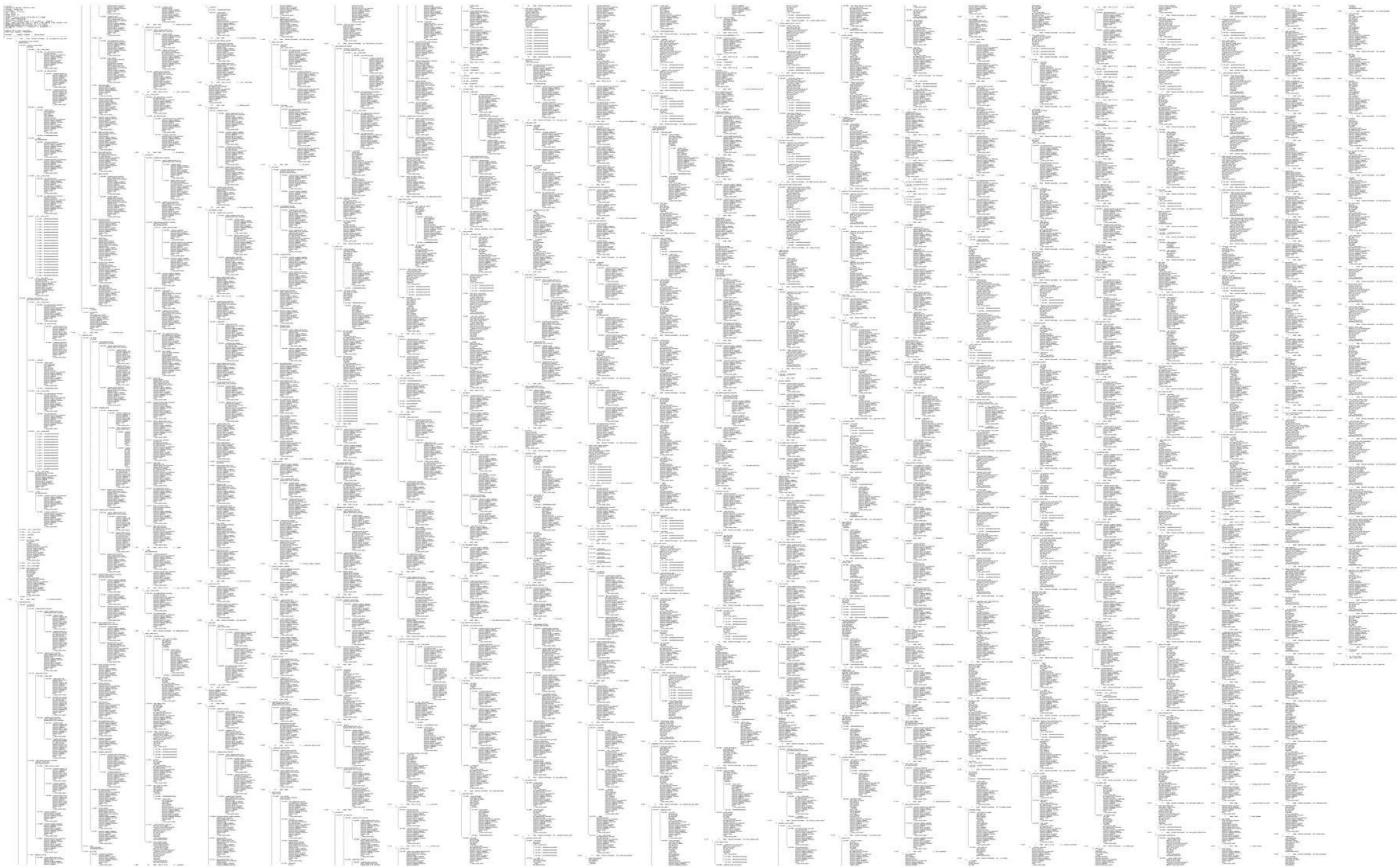
```
usage: perf [--version] [--help] [OPTIONS] COMMAND [ARGS]

The most commonly used perf commands are:
  annotate        Read perf.data (created by perf record) and display annotated code
  archive         Create archive with object files with build-ids found in perf.data file
  bench           General framework for benchmark suites
  buildid-cache   Manage build-id cache.
  buildid-list    List the buildids in a perf.data file
  data            Data file related processing
  diff            Read perf.data files and display the differential profile
  evlist          List the event names in a perf.data file
  inject          Filter to augment the events stream with additional information
  kmem            Tool to trace/measure kernel memory(slab) properties
  kvm             Tool to trace/measure kvm guest os
  list            List all symbolic event types
  lock            Analyze lock events
  mem             Profile memory accesses
  record          Run a command and record its profile into perf.data
  report          Read perf.data (created by perf record) and display the profile
  sched           Tool to trace/measure scheduler properties (latencies)
  script          Read perf.data (created by perf record) and display trace output
  stat            Run a command and gather performance counter statistics
  test            Runs sanity tests.
  timechart       Tool to visualize total system behavior during a workload
  top             System profiling tool.
  trace           strace inspired tool
  probe           Define new dynamic tracepoints

See 'perf help COMMAND' for more information on a specific command.
```

perf_events: CPU profiling

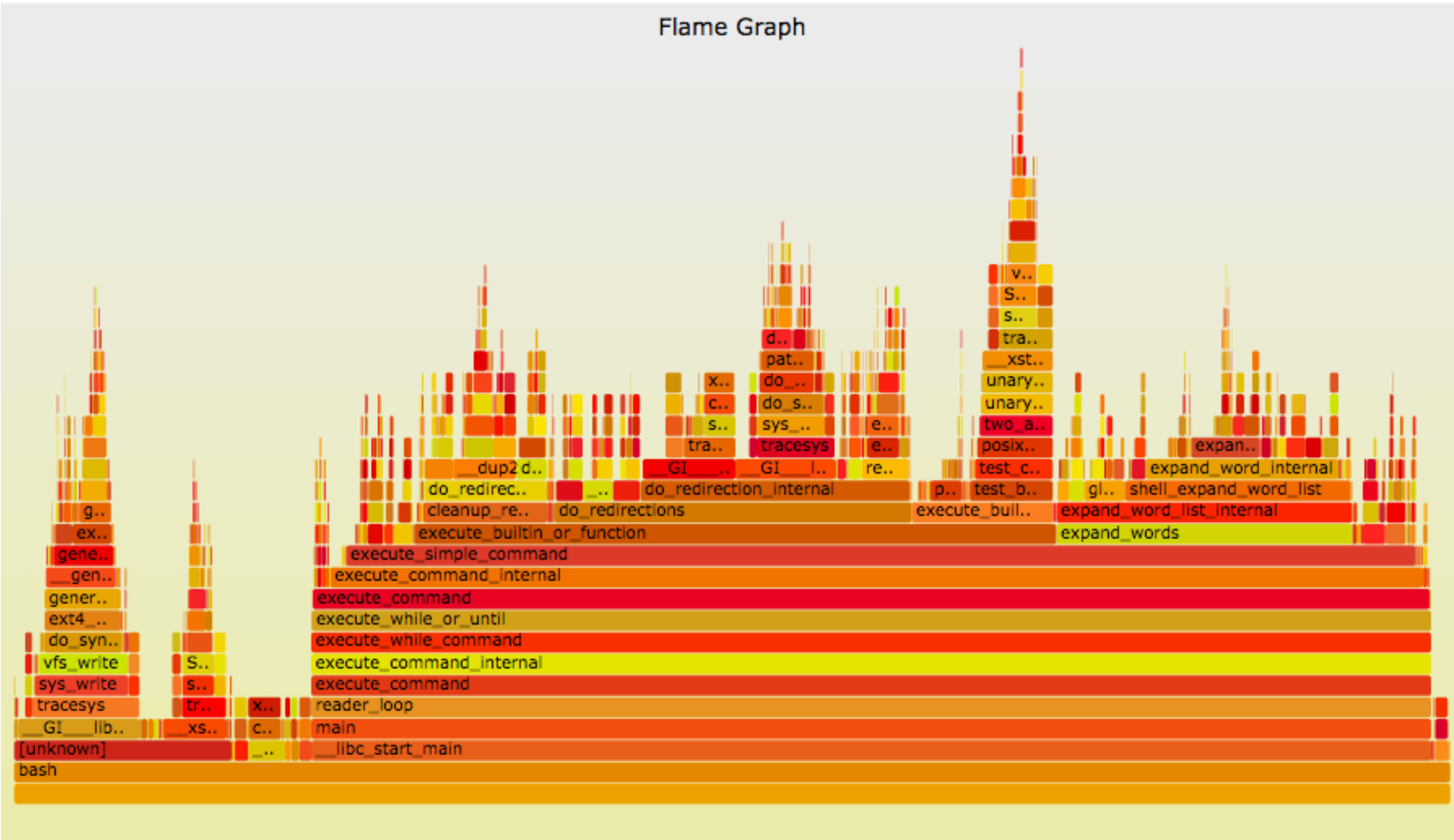
- Sampling full stack traces at 99 Hertz, for 30 secs:

```
# perf record -F 99 -ag -- sleep 30
[ perf record: Woken up 9 times to write data ]
[ perf record: Captured and wrote 2.745 MB perf.data (~119930 samples) ]
# perf report -n --stdio
1.40%   162              java  [kernel.kallsyms]       [k] _raw_spin_lock
          |
          --- _raw_spin_lock
             |
             |--63.21%-- try_to_wake_up
             |          |
             |          |--63.91%-- default_wake_function
             |          |          |
             |          |          |--56.11%-- __wake_up_common
             |          |          |          __wake_up_locked
             |          |          |          ep_poll_callback
             |          |          |          __wake_up_common
             |          |          |          __wake_up_sync_key
             |          |          |          |
             |          |          |          |--59.19%-- sock_def_readable
[…78,000 lines truncated…]
```

perf_events: Full "report" Output



… as a Flame Graph



perf_events: Flame Graphs

```
git clone --depth 1 https://github.com/brendangregg/FlameGraph
cd FlameGraph
perf record -F 99 -a –g -- sleep 30
perf script | ./stackcollapse-perf.pl |./flamegraph.pl > perf.svg
```

- Flame Graphs:
  - **x-axis**: alphabetical stack sort, to maximize merging
  - **y-axis**: stack depth
  - **color**: random, or hue can be a dimension (eg, diff)
- Interpretation:
  - Top edge is on-CPU, beneath it is ancestry
- Currently made from Perl + JavaScript & SVG
- Easy to get working
  - http://www.brendangregg.com/FlameGraphs/cpuflamegraphs.html

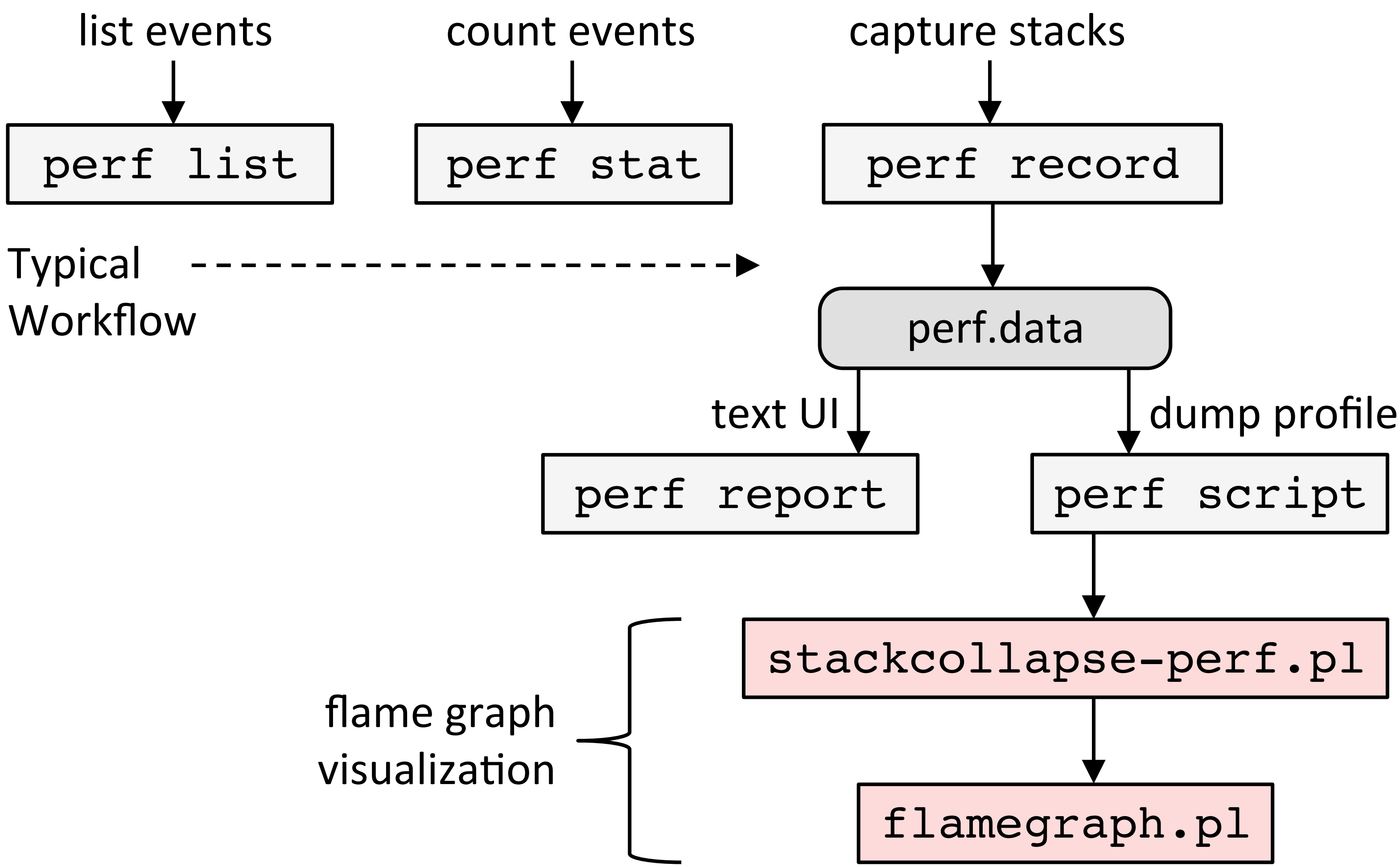
Mysterious CPU consumer…

DEMO

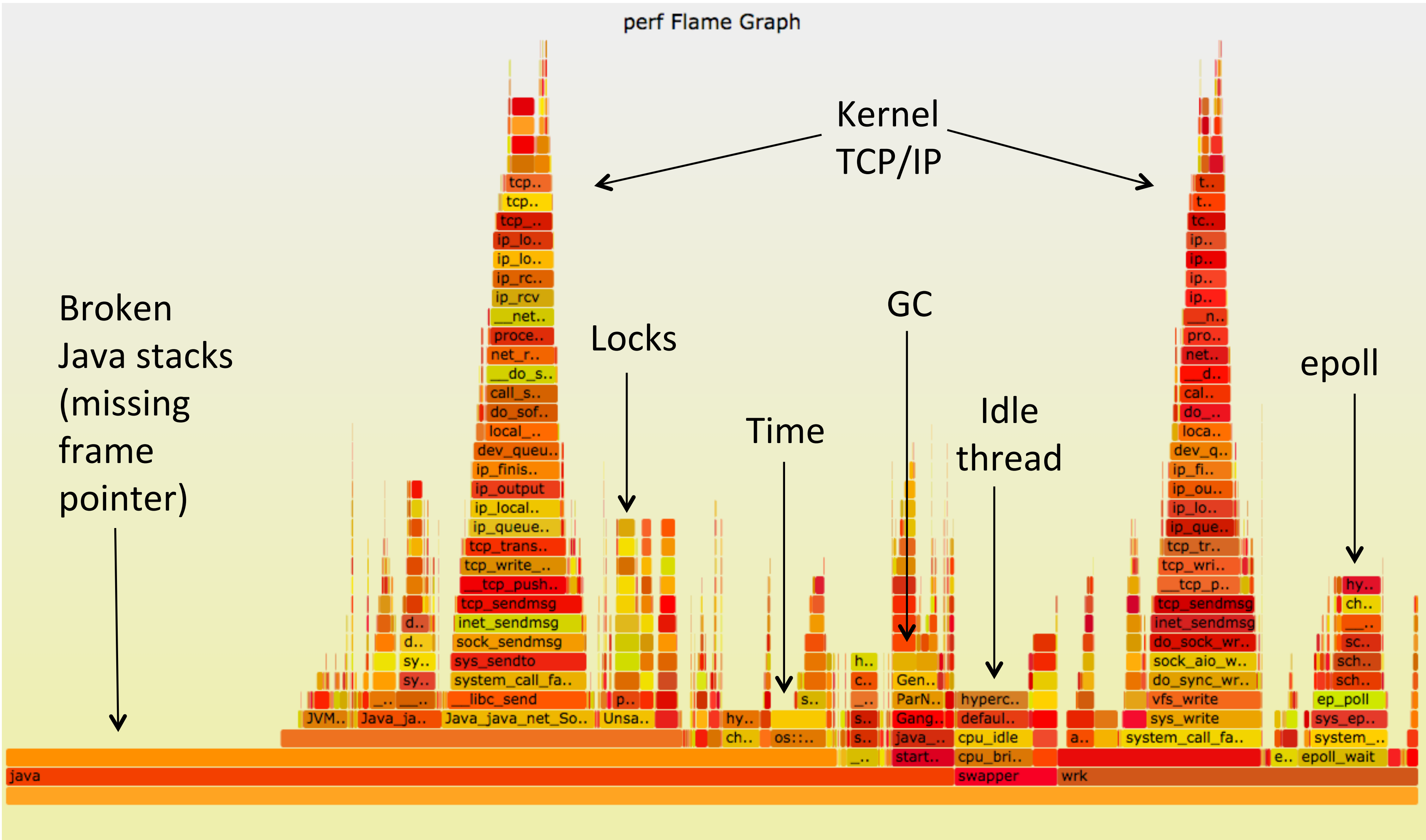
&

DISCUSSION

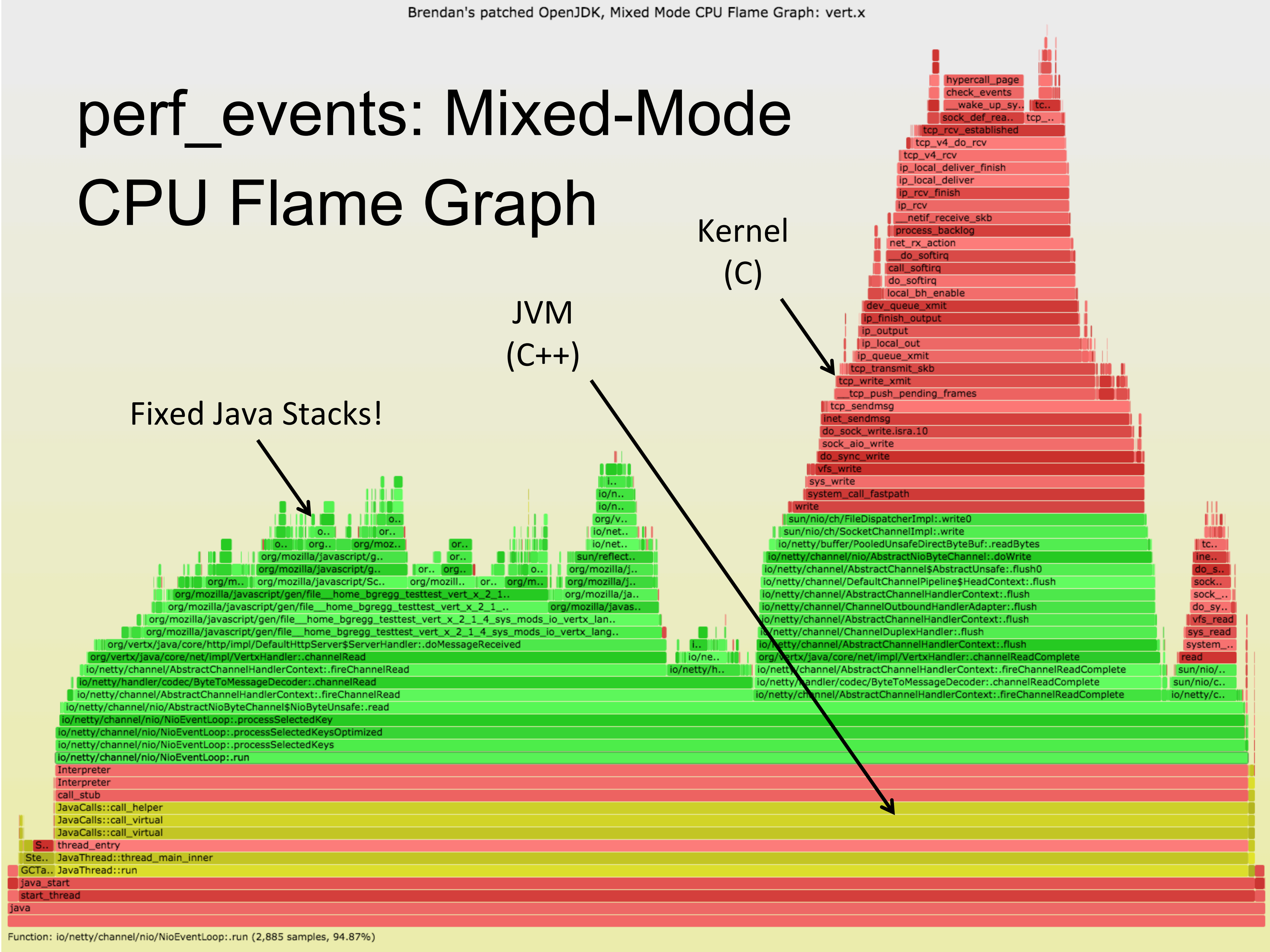
perf_events: Workflow



perf_events: CPU Flame Graph



perf_events: Mixed-Mode CPU Flame Graph



perf_events: Gotchas

- Stack traces and symbols often don't work.
  - Can be a significant project to fix them. It is worth it!
- C:
  - stacks: --fno-omit-frame-pointer
- Java:
  - stacks on x86: -XX:+PreserveFramePointer (JDK-8068945 for JDK9, JDK-8072465 for JDK8)
  - symbols: perf-map-agent (other solutions exist)
- Node.js:
  - symbols: run v8 with --perf_basic_prof

http://www.brendangregg.com/blog/2015-02-27/linux-profiling-at-netflix.html

perf_events: Counters

- Performance Monitoring Counters (PMCs):

```
$ perf list | grep –i hardware
  cpu-cycles OR cycles                                  [Hardware event]
  stalled-cycles-frontend OR idle-cycles-frontend       [Hardware event]
  stalled-cycles-backend OR idle-cycles-backend         [Hardware event]
  instructions                                          [Hardware event]
[…]
  branch-misses                                         [Hardware event]
  bus-cycles                                            [Hardware event]
  L1-dcache-loads                                       [Hardware cache event]
  L1-dcache-load-misses                                 [Hardware cache event]
[…]
  rNNN (see 'perf list --help' on how to encode it)     [Raw hardware event …
  mem:<addr>[:access]                                   [Hardware breakpoint]
```

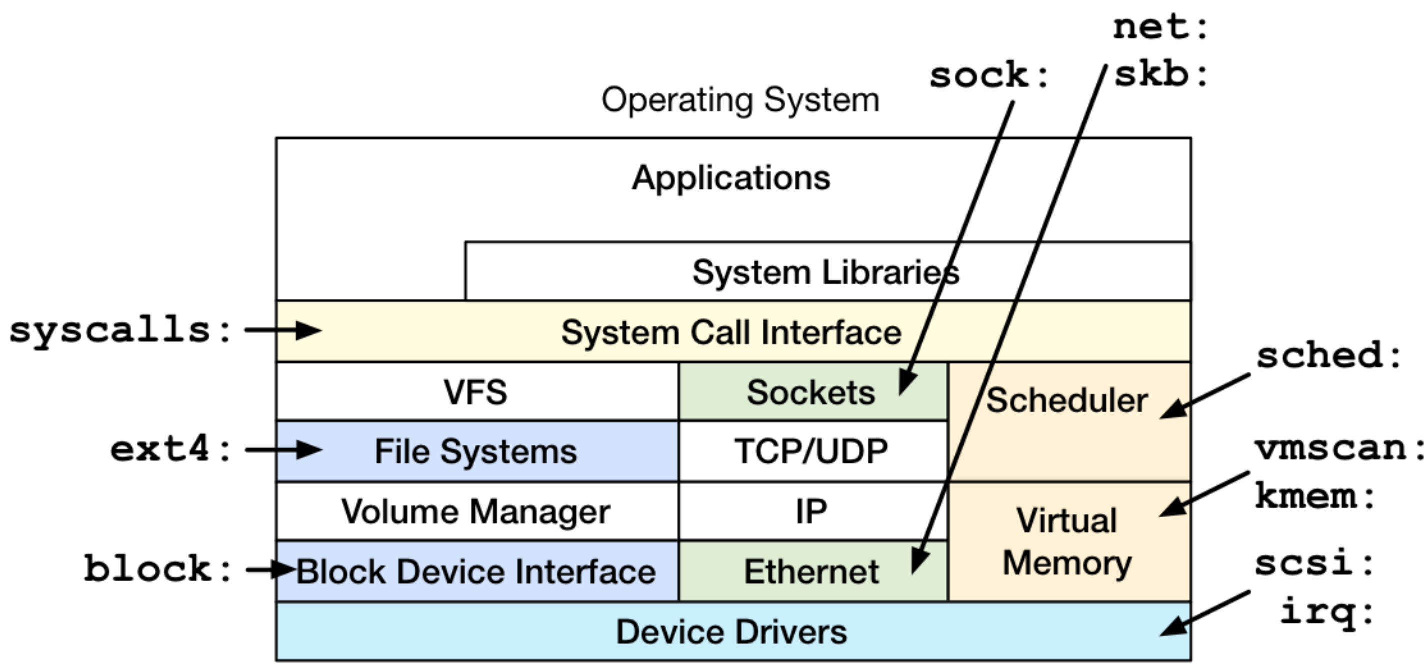
- Identify CPU cycle breakdowns, esp. stall types
- PMCs not enabled by-default in clouds (yet)
- Can be time-consuming to use (CPU manuals)
  - Please develop front-ends. Eg, tiptop.

Tracing

Tracing

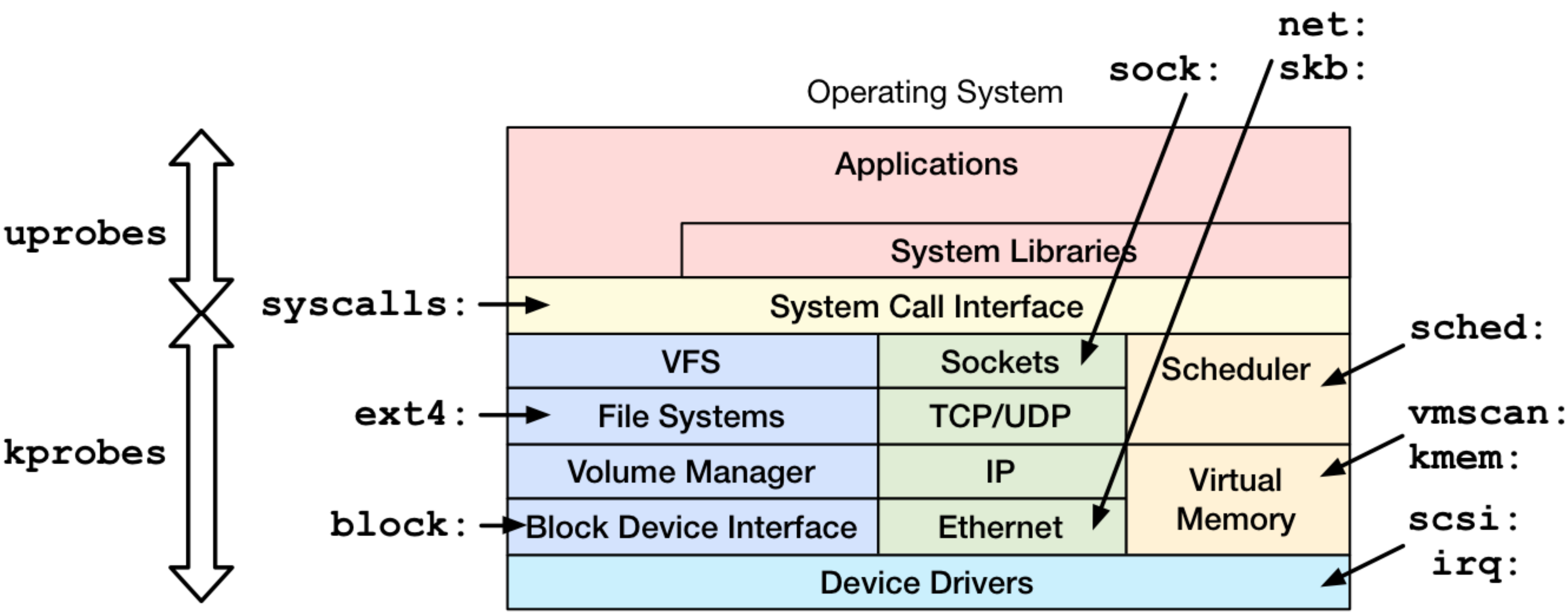
- Objectives:
  - Understand frameworks: tracepoints, kprobes, uprobes
  - Understand mainline tracers: ftrace, perf_events, eBPF
  - Awareness of other tracers: SystemTap, LTTng, ktap, sysdig
  - Awareness of what tracing can accomplish (eg, perf-tools)

Tracing Frameworks: Tracepoints



- Statically placed at logical places in the kernel
- Provides key event details as a "format" string

Tracing Frameworks: + probes



- kprobes: dynamic kernel tracing
  - function calls, returns, line numbers
- uprobes: dynamic user-level tracing

http://www.brendangregg.com/perf.html 2015

Linux Tracing Tools

ftrace

perf_events

eBPF

SystemTap

LTTng

ktap

dtrace4linux

OEL DTrace

sysdig

- Many choices (too many?), all still in development

Linux Tracing is Magic!

ftrace

perf_events

eBPF

SystemTap

LTTng

ktap

dtrace4linux

OEL DTrace

sysdig

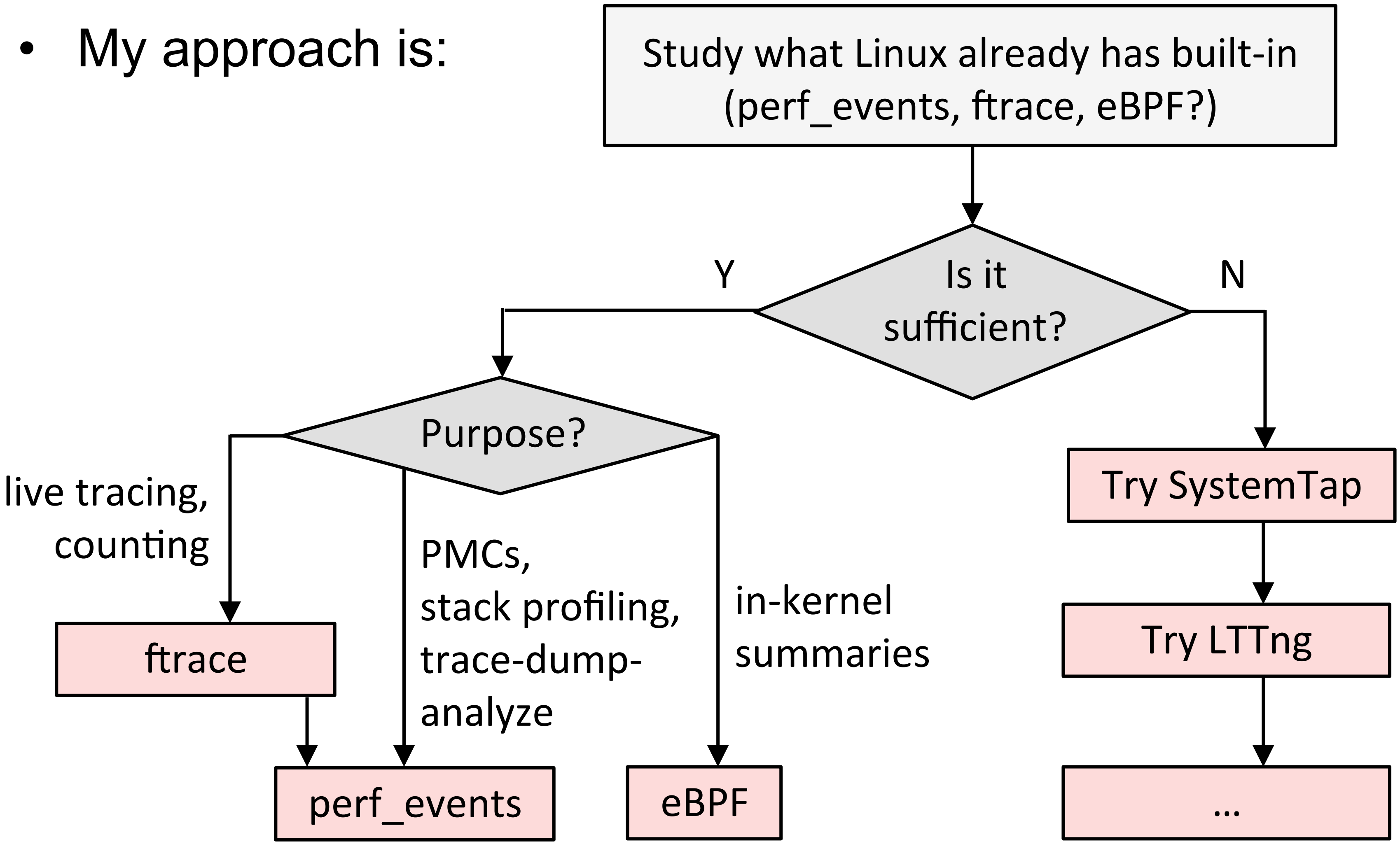
- (Thanks Deirdré Straughan & General Zoi's Pony Creator)

Choosing a Tracer

- Some companies standardize on one tracer
  - eg, SystemTap, LTTng, …

Choosing a Tracer

- My approach is:



ftrace

ftrace

- Added by Steven Rostedt and others since 2.6.27
- Already enabled on our servers (3.2+)
  - CONFIG_FTRACE, CONFIG_FUNCTION_PROFILER, …
  - Use directly via /sys/kernel/debug/tracing:

```
linux-4.0.0+# ls /sys/kernel/debug/tracing/
available_events            max_graph_depth         stack_max_size
available_filter_functions  options                 stack_trace
available_tracers           per_cpu                 stack_trace_filter
buffer_size_kb              printk_formats          trace
buffer_total_size_kb        README                  trace_clock
current_tracer              saved_cmdlines          trace_marker
dyn_ftrace_total_info       saved_cmdlines_size     trace_options
enabled_functions           set_event               trace_pipe
events                      set_ftrace_filter       trace_stat
free_buffer                 set_ftrace_notrace      tracing_cpumask
function_profile_enabled    set_ftrace_pid          tracing_max_latency
instances                   set_graph_function      tracing_on
kprobe_events               set_graph_notrace       tracing_thresh
kprobe_profile              snapshot
```

  - See Linux source: Documentation/trace/ftrace.txt

ftrace Front-Ends

- Steven wrote a front-end: trace-cmd
  - Multi-tool, works well
- I've developed the "perf-tools" front-ends
  - https://github.com/brendangregg/perf-tools
  - Both single & multi-purpose, Unix-like
  - Unsupported hacks: see WARNINGs
- perf-tools:
  - single-purpose: iosnoop, iolatency, opensnoop
  - multi-tools: funccount, funcgraph, kprobe

iosnoop

- Block I/O (disk) events with latency:

```
# ./iosnoop –ts
Tracing block I/O. Ctrl-C to end.
STARTs         ENDs           COMM      PID   TYPE DEV    BLOCK     BYTES LATms
5982800.302061 5982800.302679 supervise 1809  W    202,1  17039600  4096   0.62
5982800.302423 5982800.302842 supervise 1809  W    202,1  17039608  4096   0.42
5982800.304962 5982800.305446 supervise 1801  W    202,1  17039616  4096   0.48
5982800.305250 5982800.305676 supervise 1801  W    202,1  17039624  4096   0.43
[…]
```

```
# ./iosnoop –h
USAGE: iosnoop [-hQst] [-d device] [-i iotype] [-p PID] [-n name] [duration]
                 -d device       # device string (eg, "202,1)
                 -i iotype       # match type (eg, '*R*' for all reads)
                 -n name         # process name to match on I/O issue
                 -p PID          # PID to match on I/O issue
                 -Q              # include queueing time in LATms
                 -s              # include start time of I/O (s)
                 -t              # include completion time of I/O (s)
                 -h              # this usage message
                 duration        # duration seconds, and use buffers
[…]
```

iolatency

- Block I/O (disk) latency distributions:

```
# ./iolatency
Tracing block I/O. Output every 1 seconds. Ctrl-C to end.

  >=(ms) .. <(ms)   : I/O      |Distribution                          |
       0 -> 1       : 2104     |######################################|
       1 -> 2       : 280      |######                                |
       2 -> 4       : 2        |#                                     |
       4 -> 8       : 0        |                                      |
       8 -> 16      : 202      |####                                  |

  >=(ms) .. <(ms)   : I/O      |Distribution                          |
       0 -> 1       : 1144     |######################################|
       1 -> 2       : 267      |#########                             |
       2 -> 4       : 10       |#                                     |
       4 -> 8       : 5        |#                                     |
       8 -> 16      : 248      |#########                             |
      16 -> 32      : 601      |####################                  |
      32 -> 64      : 117      |####                                  |
[…]
```

opensnoop

- Trace open() syscalls showing filenames:

```
# ./opensnoop -t
Tracing open()s. Ctrl-C to end.
TIMEs            COMM          PID     FD FILE
4345768.332626   postgres      23886   0x8 /proc/self/oom_adj
4345768.333923   postgres      23886   0x5 global/pg_filenode.map
4345768.333971   postgres      23886   0x5 global/pg_internal.init
4345768.334813   postgres      23886   0x5 base/16384/PG_VERSION
4345768.334877   postgres      23886   0x5 base/16384/pg_filenode.map
4345768.334891   postgres      23886   0x5 base/16384/pg_internal.init
4345768.335821   postgres      23886   0x5 base/16384/11725
4345768.347911   svstat        24649   0x4 supervise/ok
4345768.347921   svstat        24649   0x4 supervise/status
4345768.350340   stat          24651   0x3 /etc/ld.so.cache
4345768.350372   stat          24651   0x3 /lib/x86_64-linux-gnu/libselinux…
4345768.350460   stat          24651   0x3 /lib/x86_64-linux-gnu/libc.so.6
4345768.350526   stat          24651   0x3 /lib/x86_64-linux-gnu/libdl.so.2
4345768.350981   stat          24651   0x3 /proc/filesystems
4345768.351182   stat          24651   0x3 /etc/nsswitch.conf
[…]
```

tpoint

- Who is creating disk I/O, and of what type?

```
# ./tpoint -H block:block_rq_insert
Tracing block:block_rq_insert. Ctrl-C to end.
# tracer: nop
#
#     TASK-PID    CPU#    TIMESTAMP  FUNCTION
#        | |       |          |         |
 flush-9:0-9318  [013] 1936182.007914: block_rq_insert: 202,16 W 0 () 160186560 + 8 [flush-9:0]
 flush-9:0-9318  [013] 1936182.007939: block_rq_insert: 202,16 W 0 () 280100936 + 8 [flush-9:0]
      java-9469  [014] 1936182.316184: block_rq_insert: 202,1 R 0 () 1319592 + 72 [java]
      java-9469  [000] 1936182.331270: block_rq_insert: 202,1 R 0 () 1125744 + 8 [java]
      java-9469  [000] 1936182.341418: block_rq_insert: 202,1 R 0 () 2699008 + 88 [java]
      java-9469  [000] 1936182.341419: block_rq_insert: 202,1 R 0 () 2699096 + 88 [java]
      java-9469  [000] 1936182.341419: block_rq_insert: 202,1 R 0 () 2699184 + 32 [java]
      java-9469  [000] 1936182.345870: block_rq_insert: 202,1 R 0 () 1320304 + 24 [java]
      java-9469  [000] 1936182.351590: block_rq_insert: 202,1 R 0 () 1716848 + 16 [java]
^C
Ending tracing...
```

tracepoint

type

size (sectors)

dev

offset

- tpoint traces a given tracepoint. -H prints the header.

tpoint -l

```
# ./tpoint -l
block:block_bio_backmerge
block:block_bio_bounce
block:block_bio_complete
block:block_bio_frontmerge
block:block_bio_queue
block:block_bio_remap
block:block_getrq
block:block_plug
block:block_rq_abort
block:block_rq_complete
block:block_rq_insert
block:block_rq_issue
block:block_rq_remap
block:block_rq_requeue
[…]
# ./tpoint –l | wc –l
1257
```

Listing tracepoints

- 1,257 tracepoints for this Linux kernel

funccount

- Count a kernel function call rate:

```
# ./funccount -i 1 'bio_*'
Tracing "bio_*"... Ctrl-C to end.

FUNC                                      COUNT
bio_attempt_back_merge                       26
bio_get_nr_vecs                             361
bio_alloc                                   536
bio_alloc_bioset                            536
bio_endio                                   536
bio_free                                    536
bio_fs_destructor                           536
bio_init                                    536
bio_integrity_enabled                       536
bio_put                                     729
bio_add_page                               1004

[...]
```

Counts are in-kernel, for low overhead

  - -i: set an output interval (seconds), otherwise until Ctrl-C

funcgraph

- Trace a graph of kernel code flow:

```
# ./funcgraph -Htp 5363 vfs_read
Tracing "vfs_read" for PID 5363... Ctrl-C to end.
# tracer: function_graph
#
#     TIME        CPU  DURATION                  FUNCTION CALLS
#      |          |     |   |                     |   |   |   |
4346366.073832 |   0)               |  vfs_read() {
4346366.073834 |   0)               |    rw_verify_area() {
4346366.073834 |   0)               |      security_file_permission() {
4346366.073834 |   0)               |        apparmor_file_permission() {
4346366.073835 |   0)   0.153 us    |          common_file_perm();
4346366.073836 |   0)   0.947 us    |        }
4346366.073836 |   0)   0.066 us    |        __fsnotify_parent();
4346366.073836 |   0)   0.080 us    |        fsnotify();
4346366.073837 |   0)   2.174 us    |      }
4346366.073837 |   0)   2.656 us    |    }
4346366.073837 |   0)               |    tty_read() {
4346366.073837 |   0)   0.060 us    |      tty_paranoia_check();
[…]
```

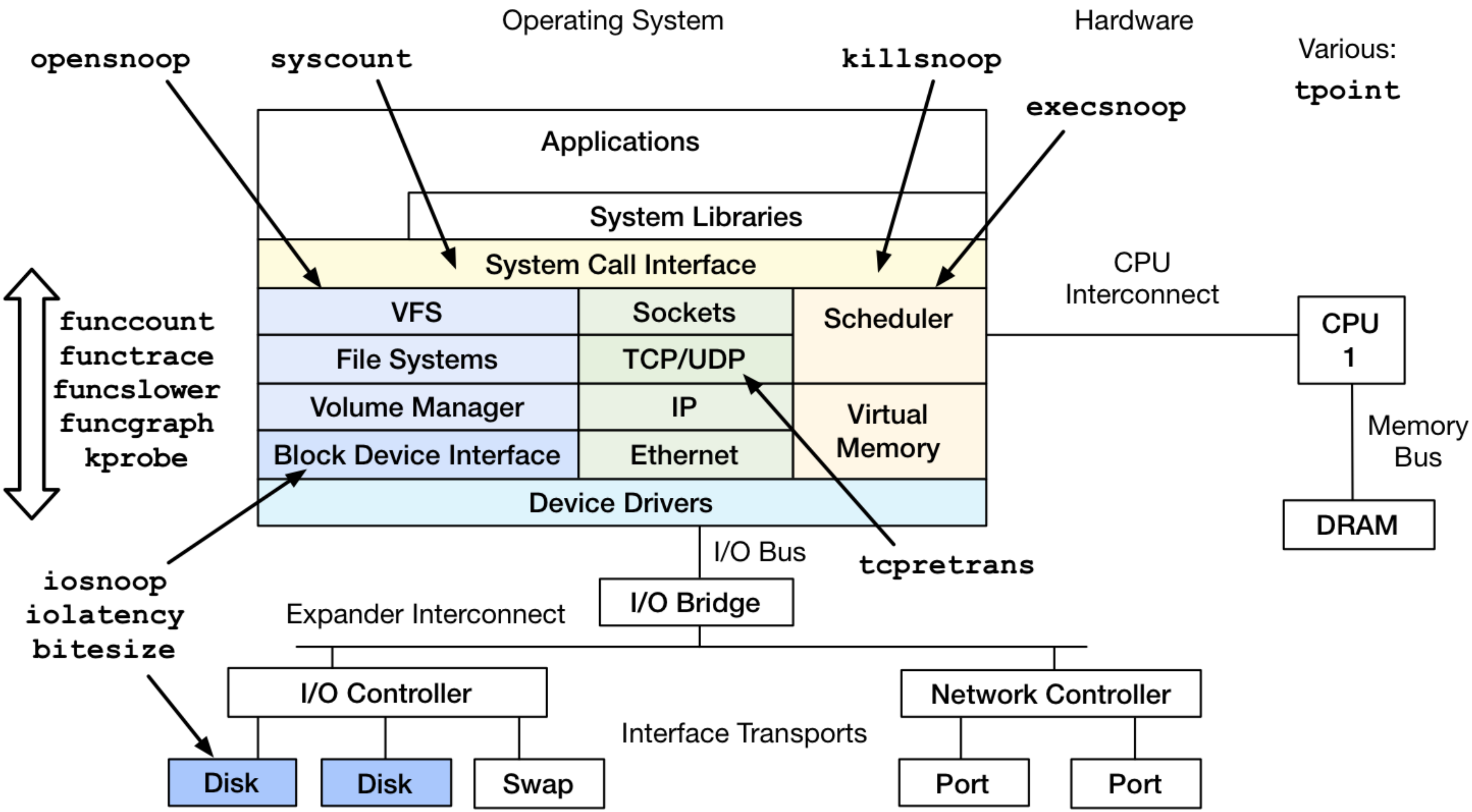
kprobe

- Dynamically trace a kernel function call or return, with variables, and in-kernel filtering:

```
# ./kprobe 'p:open do_sys_open filename=+0(%si):string' 'filename ~ "*stat"'
Tracing kprobe myopen. Ctrl-C to end.
        postgres-1172  [000] d... 6594028.787166: open: (do_sys_open
+0x0/0x220) filename="pg_stat_tmp/pgstat.stat"
        postgres-1172  [001] d... 6594028.797410: open: (do_sys_open
+0x0/0x220) filename="pg_stat_tmp/pgstat.stat"
        postgres-1172  [001] d... 6594028.797467: open: (do_sys_open
+0x0/0x220) filename="pg_stat_tmp/pgstat.stat"
^C
Ending tracing...
```

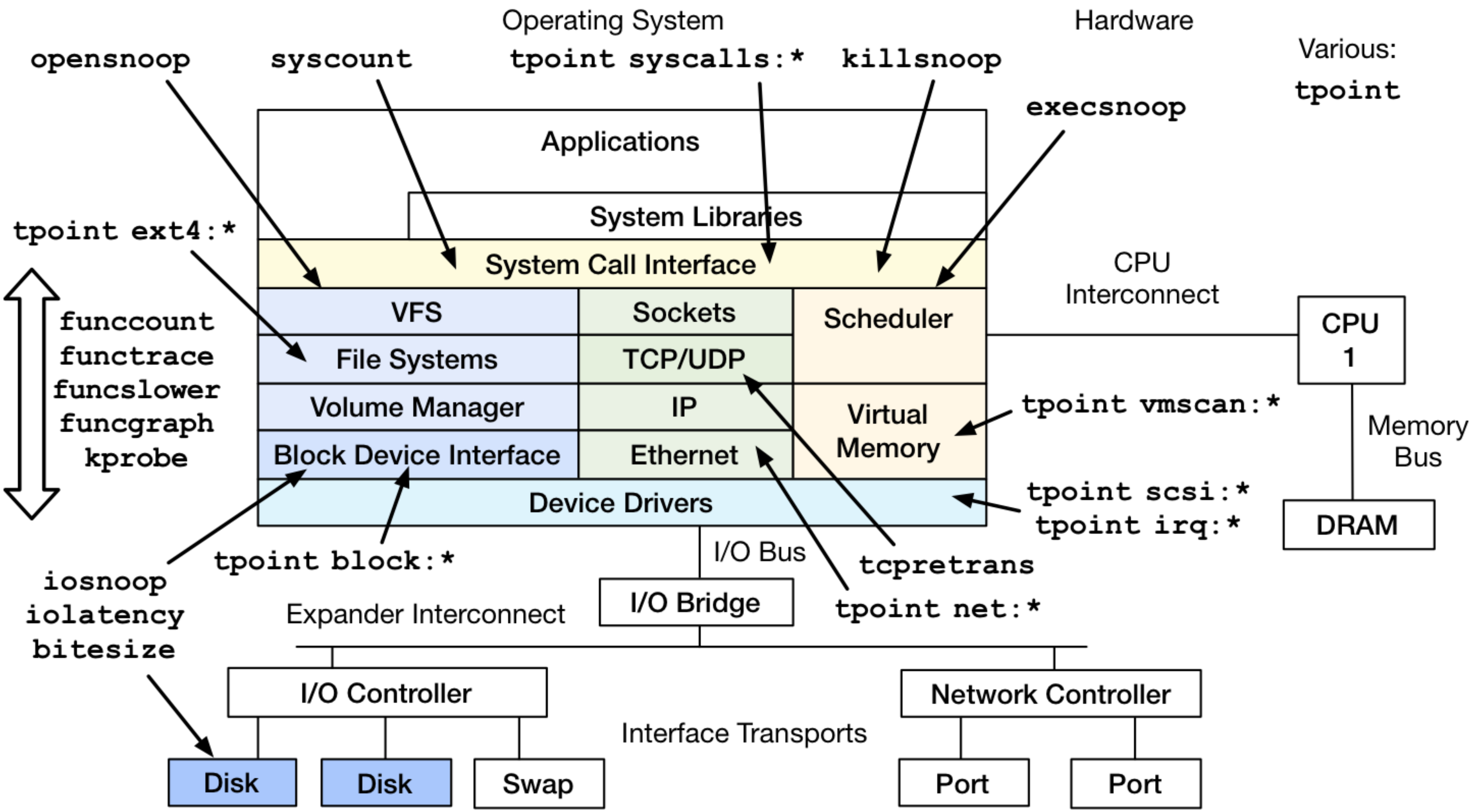
- Add -s for stack traces; -p for PID filter in-kernel.
- Quickly confirm kernel behavior; eg: did a tunable take effect?

perf-tools (so far…)



http://www.brendangregg.com/linuxperf.html 2015

perf-tools (so far…)



perf_events

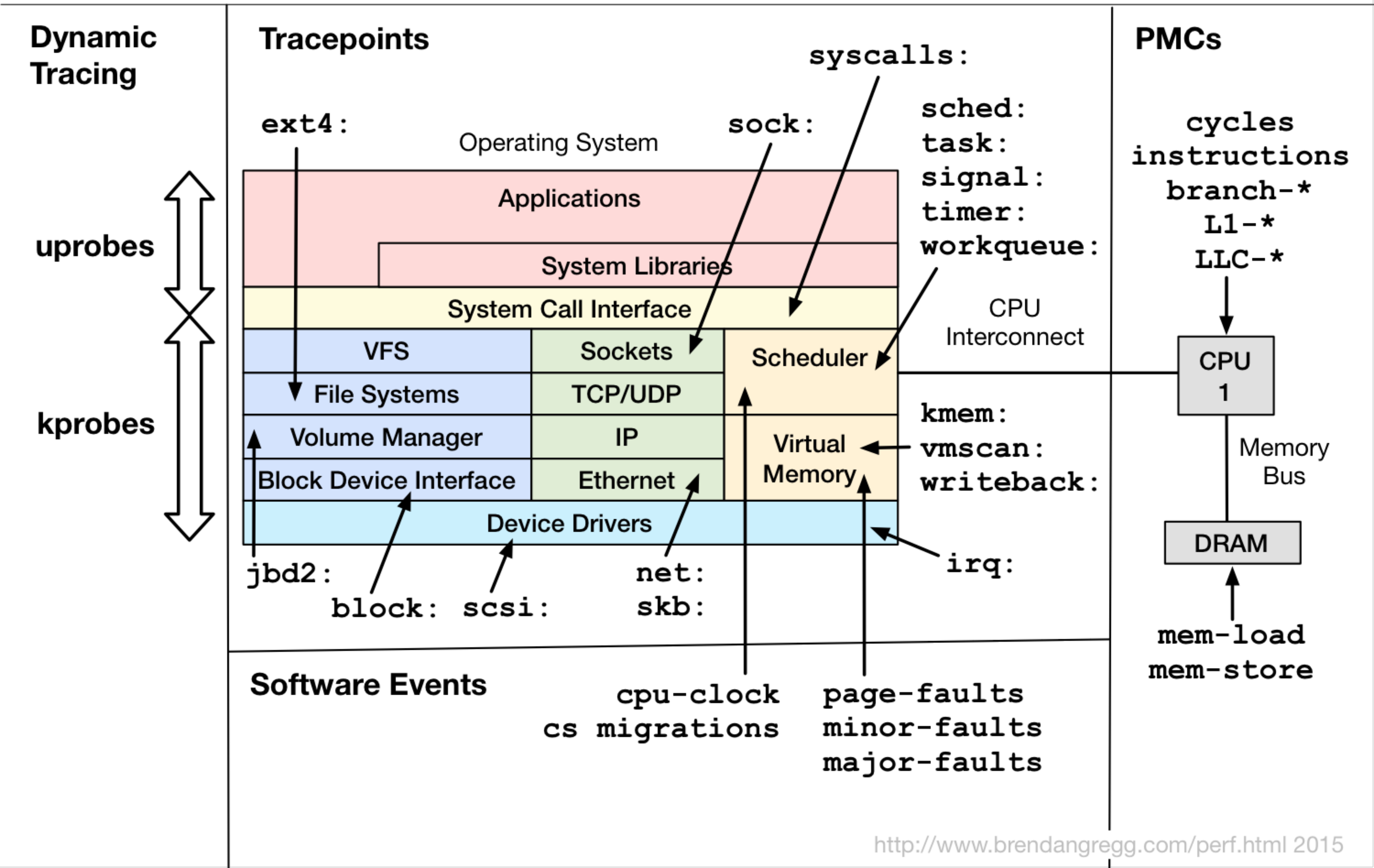
perf_events

- Powerful profiler (covered earlier)
- … and tracer:
  - User-level and kernel dynamic tracing
  - Kernel line tracing and local variables (debuginfo)
  - Kernel filtering expressions
  - Efficient in-kernel counts (perf stat)
- Not very programmable, yet
  - Limited kernel summaries. Should improve with eBPF.

perf_events Listing Tracepoints

```
# perf list 'block:*'
  skb:kfree_skb                                        [Tracepoint event]
  skb:consume_skb                                      [Tracepoint event]
  skb:skb_copy_datagram_iovec                          [Tracepoint event]
  net:net_dev_xmit                                     [Tracepoint event]
  net:net_dev_queue                                    [Tracepoint event]
  net:netif_receive_skb                                [Tracepoint event]
  net:netif_rx                                         [Tracepoint event]
[…]
  block:block_touch_buffer                             [Tracepoint event]
  block:block_dirty_buffer                             [Tracepoint event]
  block:block_rq_abort                                 [Tracepoint event]
  block:block_rq_requeue                               [Tracepoint event]
  block:block_rq_complete                              [Tracepoint event]
  block:block_rq_insert                                [Tracepoint event]
  block:block_rq_issue                                 [Tracepoint event]
  block:block_bio_bounce                               [Tracepoint event]
  block:block_bio_complete                             [Tracepoint event]
  block:block_bio_backmerge                            [Tracepoint event]
[...]
```

Linux Event Sources



perf_events Tracing Tracepoints

```
# perf record -e block:block_rq_complete -a sleep 10
[ perf record: Woken up 1 times to write data ]
[ perf record: Captured and wrote 0.428 MB perf.data (~18687 samples) ]
# perf script
        run 30339 [000] 2083345.722767: block:block_rq_complete: 202,1 W () 12984648 + 8 [0]
        run 30339 [000] 2083345.722857: block:block_rq_complete: 202,1 W () 12986336 + 8 [0]
        run 30339 [000] 2083345.723180: block:block_rq_complete: 202,1 W () 12986528 + 8 [0]
    swapper     0 [000] 2083345.723489: block:block_rq_complete: 202,1 W () 12986496 + 8 [0]
    swapper     0 [000] 2083346.745840: block:block_rq_complete: 202,1 WS () 1052984 + 144 [0]
  supervise 30342 [000] 2083346.746571: block:block_rq_complete: 202,1 WS () 1053128 + 8 [0]
  supervise 30342 [000] 2083346.746663: block:block_rq_complete: 202,1 W () 12986608 + 8 [0]
        run 30342 [000] 2083346.747003: block:block_rq_complete: 202,1 W () 12986832 + 8 [0]
[...]
```

- If -g is used in "perf record", stack traces are included
- If "perf script" output is too verbose, try "perf report", or making a flame graph

perf_events Report

```
# perf record –e skb:consume_skb -ag
^C[ perf record: Woken up 1 times to write data ]
[ perf record: Captured and wrote 0.065 MB perf.data (~2851 samples) ]
# perf report -n --stdio
[...]
    74.42%  swapper  [kernel.kallsyms]  [k] consume_skb
            |
            --- consume_skb
                arp_process
                arp_rcv
                __netif_receive_skb_core
                __netif_receive_skb
                netif_receive_skb
                virtnet_poll
                net_rx_action
                __do_softirq
                irq_exit
                do_IRQ
                ret_from_intr
                default_idle
                cpu_idle
                start_secondary
[…]
```

Summarizing stack traces for a tracepoint

eBPF

eBPF

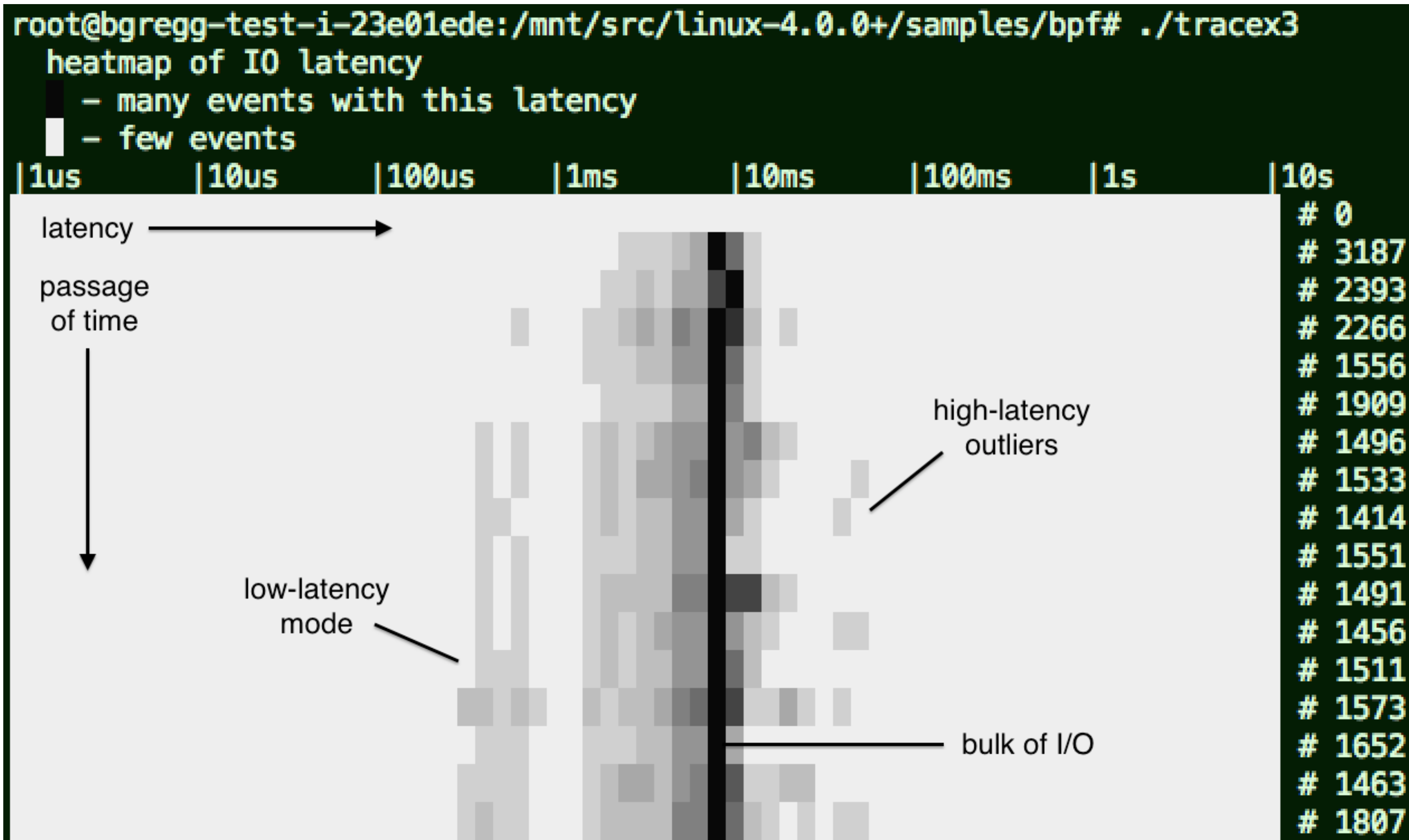
- Extended BPF: programs on tracepoints
  - High performance filtering: JIT
  - In-kernel summaries: maps
  - Developed by Alexei Starovoitov (Plumgrid)
- Currently being integrated in parts (Linux 3.18, 4.1, …)

```
# ./bitehist
Tracing block device I/O... Interval 5 secs. Ctrl-C to end.

     kbytes           : count     distribution
       0 -> 1         : 3        |                                      |
       2 -> 3         : 0        |                                      |
       4 -> 7         : 3395     |**************************************|
       8 -> 15        : 1        |                                      |
      16 -> 31        : 2        |                                      |
      32 -> 63        : 738      |*******                               |
      64 -> 127       : 3        |                                      |
     128 -> 255       : 1        |                                      |
```

in-kernel summary

eBPF

- Example in-kernel latency heat map:



Other Tracers

SystemTap

- Fully programmable, fully featured
  - Including access to user-level tracepoints
- Compiles tracing programs into kernel modules
  - Needs a compiler, and takes time
- “Works great on Red Hat”
  - I keep trying on other distros and have hit trouble in the past
  - Make sure you are on the latest version (>=2.6)
- "Works great with kernel debuginfo"
  - Suited for kernel developers who have it handy
  - A difficult requirement for our cloud environment

"Lightweight" SystemTap

- SystemTap can be used without kernel debuginfo
  - Makes life harder, but some tasks are still possible
  - **providers**: nd_syscall, kprobe.function, kernel.trace, …
  - **args** via: int_arg(), uint_arg(), pointer_arg(), user_string()
- Something I've experimented with. Examples:
  - https://github.com/brendangregg/systemtap-lwtools/

```
# stap -e 'global a; probe nd_syscall.write { a <<< int_arg(3); } probe end
{ print(@hist_log(a)); }'
^Cvalue |-------------------------------------------------- count
[…]
     8 |                                                    0
    16 |@@@@@@@@@@@@@@@@@@@@@@                             22
    32 |@@@@@@@@@@@@@@@                                    15
    64 |@@@@@@@@@@@@@@@@@                                  17
   128 |@@                                                  2
   256 |@@                                                  2
   512 |                                                    0
```

ktap

- Was a very promising new Linux tracer:
  - Sampling, static & dynamic tracing
  - Lightweight, simple. Uses bytecode.
  - Suited for embedded devices
- Development suspended while eBPF integrates
- Will it restart?

sysdig

- sysdig: Innovative new tracer. Simple expressions:

```
sysdig fd.type=file and evt.failed=true
sysdig evt.type=open and fd.name contains /etc
sysdig -p"%proc.name %fd.name" "evt.type=accept and proc.name!=httpd”
```

- Replacement for strace? (or “perf trace” will)
- Programmable “chisels”. Eg, one of mine:

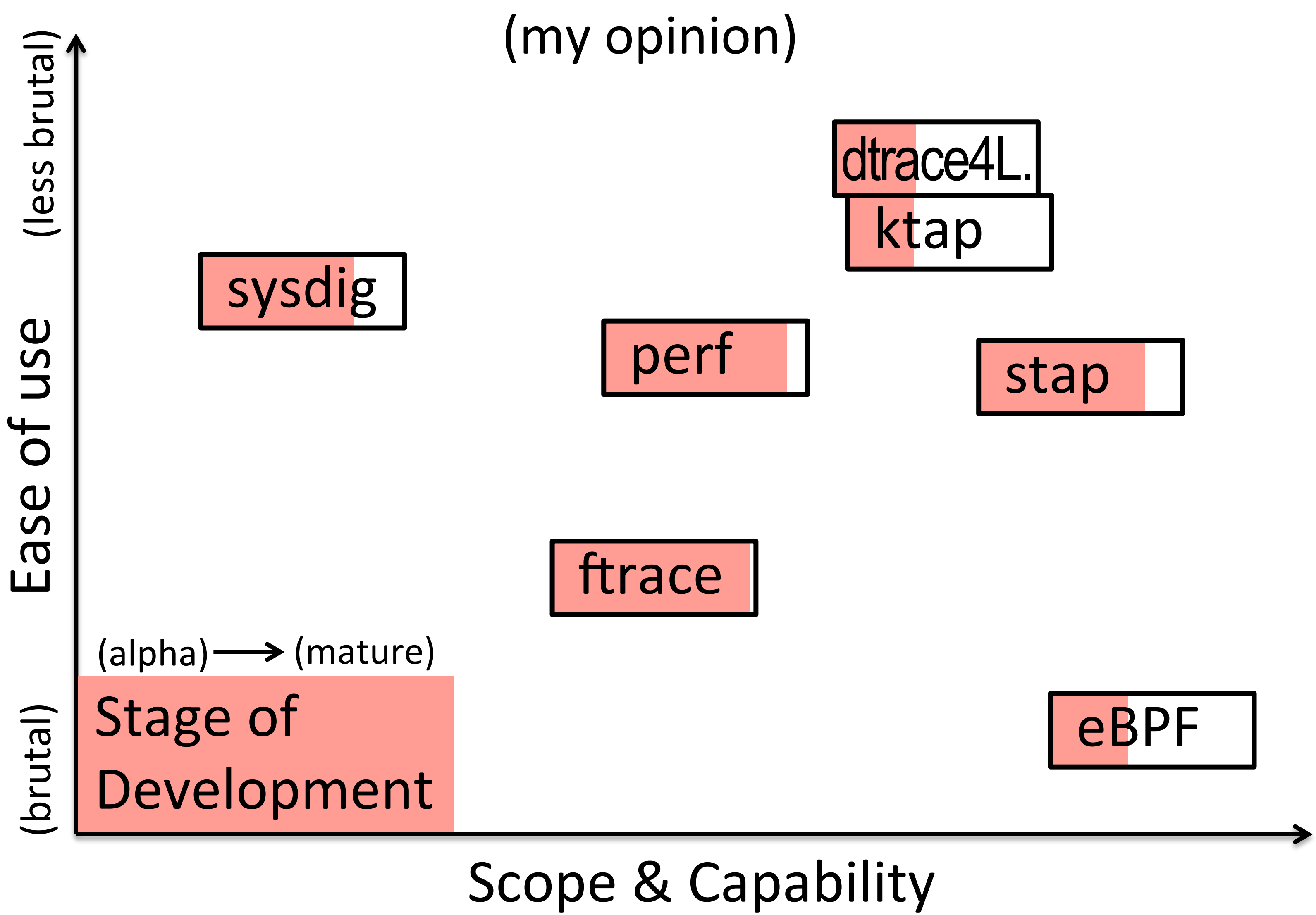
```
# sysdig -c fileslower 1
TIME                    PROCESS      TYPE     LAT(ms) FILE
2014-04-13 20:40:43.973 cksum        read           2 /mnt/partial.0.0
2014-04-13 20:40:44.187 cksum        read           1 /mnt/partial.0.0
2014-04-13 20:40:44.689 cksum        read           2 /mnt/partial.0.0
[…]
```

- Currently syscalls and user-level processing only
  – I'm not sure it can be optimized enough for kernel tracing, unless it adopts eBPF for in-kernel processing & summaries

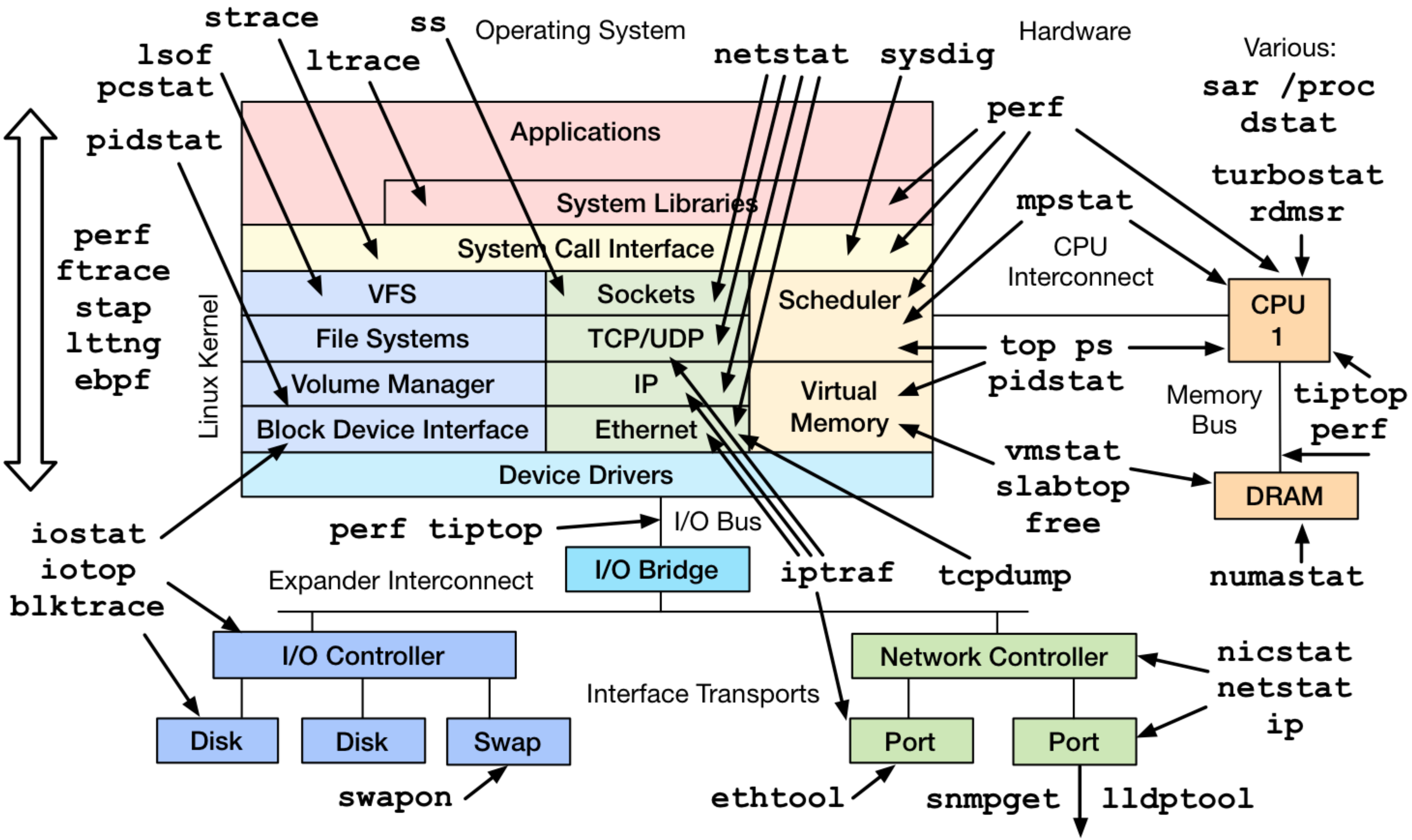
Present & Future

- Present:
  - ftrace & perf_events solving many needs today:
    - PMC profiling, stack profiling, tracepoint & dynamic tracing, …
- Expected Future:
  - eBPF for kernel summaries & advanced programs
  - eBPF perf integration to improve ease of use
- Possible Future:
  - eBPF high level language (ktap?)
  - ftrace/eBPF integration
  - Other tracer eBPF integration (SystemTap, LTTng, sysdig?)
  - One of the other tracers going mainline?

The Tracing Landscape, May 2015



In Summary…



http://www.brendangregg.com/linuxperf.html 2015

Methodologies Summary

- Objectives:
  - Recognize the Streetlight Anti-Method
  - Perform the Workload Characterization Method
  - Perform the USE Method
  - Be aware of other methodologies

Try to start with the questions (methodology), to help guide your use of the tools

Tools Summary

- Objectives:
  - Perform the USE Method for resource utilization
  - Perform Workload Characterization for disks, network
  - Have exposure to various observability tools:
    - Basic: vmstat, iostat, mpstat, ps, top, …
    - Intermediate: tcpdump, netstat, nicstat, pidstat, sar, …
    - Advanced: ss, slaptop, perf_events, …
  - Perform Active Benchmarking
  - Understand tuning risks
  - Perform Static Performance Tuning

Print out the tools diagrams for your office wall

Profiling & Tracing Summary

- Objectives:
  - Profile CPU usage by stack sampling
  - Generate CPU flame graphs
  - Understand gotchas with stacks & symbols
  - Understand frameworks: tracepoints, kprobes, uprobes
  - Understand mainline tracers: ftrace, perf_events, eBPF
  - Awareness of other tracers: SystemTap, LTTng, ktap, sysdig
  - Awareness of what tracing can accomplish (eg, perf-tools)

I've hopefully turned some unknown unknowns into known unknowns

References & Links

- Systems Performance: Enterprise and the Cloud, Prentice Hall, 2013
- http://www.brendangregg.com/linuxperf.html incl. tools diagrams as PNGs
- http://www.brendangregg.com/perf.html#FlameGraphs
- http://www.brendangregg.com/blog/2015-02-27/linux-profiling-at-netflix.html
- http://www.brendangregg.com/blog/2015-03-17/linux-performance-analysis-perf-tools.html
- http://www.brendangregg.com/blog/2015-05-15/ebpf-one-small-step.html
- nicstat: http://sourceforge.net/projects/nicstat/
- tiptop: http://tiptop.gforge.inria.fr/
  - Tiptop: Hardware Performance Counters for the Masses, Erven Rohou, Inria Research Report 7789, Nov 2011.
- ftrace & perf-tools
  - https://github.com/brendangregg/perf-tools
  - http://lwn.net/Articles/608497/ Ftrace: The hidden light switch
- MSR tools: https://github.com/brendangregg/msr-cloud-tools
- pcstat: https://github.com/tobert/pcstat
- eBPF: http://lwn.net/Articles/603983/
- ktap: http://www.ktap.org/
- SystemTap: https://sourceware.org/systemtap/
- sysdig: http://www.sysdig.org/
- Tux by Larry Ewing; Linux® is the registered trademark of Linus Torvalds in the U.S. and other countries.

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Thanks

- Questions?
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